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Intermediates of α-Eliminations [*]

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α-Elimination denotes the removal of two substituents from the same carbon atom. Present-day knowledge of these reactions, their intermediates, and end-products is reviewed, with particular emphasis on the question of the occurrence of carbenes and the role of organometallic (carbanion) intermediates.

1. Introduction

Elimination reactions cover a wide field in preparative and theoretical organic chemistry. However, α- or 1,1-elimination has long been overshadowed by the more familiar β- or 1,2-elimination [1] which has been more extensively investigated. This is the reason for the cursory treatment of α-elimination even in modern textbooks. Nevertheless, interest in these reactions can be traced back a long way. Attempts were made to prepare methylene from methanol [2], methyl chloride [3], and methylene iodide [4] before the tetravalency of carbon had yet been established. Influenced by his work on isonitriles and fulminic acid derivatives, *Nef* [5] published his "general methylene theory" in 1897, in which he tried to explain all substitutions as resulting from α-elimination and addition. This concept fell into disfavor because of its excessive generalization, and only recently has it been reinstated in certain special cases. Isolated references to α-elimination may be found in the works of *Löb* [6], *Staudinger* [7], and *Ingold* [8].

The development of carbene chemistry [9] has given a new impetus to the work, since α-elimination was of interest as a possible route to "energy-deficient" carbenes. The results obtained were first interpreted simply as carbene reactions. It was soon shown, however, that organometallic (carbanion) intermediates could also play an important part, and in certain cases the appearance of carbenes was denied [10]. It is hoped that a critical survey of the field, including own results, some of which have not been published, will contribute to the elucidation of these problems.

2. Solvolysis of Haloforms

As a result of the excellent work of *Hine* and his school, the reaction of haloforms (trihalogenomethanes) with bases is one of the most thoroughly investigated cases of α-elimination. The most important results will now be summarized, since they present several problems of α-elimination in a particularly clear light.

In fluorine-free haloforms the base-catalysed H–D interchange is 10^3 to 10^5 times faster than any other reaction [11–15]. Solvolysis is therefore introduced by

[*] Extended version of lectures delivered by the author in Gießen, München, Freiburg, Darmstadt, Heidelberg, and Braunschweig (Germany).

[1] More recent summaries: *J. F. Bunnett*, Angew. Chem. *74*, 731 (1962); Angew. Chem. internat. Edit. *1*, 225 (1962); *R. F. Hudson*, Chimia *16*, 173 (1962); *D. V. Banthorpe:* Elimination Reactions. Elsevier, Amsterdam 1963.

[2] *J. B. Dumas*, Ann. Chim. Physique [2] *58*, 28 (1835); *H. V. Regnault*, ibid. [2] *71*, 427 (1839).

[3] *A. Perrot*, Liebigs Ann. Chem. *101*, 374 (1857).

[4] *A. M. Butlerov*, Liebigs Ann. Chem. *120*, 356 (1861).

[5] *J. U. Nef*, Liebigs Ann. Chem. *298*, 202 (1897).

[6] *W. Löb*, Z. Elektrochem. angew. physik. Chem. *7*, 903 (1901); Ber. dtsch. chem. Ges. *36*, 3059 (1903).

[7] *H. Staudinger* and *O. Kupfer*, Ber. dtsch. chem. Ges. *44*, 2197 (1911); *45*, 501 (1912).

[8] *C. K. Ingold* and *J. A. Jessop*, J. chem. Soc. (London) *1930*, 709.

[9] *J. Hine:* Divalent Carbon. Ronald Press, New York 1964; *W. Kirmse:* Carbene Chemistry. Academic Press, New York 1964.

[10] *H. Hoberg*, Liebigs Ann. Chem. *656*, 1 (1962).

[11] *J. Hine, R. C. Peek jr.*, and *B. D. Oakes*, J. Amer. chem. Soc. *76*, 827 (1954).

[12] *J. Hine* and *N. W. Burske*, J. Amer. chem. Soc. *78*, 3337 (1956).

[13] *J. Hine, N. W. Burske, M. Hine*, and *P. B. Langford*, J. Amer. chem. Soc. *79*, 1406 (1957).

[14] *J. Hine* and *P. B. Langford*, J. Amer. chem. Soc. *79*, 5497 (1957).

[15] *J. Hine, R. Butterworth*, and *P. B. Langford*, J. Amer. chem. Soc. *80*, 819 (1958).

the rapid and reversible formation of a trihalogenocarbanion [Equation (a)].

$$HCX_3 + B^{\ominus} \rightleftharpoons X_3C^{\ominus} + BH \qquad (a)$$

The rate-determining step of the solvolysis is to be found among the subsequent reactions of the trihalogenocarbanion. There are two possible interpretations which fit the kinetic data (the reaction is first order with respect to the haloform and the base [16,17]):

α) A slow S_N1 reaction of the trihalogenocarbanion to give a dihalogenocarbene, followed by rapid conversion of the carbene into carbon monoxide and formate (the course of which does not concern us here) [see Equation (b)].

$$X_3C^{\ominus} \xrightarrow{\text{slow}} X_2C: + X^{\ominus}$$
$$X_2C: \xrightarrow[H_2O,\ HO^{\ominus}]{\text{fast}} CO,\ HCO_2^{\ominus} \qquad (b)$$

β) A slow S_N2 reaction of the trihalogenocarbanion, according to Equation (c).

$$X_3C^{\ominus} + H_2O \xrightarrow{\text{slow}} X_2C^{\ominus}\text{-}\overset{\oplus}{O}H_2 + X^{\ominus}$$
$$X_2C^{\ominus}\text{-}\overset{\oplus}{O}H_2 \xrightarrow[H_2O,\ HO^{\ominus}]{\text{fast}} CO,\ HCO_2^{\ominus} \qquad (c)$$

In the carbene mechanism (b), the nucleophilic attack takes place after the rate-determining step, whereas in mechanism (c) the nucleophilic attack is identical with the rate-determining step. It follows that the effect of added anions $X^{\ominus}$ on the kinetics provides a means of distinguishing between the two mechanisms (b) and (c). In (c), the starting materials and the end-products of the substitution are identical:

$$X^{\ominus} + X_3C:^{\ominus} \rightarrow X^{\ominus} + X_3C:^{\ominus}$$

Such a reaction cannot affect the kinetics. In (b), on the other hand, the step

$$X^{\ominus} + :CX_2 \rightarrow X_3C:^{\ominus}$$

constitutes a reversal of the rate-determining step, and hence leads to a decrease in the overall rate of the reaction. Such an effect has in fact been observed on addition of halide ions [17]. The action of nucleophilic anions in the reaction of haloforms with bases therefore consists, at least partly, in addition to the intermediate carbene. The addition of olefins, preferably in aprotic media, yields 1,1-dihalogenocyclopropanes [see Reaction (d)] [9,18,19]. Competitive experiments have shown that the olefin behaves as a nucleophile in this reaction (the rate of the reaction increases with increasing electron density of the C=C bond). By analogy with the behavior of nucleophilic anions, it could be assumed that olefins react with the dihalogenocarbene and not with the trihalogeno carbanion. However, this view has been shaken by the latest observations according to which trichloromethyllithium, which is stable at low temperatures, attacks olefins as an electrophile [20].

$$B^{\ominus} + HCX_3 + \rangle C{=}C\langle \rightarrow \text{(cyclopropane, X X)} + BH + X^{\ominus} \qquad (d)$$

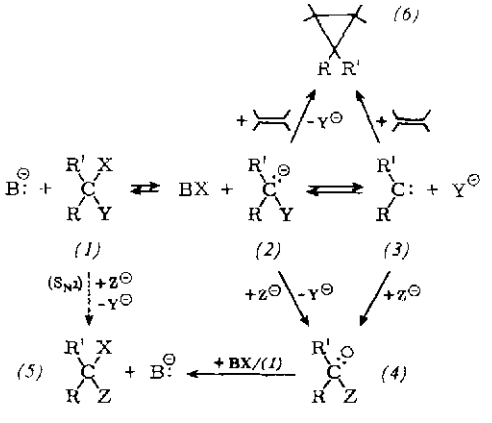
Haloforms with two fluorine substituents occupy a special position. The solvolysis of these compounds is unexpectedly fast, and takes place without H–D exchange [14,21,22]. The behavior of haloforms containing one fluorine atom [13,23] shows that fluorine makes carbanion formation more difficult, and stabilizes the carbene. *Hine* has therefore suggested a concerted α-elimination mechanism for haloforms containing two fluorine atoms. The energetically unfavorable trihalogenocarbanion stage is by-passed, and the relatively stable difluorocarbene is formed directly [Equation (e)].

$$B:^{\ominus} + HCF_2X \rightarrow B^{\delta\ominus}\cdots H\cdots CF_2\cdots X^{\delta\ominus} \rightarrow BH + :CF_2 + X^{\ominus} \qquad (e)$$

On the other hand, difluoromethyl phenyl sulfone, $C_6H_5{-}SO_2{-}CHF_2$, follows the two-step mechanism (stabilization of the carbanion) [24].

3. Scheme of the α-Elimination

On the basis of the special case of the solvolysis of haloforms, a scheme for the α-elimination will now be formulated and its general applicability tested [see Scheme 1].



Scheme 1. The general principle of α-elimination.

Two substituents (R, R') on the reacting carbon atom do not participate directly in the α-elimination. One group (X) can be removed as a cation by means of a base ($B:^{\ominus}$), while a second group (Y) may be lost as an anion. If these steps occur in suc-

[16] *J. Hine*, J. Amer. chem. Soc. *72*, 2438 (1950).

[17] *J. Hine* and *A. M. Dowell jr.*, J. Amer. chem. Soc. *76*, 2688 (1954).

[18] *W. v. E. Doering* and *A. K. Hoffmann*, J. Amer. chem. Soc. *76*, 6162 (1954).

[19] *P. S. Skell* and *A. Y. Garner*, J. Amer. chem. Soc. *78*, 3409 (1956).

[20] *W. T. Miller jr.* and *D. M. Whalen*, J. Amer. chem. Soc. *86*, 2089 (1964).

[21] *J. Hine* and *J. J. Porter*, J. Amer. chem. Soc. *79*, 5493 (1957).

[22] *J. Hine* and *A. D. Ketley*, J. org. Chemistry *25*, 606 (1960).

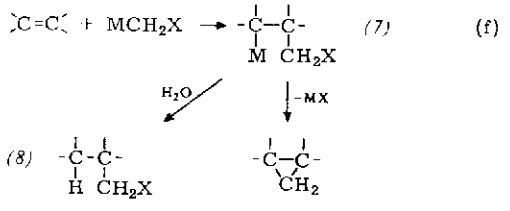
[23] *J. Hine* and *S. J. Ehrenson*, J. Amer. chem. Soc. *80*, 824 (1958).

[24] *J. Hine* and *J. J. Porter*, J. Amer. chem. Soc. *82*, 6178 (1960).

cession, an organometallic (or carbanion) intermediate *(2)* is formed. Direct formation of carbene *(3)* from *(1)* is also possible, as seen in the case of haloforms with two fluorine atoms. These reactions finally lead to substitution products *(5)* and/or olefin addition products *(6)*. In certain cases, "dimers" of the type RR'C=CRR' are formed. All the end-products can be derived from the intermediates *(2)* or *(3)*.

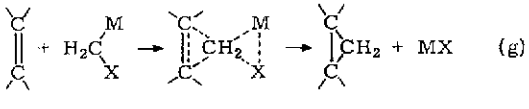
A nucleophile $Z^{\ominus}$ can yield a new organometallic (carbanion) intermediate *(4)*, either by addition to the carbene *(3)*, or by substitution in *(2)*. This intermediate then adds on X to form the substitution product *(5)*. Direct substitution in the starting material *(1)* can also lead to *(5)*. It is generally comparatively easy to rule out this alternative. It is much more difficult to decide whether the reaction proceeds *via (2)* or *via (3)*. The solvolysis of haloforms provides an example of the addition of nucleophiles to carbenes. On the other hand, halogen in the halogenomethyl derivatives of zinc [25,26], aluminum [10,26], and mercury [27] very readily undergoes nucleophilic substitution. An analogous reaction must therefore be expected in the case of unstable intermediates of type *(2)*. The origin of the olefin addition products *(6)* is also ambiguous. Photolysis and thermolysis of diazo compounds show beyond doubt that carbenes can add onto olefins. However, the halogenomethyl derivatives of zinc [ICH_2ZnI, $(ClCH_2)_2Zn$] [28,29], aluminum [10] (R_2AlCH_2X), and other metals [29] also convert olefins into cyclopropane derivatives. A preliminary decompositon into metal halide and carbene can be ruled out with reasonable certainty.

The course of these organometallic syntheses of cyclopropanes is subject to some controversy. *Hoberg* [10] has suggested a two-stage mechanism (f) which he has supported by isolating hydrolysis products *(8)* of the intermediate *(7)*. The strict stereospecificity of the cyclopropane formation requires that the *Hoberg* mechanism

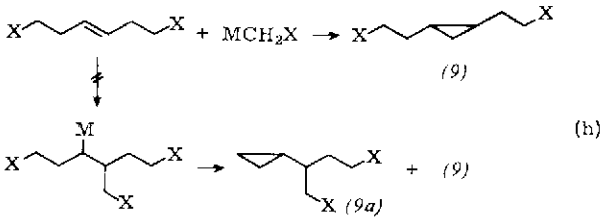


should involve not only stereospecific addition and elimination, but also configurational stability of the intermediate *(7)*. (The addition products *(7)* obtained from geometrically isomeric olefins are diastereoisomers.)

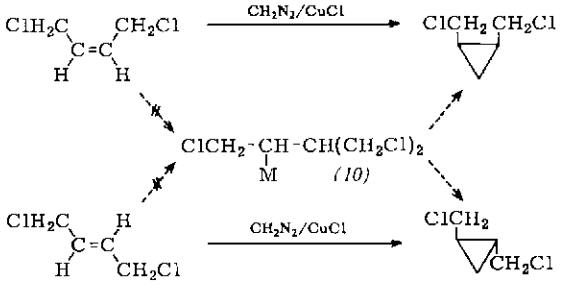
Wittig [29], *Simmons* [28], and *Closs* [30] have postulated a single-step mechanism (g), in which the organometallic reagent is assigned the role of a "carbene-complex".



This mechanism readily explains the stereospecificity and the electrophilic behavior of MCH_2X. A convincing argument in favor of mechanism (g) is provided by the reaction of 1,6-dihalogeno-3-hexenes with halogenomethyl derivatives of zinc [31], which yields only the cyclopropane derivative *(9)* expected from mechanism (g), without any of the isomer *(9a)* required by mechanism (f) [see Equations (h)].



Furthermore, the cupric chloride-catalysed reaction of diazomethane with olefins [32] does not proceed *via* intermediates of type *(7)*. *Cis*- and *trans*-1,4-dichlorobut-2-enes are converted stereospecifically into *cis*- and *trans* - 1,2 - bis(chloromethyl)cyclopropanes [33] in accordance with mechanism (g), whereas mechanism (f) should lead *via* a common intermediate *(10)* to an identical mixture of the isomers [see Scheme 2].



Scheme 2. The cupric chloride-catalysed reaction of diazomethane with olefins.

4. Methyl and Methylene Derivatives

Attempts to prepare methylene by α-elimination from methyl alkyl ethers and butyl-lithium [34], as well as from methyl chloride and phenylsodium [35], or pentylsodium [36] led to homologous hydrocarbons. These are substitution products in accordance with Scheme 1. The organometallic compound functions as a base ($B:^{\ominus}$) and, at the same time, as a nucleophile ($Z^{\ominus}$) [see Scheme 3].

[25] *G. Wittig* and *F. Wingler*, Liebigs Ann. Chem. *656*, 18 (1962).

[26] *H. Hoberg*, Liebigs Ann. Chem. *656*, 15 (1962).

[27] *A. Ledwith* and *L. Phillipps*, J. chem. Soc. (London) *1962*, 3796.

[28] *H. E. Simmons* and *R. D. Smith*, J. Amer. chem. Soc. *80*, 5323 (1958); *H. E. Simmons* and *E. P. Blanchard*, ibid. *86*, 1337, 1347 (1964).

[29] *G. Wittig* and *K. Schwarzenbach*, Liebigs Ann. Chem. *650*, 1 (1961).

[30] *G. L. Closs* and *L. E. Closs*, Angew. Chem. *74*, 431 (1962); Angew. Chem. internat. Edit. *1*, 334 (1962).

[31] *G. Wittig* and *F. Wingler*, Chem. Ber. *97*, 2146 (1964); *F. Wingler*, Ph. D. Thesis, Universität Heidelberg, 1964.

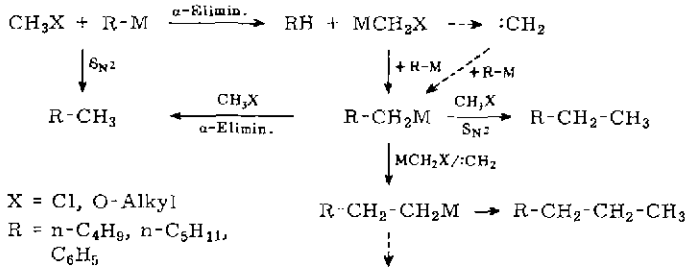
[32] *W. v. E. Doering* and *W. Roth*, Tetrahedron *19*, 715 (1963); *E. Vogel*, *W. Wiedemann*, *H. Kiefer* and *W. F. Harrison*, Tetrahedron Letters *1963*, 673. Cf. also the corresponding reactions with aromatic compounds: *E. Müller* et al., Liebigs Ann. Chem. *661*, 38 (1963); *662*, 38 (1963); Tetrahedron Letters *1963*, 1047, 1501.

[33] *W. Kirmse* and *R. B. Hager*, unpublished work.

[34] *K. Ziegler* and *H. G. Gellert*, Liebigs Ann. Chem. *567*, 185 (1950).

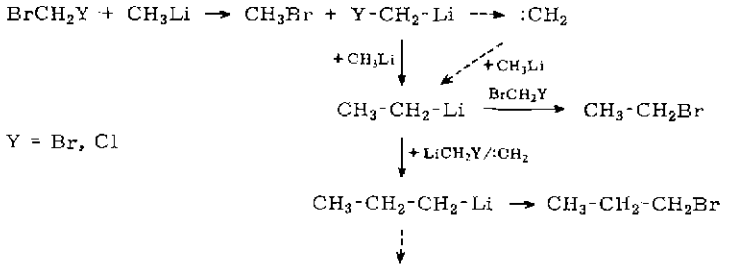
[35] *L. Friedman* and *H. G. Berger*, J. Amer. chem. Soc. *82*, 5758 (1960).

[36] *W. Kirmse* and *H. J. Schladetsch*, unpublished work; cf. Angew. Chem. *73*, 540 (1961).



Scheme 3. The preparation of homologous hydrocarbons from organometallic compounds and methyl ethers or methyl halides.

Only the higher homologs ($R-CH_2-CH_3$, etc.) in Scheme 3 can definitely be regarded as products of α-elimination, since the $R-CH_3$ hydrocarbons probably result mainly from Wurtz reactions (S_N2). It has been possible to show that the analogous reaction of methylene bromide or chlorobromomethane with methyl-lithium [37] probably involves pure α-elimination, induced by halogen-metal interchange (see Scheme 4). (Earlier experiments with phenyl-lithium [38] did not lead to any definite conclusion regarding the mechanism.)



Scheme 4. The preparation of homologous alkyl halides from methylene halides and organometallic compounds.

Olefins can be converted into cyclopropane derivatives in moderate yields by any of the α-elimination reactions discussed above [10,35,39]. This fact can be no longer regarded as evidence of the existence of free methylene (cf. Section 3). The characteristic insertion into C–H bonds, such as is observed with methylene from diazomethane or ketene, does not occur in α-eliminations. The existence of free methylene is very improbable in these reactions.

Similar problems arise in the chemistry of chlorocarbene. As expected, the abstraction of a proton from methylene chloride is easier than from methyl chloride [see Equation (i)]. Alkyl-lithium compounds are suitable bases [40], poor yields being obtained with potassium t-butoxide [41].

$$CH_2Cl_2 + R-Li \rightarrow R-H + LiCHCl_2 \dashrightarrow :CHCl + LiCl \qquad (i)$$

Closs has successfully carried out stereospecific additions to olefins, using a methylene chloride/base system. Whenever isomerism is possible, the formation of the sterically more hindered product is favored in these reactions [40,42]. The olefin again behaves as a nucleophile [43]. Consequently, benzene is attacked with difficulty [41,44], while phenoxides [45], pyrrole, and indole [46] react much more readily. Methylene chloride and triphenylphosphine form an ylide [47,48]. The reaction of methylene chloride with excess alkyl-lithium leads to alkylcarbenes and their secondary products [49].

Closs has recently succeeded in preparing chlorodiazomethane in solution and decomposing it [50]. Chlorocarbene prepared in this way was substantially more reactive than that obtained by α-elimination. This observation lead *Closs* to believe, "... that in the α-elimination a truly free carbene might be bypassed" [50]. The situation cannot be more accurately described at present, since the different energy contents of intermediates produced in different ways must also be considered. The recent successful preparation of dichloromethyllithium in solution at low temperature [51] (detection by reaction with carbonyl compounds) promises further elucidation of this problem.

The α-elimination of hydrogen chloride from α-chloroethers in accordance with Equation (k) requires the use of alkyl-lithium compounds (t-butyl-lithium on occasions, to suppress S_N2 reactions) [52,53], while potassium t-butoxide is sufficient in the case of the corresponding sulfur [54] and selenium compounds [55]. The

$$R-A-CH_2Cl + B^{\ominus} \rightarrow BH + R-A-\overset{\ominus}{\underset{\cdot\cdot}{C}}HCl \dashrightarrow R-A-CH: \qquad A = O, S, Se \qquad (k)$$

smooth addition of the intermediates to olefins was interpreted as a carbene reaction. The objections to this view have been discussed already.

In the reaction of trithio-orthoformates *(11)* with potassium amide in liquid ammonia, the presence of the carbanion intermediate *(12)* is indicated by a green color. The intermediate can be trapped by alkylation with methyl iodide [56]. The main product, tetraethylthio-

[37] *W. Kirmse* and *B. v. Wedel*, Liebigs Ann. Chem. *666*, 1 (1963).

[38] *G. Wittig* and *H. Witt*, Ber. dtsch. chem. Ges. *74*, 1474 (1941).

[39] *W. T. Miller jr.* and *C. S. Y. Kim*, J. Amer. chem. Soc. *81*, 5008 (1959).

[40] *G. L. Closs* and *L. E. Closs*, J. Amer. chem. Soc. *81*, 4996 (1959); *82*, 5723 (1960).

[41] *M. E. Volpin, D. N. Kursavov* and *V. G. Dulova*, Tetrahedron *8*, 33 (1960).

[42] *G. L. Closs, R. A. Moss*, and *J. J. Coyle*, J. Amer. chem. Soc. *84*, 4985 (1962).

[43] *G. L. Closs* and *G. M. Schwartz*, J. Amer. chem. Soc. *82*, 5729 (1960).

[44] *G. L. Closs* and *L. E. Closs*, Tetrahedron Letters *1960*, No. 10, 38.

[45] *G. L. Closs* and *L. E. Closs*, J. Amer. chem. Soc. *83*, 599 (1961).

[46] *G. L. Closs* and *G. M. Schwartz*, J. org. Chemistry *26*, 2609 (1961).

[47] *G. Wittig* and *M. Schlosser*, Angew. Chem. *72*, 324 (1960).

[48] *D. Seyferth, S. O. Grim*, and *T. O. Read*, J. Amer. chem. Soc. *82*, 1510 (1960); *83*, 1617 (1961).

[49] *G. L. Closs*, J. Amer. chem. Soc. *84*, 809 (1962).

[50] *G. L. Closs* and *J. J. Coyle*, J. Amer. chem. Soc. *84*, 4350 (1962).

[51] *G. Köbrich, K. Flory*, and *W. Drischel*, Angew. Chem. *76*, 536 (1964); Angew. Chem. internat. Edit. *3*, 513 (1964).

[52] *U. Schöllkopf* and *A. Lerch*, Angew. Chem. *73*, 27 (1961).

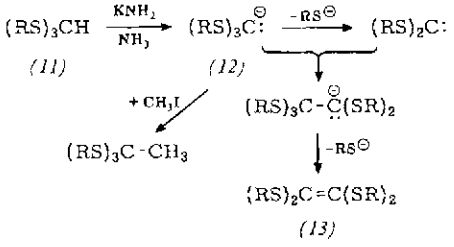
[53] *U. Schöllkopf, A. Lerch*, and *W. Pitteroff*, Tetrahedron Letters *1962*, 241; Chem. Ber. *97*, 636 (1964).

[54] *U. Schöllkopf* and *G. J. Lehmann*, Tetrahedron Letters *1962*, 165; *U. Schöllkopf, G. J. Lehmann, J. Paust*, and *H. D. Härtl*, Chem. Ber. *97*, 1527 (1964).

[55] *U. Schöllkopf* and *H. Küppers*, Tetrahedron Letters *1963*, 105.

[56] *J. Hine, R. P. Bayer*, and *G. G. Hammer*, J. Amer. chem. Soc. *84*, 1751 (1962).

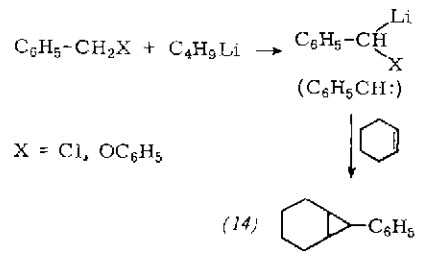
ethylene *(13)* is thought to result from the combination of diethylthiocarbene with *(12)*. However, there is no independent evidence for the occurrence of the carbene.



5. Benzyl and Vinyl Derivatives

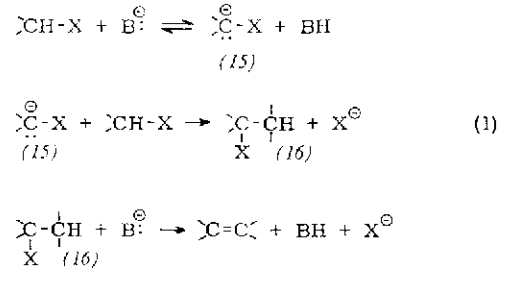
The reaction of benzyl halides or benzyl ethers with bases has only occasionally led to intermediates which can add onto olefins.

Diphenylmethyl bromide reacts with potassium amide in the presence of 1-octene to give 1,1-diphenyl-2-hexylcyclopropane in 7% yield [57]. A 14% yield of 7-phenylnorcarane



(14) has been obtained from benzyl chloride, n-butyl-lithium, and cyclohexane [58], while the corresponding reaction with benzyl phenyl ether gave only 2% of 7-phenylnorcarane [59].

The action of bases on benzyl halides generally yields stilbene derivatives [*]. Good preparative results are obtained with alkali metal amides in liquid ammonia [63]. The first plausible mechanism was suggested by *Hahn* [64] and *Kleucker* [65]. According to this the



carbanion intermediate *(15)* is thought to be alkylated by more benzyl halide, followed by elimination of hydrogen halide from the "dimeric halide" *(16)* [see Equation (1)].

Halides of type *(16)* have been isolated in good yields [63], and recently even from the reaction of benzyl chloride with butyl-lithium [65a]. The substitution *(15)* → *(16)* in the case of α-phenylethyl chloride proceeds with inversion of configuration [66]. H–D exchange in the case of 9-bromofluorene is fast compared to the elimination of hydrogen bromide; the rate of formation of difluorenylidene is proportional to the square of the 9-bromofluorene concentration [67]. These results confirm the postulated course of Reaction (1), and largely rule out the possibility of a carbene intermediate.

However, there are also observations which are less compatible with Scheme 1. Benzyl chloride, 4-nitrobenzyl chloride [68], and 4-nitrobenzyldimethylsulfonium salts [69] obey a first-order rate-law with respect to the concentration of >CHX and of base. Only in the last case has preliminary H–D exchange definitely been observed [70]. No satisfactory interpretation has yet been found for these reactions, especially with regard to the isotope effect [68,69], and the substituent effect [69,70].

1-Halogeno-2,2-diarylethylenes are converted into diarylacetylenes by alkali metal alkoxides [71–73], hydroxides [74], or amides [75], as well as by organolithium compounds [76]. The corresponding reaction of 1,1-dihalogeno-2,2-diarylethylenes proceeds with lithium [77], alkyl-lithium compounds [76], phenyl-lithium or triphenylmethylpotassium [78].

On the basis of careful investigations on the H–D exchange [79], the stereospecificity of the rearrangement [80,81], and the effect of substituents [82], it seems

[57] *A. Y. Garner*, Ph. D. Thesis Abstracts *17*, 224 (1957).

[58] *G. L. Closs* and *L. E. Closs*, Tetrahedron Letters *1960*, No. 24, 26.

[59] *U. Schöllkopf* and *M. Eisert*, Liebigs Ann. Chem. *664*, 76 (1963).

[*] Early examples: [60–62].

[60] *C. A. Bischoff*, Ber. dtsch. chem. Ges. *21*, 2071 (1888).

[61] *P. Walden* and *A. Kernbaum*, Ber. dtsch. chem. Ges. *23*, 1958 (1890).

[62] *J. Thiele* and *A. Wanscheidt*, Liebigs Ann. Chem. *376*, 278 (1910).

[63] *Ch. R. Hauser* et al., J. Amer. chem. Soc. *78*, 1635, 4942 (1956); *79*, 3142 (1957).

[64] *G. Hahn*, Ber. dtsch. chem. Ges. *62*, 2485 (1929).

[65] *E. Kleucker*, Ber. dtsch. chem. Ges. *62*, 2587 (1929).

[65a] *D. F. Hoeg* and *D. I. Lusk*, J. Amer. chem. Soc. *86*, 928 (1964).

[66] *W. R. Brasen, S. W. Kantor, P. S. Skell*, and *Ch. R. Hauser*, J. Amer. chem. Soc. *79*, 397 (1957).

[67] *D. Bethell*, J. chem. Soc. (London) *1963*, 666.

[68] *S. B. Hanna, Y. Iskander*, and *Y. Riad*, J. chem. Soc. (London) *1961*, 217.

[69] *C. G. Swain* and *E. R. Thornton*, J. Amer. chem. Soc. *83*, 4033 (1961); J. org. Chemistry *26*, 4808 (1961).

[70] *I. Rothberg* and *E. R. Thornton*, J. Amer. chem. Soc. *85*, 1704 (1963); *86*, 3296, 3302 (1964).

[71] *P. Fritsche*, Liebigs Ann. Chem. *279*, 319 (1894).

[72] *W. P. Buttenberg*, Liebigs Ann. Chem. *279*, 324 (1894).

[73] *H. Wiechell*, Liebigs Ann. Chem. *279*, 337 (1894).

[74] *M. M. Tiffeneau*, C. R. hebd. Séances Acad. Sci. *135*, 1374 (1902).

[75] *G. H. Coleman* and *R. D. Maxwell*, J. Amer. chem. Soc. *56*, 132 (1934); *58*, 2310 (1936).

[76] *D. Y. Curtin* and *E. W. Flynn*, J. Amer. chem. Soc. *81*, 4714 (1959); *D. Y. Curtin* and *W. H. Richardson*, J. Amer. chem. Soc. *81*, 4719 (1959).

[77] *W. Schlenk* and *E. Bergmann*, Liebigs Ann. Chem. *463*, 71 (1928).

[78] *F. B. Kirby, W. G. Kofron*, and *Ch. R. Hauser*, J. org. Chemistry *28*, 2176 (1963).

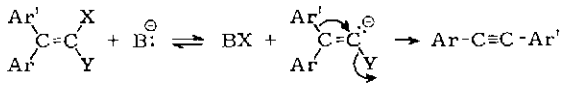
[79] *J. G. Pritchard* and *A. A. Bothner-By*, J. physic. Chem. *64*, 1271 (1960).

[80] *A. A. Bothner-By*, J. Amer. chem. Soc. *77*, 3293 (1955).

[81] *D. Y. Curtin, E. W. Flynn*, and *R. F. Nystrom*, Chem. and Ind. *1957*, 1453; J. Amer. chem. Soc. *80*, 4599 (1958).

[82] *W. M. Jones* and *R. Damico*, J. Amer. chem. Soc. *85*, 2273 (1963).

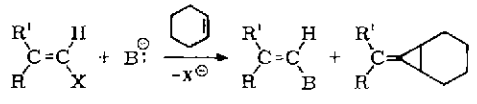
probable that the rearrangement takes place at a vinyl anion stage *(17)*, and that alkylidenecarbenes do not take part in it [83].



X = H, Halogen
Y = Halogen

(17)

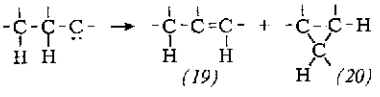
1-Halogeno-2,2-dialkylethylenes *(18)* do not rearrange to give acetylenes. On treatment with potassium t-butoxide [84], or with phenyl-lithium [85], substitution and olefin addition have been observed. 1,1-Dibromo-2-methylprop-1-ene behaves similarly in the halogen-metal exchange with methyl-lithium [85a]. These reactions do not permit any distinction between carbene and carbanion intermediates.



(18)

6. Halogeno- and Dihalogeno-alkanes

The reactions discussed in Sections 4 and 5 were ambiguous in the sense indicated in Scheme 1. On the other hand, α-eliminations on halogeno- and dihalogeno-alkanes permit a clear differentiation between the intermediates. Alkyl- and dialkylcarbenes are stabilized by intramolecular insertion to form olefins *(19)* and cyclopropanes *(20)* [9]. Since such reactions are unknown with carbanions, they provide a good indication of the appearance of carbenes, particularly in the quantitative comparison of elimination reactions with the decomposition of diazo compounds.

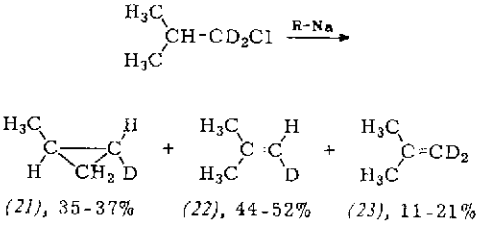


(19) *(20)*

a) α-Elimination of Hydrogen Halide

Whitmore has obtained cyclopropane derivatives by reaction of neopentyl chloride [86,87] or neophyl chloride [*] [88] with sodium or alkylsodium compounds.

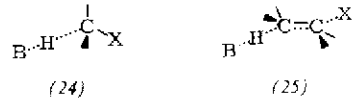
More recent work has shown [89,90] that cyclopropanes are also formed from alkyl chlorides with hydrogen in the β-position. Whereas *Whitmore* had postulated a γ-elimination, experiments with D-labelled compounds have shown that α-elimination occurs [89–92]. Cyclopropane derivatives obtained from alkyl chlorides doubly deuterated in the α-position contained only one deuterium atom, *e.g. (21)* [89,90].



(21), 35-37% *(22)*, 44-52% *(23)*, 11-21%

The olefins *(22)* and *(23)* produced in the same reaction, on the other hand, consisted of a mixture of singly and doubly deuterated compounds, *i.e.* β-elimination competes with α-elimination to a varying extent. This competition depends on the strength of the base. Hardly any α-elimination is observed with alkyl-lithium compounds [89] or with sodamide [90] provided that β-hydrogen is present. In the case of neopentyl chloride, however, α-elimination occurs even with sodamide [91].

The activation energy of the α-elimination must therefore decrease much more rapidly with increasing base-strength than does that of β-elimination. This seems plausible from a consideration of the transition states. In the case of α-elimination, the energy required to remove hydrogen is compensated only by the energy of the new bond to the attacking base. This bond will be relatively strong, even in the transition state *(24)*. This is further substantiated by the small isotope effect in the α-elimination [89]. In the transition state of the β-elimination *(25)*, on the other hand, not only is a new B–H bond formed, but also a new C–C bond. The B–H bond is therefore weaker (the reaction shows a greater isotope effect [93]) and makes a smaller contribution to the energy balance.



(24) *(25)*

Easier cleavage of the C–X bond also favors β-elimination. The incidence of α-elimination decreases on passing from alkyl chlorides to alkyl bromides, and thence to alkyl iodides (using the same base) [90]. Only β-elimination occurs in the case of secondary alkyl chlorides, even with the strongest bases [89,90].

Experiments with deuterium-labelled compounds have shown that the cyclopropane derivatives prepared from primary alkyl halides result from an intramolecular

[83] *G. Köbrich*, Angew. Chem., in the press.

[84] *M. Tanabe* and *R. A. Walsh*, J. Amer. chem. Soc. *85*, 3522 (1963).

[85] *H. Günther* and *A. A. Bothner-By*, Chem. Ber. *96*, 3112 (1963).

[85a] *H. D. Hartzler*, J. Amer. chem. Soc. *86*, 526 (1964).

[86] *F. C. Whitmore*, *A. H. Popkin*, *H. I. Bernstein*, and *J. P. Wilkins*, J. Amer. chem. Soc. *63*, 124 (1941).

[87] *F. C. Whitmore* and *H. D. Zook*, J. Amer. chem. Soc. *64*, 1783 (1942).

[*] "Neophyl" is a contraction denoting the 2,2-dimethyl-2-phenylethyl radical.

[88] *F. C. Whitmore*, *C. A. Weisgerber*, and *A. C. Shabica jr.*, J. Amer. chem. Soc. *65*, 1469 (1943).

[89] *W. Kirmse* and *W. v. E. Doering*, Tetrahedron *11*, 266 (1960).

[90] *L. Friedman* and *J. G. Berger*, J. Amer. chem. Soc. *83*, 492 (1961).

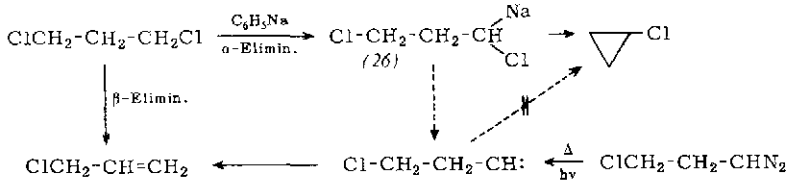
[91] *L. Friedman* and *J. G. Berger*, J. Amer. chem. Soc. *83*, 500 (1961).

[92] *P. S. Skell* and *A. P. Krapcho*, J. Amer. chem. Soc. *83*, 754 (1961).

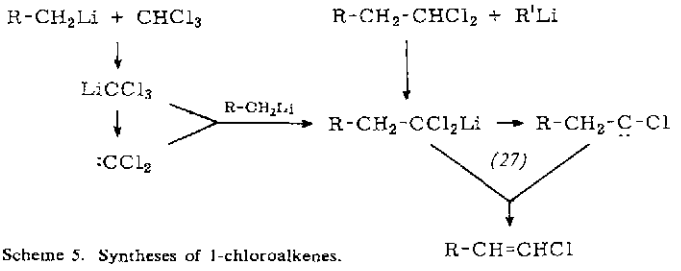
[93] *W. H. Saunders jr.*, and *D. H. Edison*, J. Amer. chem. Soc. *83*, 754 (1961).

carbene reaction (cf. [94,95]). In agreement with this, the nature of the halogen atom has no effect on the composition of the α-elimination products [90,91]. The formation of the carbene stage is further corroborated by good agreement with the results of the decomposition of the diazo compounds.

Whether the carbenes are formed *via* an organometallic (carbanion) intermediate or in a concerted mechanism is less certain. The reaction of 1,3 dichloropropane with phenylsodium [96] points to a two-step mechanism. A mixture of 40 % cyclopropyl chloride and 60 % allyl chloride is obtained in moderate yield. The photochemical or catalytic decomposition of 3-chlorodiazopropane, on the other hand, yields more than 95 % of allyl chloride (cyclopropyl chloride occurs at most in traces) [96]. It seems likely that the high yield of cyclopropyl chloride is due to a 1,3-elimination from the organometallic intermediate *(26)* (cf. Section 6b). The question as to whether allyl chloride results from α- or from β-elimination must remain unanswered.



The α-hydrogen atom in 1,1-dichloroalkanes is more readily removed than in alkyl chlorides, even with alkyl-lithium compounds [97]. Whereas the reaction of the intermediate with more alkyl-lithium predominates in the case of 1,1-dichloroethane [98], higher 1,1-chloroalkanes yield considerable quantities of 1-chloroalkenes. These 1-chloroalkenes may be regarded as α-elimination products for the following reasons: 1-chloroalkenes are obtained in the same *cis/trans* ratio (approximately 9:1) from alkyl-lithium compounds and chloroform as from 1,1-dichloroalkanes. A common intermediate *(27)*, in accordance with Scheme 5, is the best explanation of this fact. β-Elimination from 1,1-dichloroalkanes takes place with alkoxides and gives an entirely different *cis/trans* ratio (approximately 1:1).

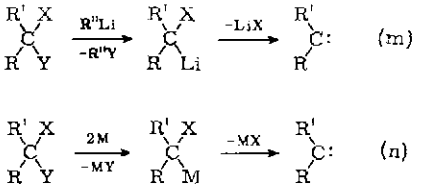


Scheme 5. Syntheses of 1-chloroalkenes.

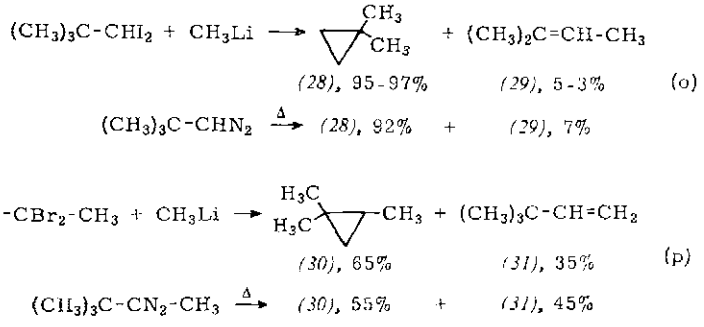
As long as corresponding rearrangements are unknown in the case of carbanions, hydrogen shift to form the 1-chloroalkene must be regarded as an alkylchlorocarbene reaction [97].

b) α-Elimination of Halogen

Competition between α- and β-elimination must be ruled out in the case of the removal of halogen from *gem*-dihalides, since halogen-free products can be formed only by α-elimination. The α-elimination of halogen can be effected with alkyl-lithium compounds [see Equation (m)] or, less smoothly, with metals [see Equation (n)] [99]. In Reaction (m), at least one of the halogen atoms must be bromine or iodine; the first step is halogen-metal exchange. In Reaction (n), both halogen atoms are removed as anions, the necessary electrons being supplied by the metal



Carbene formation can again be detected by typical intramolecular insertion reactions [see Equations (o) and (p)]. The ratios of the product yields largely correspond to those obtained in the decomposition of diazo compounds [99].



2,2-Dibromobutane and 2-bromo-2-chlorobutane gave identical butene mixtures with different alkyl-lithium compounds. The eliminating agent and the departing halogen atom cannot therefore participate in the product-determining step. These results can hardly be explained otherwise than by a carbene intermediate.

Organometallic intermediates were also detected in Reaction (m) by intramolecular capture [100]. When 1,1,3-trihalogenoalkanes are reacted with methyl-lithium, bromine, or iodine in the 1-position is exchanged for lithium whereas unactivated halogen in the 3-position fails to react. The organometallic intermediate *(32)* can undergo 1,3-elimination of lithium halide to yield a cyclopropyl halide. If the reaction proceeds to the carbene stage (or if the carbene is formed in a concerted mechanism), allyl halide (by β-hydrogen shift) and cyclopropyl halide (by insertion into the γ-C–H or into the Cl–C bond), are to be expected as end-products. The source of the

[94] *W. v. E. Doering* and *W. Kirmse*, Tetrahedron *11*, 272 (1960).

[95] *H. G. Richey jr.* and *E. A. Hill*, J. org. Chemistry *29*, 421 (1964).

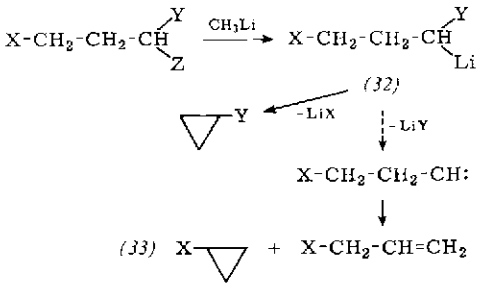
[96] *W. Kirmse* and *H. J. Schladetsch*, unpublished work.

[97] *W. Kirmse* and *B. G. v. Bülow*, Chem. Ber. *96*, 3316 (1963).

[98] *W. Kirmse* and *B. G. v. Bülow*, Chem. Ber. *96*, 3323 (1963).

[99] *W. Kirmse* and *B. v. Wedel*, Liebigs Ann. Chem. *666*, 1 (1963).

cyclopropyl halides can be ascertained by using different halogen atoms. On ring closure of *(32)*, halogen (Y) in the 1-position is retained, while cyclopropyl halide *(33)* formed from the carbene contains halogen (X) in the 3-position.



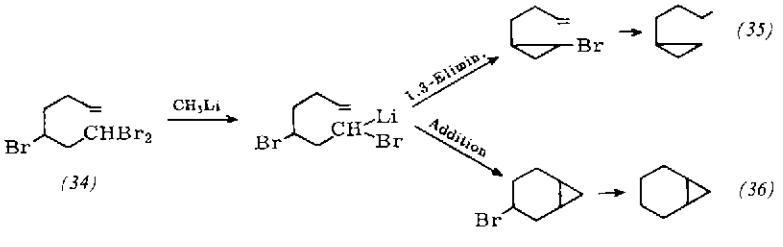
The first of these alternatives is unambiguously supported by experiment. Allyl halides (or their secondary products) have not been found in any case, whereas cyclopropyl halides have been obtained in good yields. 1,1-Dibromo-3-chloropropane gave only cyclopropyl bromide, and 1,3-dibromo-1-chloropropane gave only cyclopropyl chloride. It is thus shown that ring closure proceeds from the intermediate *(32)* with retention of the halogen atom in the 1-position.

Substitution of iodine for Y in *(32)* is observed in the presence of lithium iodide (the starting material and the end-product do not react with lithium iodide) [100]. Thus the high reactivity of halogen in the α-halogenoalkyl derivatives of zinc, aluminum and mercury (Section 3) is also found in the corresponding lithium compounds.

c) Addition of Intermediate Products of the Elimination to Olefins

As has been seen in the foregoing sections, both carbenes and organometallic (carbanion) intermediates can be detected in the α-elimination reactions of halogeno- and dihalogeno-alkanes. The question now arises: which one of these intermediates is responsible for the addition to olefins? This problem is best examined once more by means of competitive intramolecular reactions.

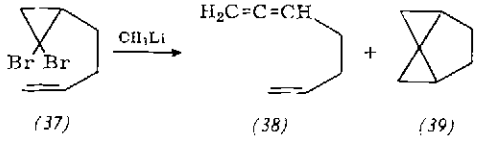
The 1,3-elimination of lithium halide involves organometallic intermediates of type *(32)*. Addition to olefins, which competes with this 1,3-elimination, would have to be a direct addition of the organometallic intermediate. However, no such competition is observed



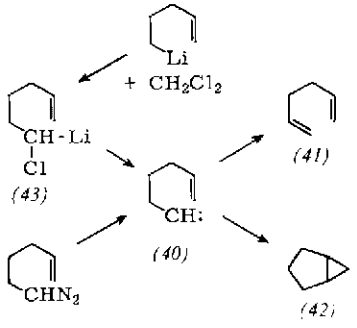
in the reaction of 5,7,7-tribromohept-1-ene *(34)* with methyl-lithium [100]. Reductive dehalogenation of the products yields n-butylcyclopropane *(35)*, but no norcarane *(36)*.

[100] *W. Kirmse* and *B. v. Wedel*, Angew. Chem. *75*, 672 (1963); Liebigs Ann. Chem., in the press.

Skatteböl has reacted 1,1-dibromo-2-(buten-3-yl)-cyclopropane *(37)* with methyl-lithium, and isolated the spirane *(39)* in addition to the allene *(38)* [101]. The ratio of the quantities of the compounds *(38)* and *(39)* was found to depend on temperature. Unfortunately, the mechanism of the conversion of 1,1-dihalogenocyclopropanes into allenes is not yet clear [102–105]. It cannot therefore be stated which intermediate of this interesting reaction is intercepted by the olefin addition.



The competition between hydrogen shift and olefin addition has been investigated with 4-pentenylcarbene *(40)* [106]. The reaction products are 1,5-hexadiene *(41)* and bicyclo[1.3.0]hexane *(42)*. The decomposition of 6-diazohex-1-ene proceeded only when catalysed by copper, and gave compounds *(41)* and *(42)* in yields of 55 % and 45 %, respectively. The reaction of 4-pentenyllithium with methylene chloride leads, *via* the organometallic intermediate *(43)*, to the same products *(41)* and *(42)* in yields of 87 % and 13 %, respectively.



The experiments described above, although as yet incomplete, give no indication of a direct reaction between α-halogenoalkyl-lithium and olefins. The experiments relate only to compounds of type R–CHX–Li and give no information concerning organometallic intermediates with two or three α-halogen atoms.

[101] *L. Skatteböl*, Chem. and Ind. *1962*, 2146.

[102] *W. v. E. Doering* and *P. LaFlamme*, Tetrahedron *2*, 75 (1958).

[103] *W. R. Moore* and *H. R. Ward*, J. org. Chemistry *25*, 2073 (1960); *27*, 4179 (1962).

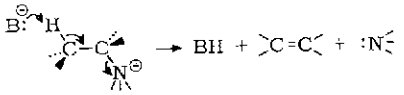
[104] *L. Skatteböl*, Tetrahedron Letters *1961*, 167.

[105] *T. J. Logan*, Tetrahedron Letters *1961*, 173.

[106] *W. Kirmse* and *D. Grassmann*, unpublished work.

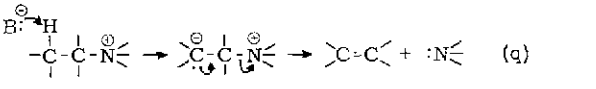
7. Quaternary Ammonium Salts and Tertiary Sulfonium Salts

The Hofmann degradation of quaternary ammonium hydroxides can generally be described as an E2 elimination with simultaneous removal of β-hydrogen and tertiary amine [107]. This requires that the participating groups should have a planar *trans*-configuration, as shown in *(44)*. The possibility of α-elimination



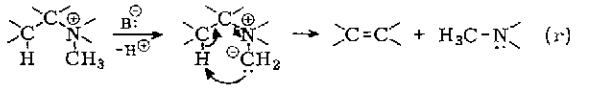
(44)

would be expected to arise whenever this *trans*-configuration cannot be achieved. Nevertheless, careful investigations on *trans*-(2-phenylcyclohexyl)trimethylammonium hydroxide [108–111] have shown only pure β-elimination. The reaction probably proceeds by an E1cB mechanism [see Equation (q)] promoted by the phenyl group.



(q)

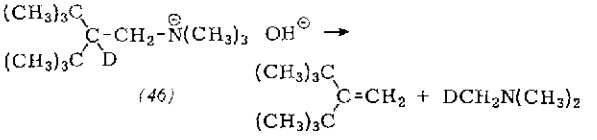
An ylide (α',β)-mechanism has been found only with quaternary ammonium hydroxides in which the β-hydrogen atom is not activated, but is strongly sterically hindered [112,113]. In such cases, an α-hydrogen atom is first removed, and the resulting ylide *(45)* gives rise to the Hofmann degradation [see Equation (r)] by a cyclic proton shift.



(45)

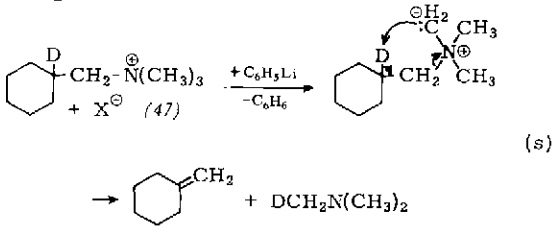
(r)

Trimethyl-(2-t-butyl-3,3-dimethyl-[2-D]-butyl)ammonium hydroxide *(46)* decomposes to the extent of 75 % in accordance with Equation (r) [113].



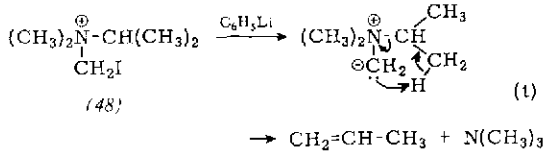
(46)

Whereas the ylide mechanism (r) is the exception with ammonium hydroxides, the reaction of quaternary ammonium salts, *e.g.* [2-D]-cyclohexylmethyltrimethylammonium salts *(47)* with organolithium compounds generally follows this route [see Equation (s)] [111,114 to 116]. Remarks made in Section 6 naturally apply to the transition from the β- to the "α,β"-elimination with increasing base-strength.



(s)

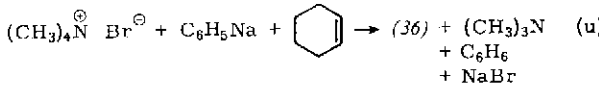
α',β-Elimination can also be induced by halogen-metal exchange on α-halogenated quaternary ammonium salts, *e.g. (48)* [Equation (t)] [114].



(48)

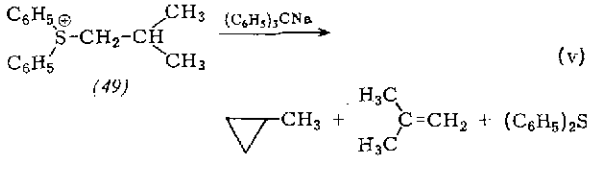
(t)

Owing to the smooth intramolecular elimination according to Equation (r), no β-hydrogen atom need be present in order to obtain carbenes from quaternary ammonium salts. Treatment of tetramethylammonium bromide with phenylsodium/phenyl-lithium in the presence of cyclohexene gives norcarane in 10 % yield, in accordance with Reaction (u) [117]. As in the experiments discussed in Section 4, the formation of methylene in this reaction is questionable [*].



(u)

The situation is clearer in the case of the tertiary sulfonium salts; β- and α',β-eliminations can again be detected according to the strength of the base [120,121]. However, alkyldiphenylsulfonium salts, *e.g. (49)*, open up a route to alkylcarbenes, which can undergo intramolecular insertion, *e.g.* according to Equation (v) [122].



(49)

(v)

[107] *A. C. Cope* and *E. R. Trumbull* in: Organic Reactions. Wiley, New York 1960, Vol. XI, p. 317.

[108] *R. T. Arnold* and *P. N. Richardson*, J. Amer. chem. Soc. *76*, 3649 (1954).

[109] *J. Weinstock* and *F. G. Bordwell*, J. Amer. chem. Soc. *77*, 6706 (1955).

[110] *A. C. Cope, G. A. Berchtold*, and *D. L. Ross*, J. Amer. chem. Soc. *83*, 3859 (1961).

[111] *G. Ayrey, E. Buncel*, and *R. N. Bourns*, Proc. chem. Soc. (London) *1961*, 458.

[112] *A. C. Cope* and *D. L. Ross*, J. Amer. chem. Soc. *83*, 3854 (1961).

[113] *A. C. Cope* and *A. S. Mehta*, J. Amer. chem. Soc. *85*, 1949 (1963).

[114] *G. Wittig* and *R. Polster*, Liebigs Ann. Chem. *599*, 13(1956).

[115] *A. C. Cope, N. A. LeBel, P. T. Moore*, and *W. R. Moore*, J. Amer. chem. Soc. *83*, 3861 (1961).

[116] *F. Weygand, H. Daniel*, and *H. Simon*, Liebigs Ann. Chem. *654*, 111 (1962).

[117] *V. Franzen* and *G. Wittig*, Angew. Chem. *72*, 417 (1960).

[*] See [118,119] for the formation of polymethylene from trimethylammonium methylide.

[118] *G. Wittig* and *R. Polster*, Liebigs Ann. Chem. *599*, 1 (1956).

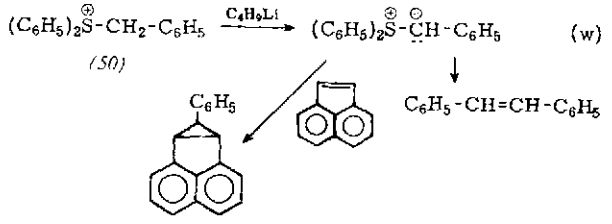
[119] *F. Weygand, H. Daniel*, and *A. Schroll*, Chem. Ber. *97*, 1217 (1964).

[120] *V. Franzen* and *C. Merz*, Chem. Ber. *93*, 2819 (1960).

[121] *V. Franzen* and *H. J. Schmidt*, Chem. Ber. *94*, 2937 (1961).

[122] *V. Franzen, H. J. Schmidt*, and *C. Merz*, Chem. Ber. *94*, 2942 (1961).

On the other hand, the addition of methylene to polar double bonds [123, 124], which can formally be achieved with trimethylsulfonium salts, as well as the formation of ethylene from these compounds [124], must be regarded as a sulfonium ylide reaction. This is probably also true of the similar reactions (w) of diphenylbenzylsulfonium salts *(50)* [125].



8. Future Prospects

The results which have been referred to illustrate the importance of α-elimination in numerous substitution and addition reactions. Investigation of these reactions is made interesting, yet at the same time difficult, by the various intermediates with similar chemical properties. According to present-day knowledge, both of substituted alkylmetal compounds (or carbanions) and carbenes behave as electrophiles. The conversion α-olefins into cyclopropane derivatives, which originally did much for the development of the carbene concept, is becoming increasingly recognized as a reaction of organometallic (carbanion) intermediates. Olefin addition has become completely useless as a means of detecting carbenes. At present the only reliable criterion for the occurrence of carbenes is the (intramolecular) insertion into C–H bonds, which has permitted detection of alkyl- and dialkylcarbenes. It is not surprising that these are the very compounds in which α-elimination proceeds to the formation of carbene intermediates.

With the transition from primary to secondary and tertiary carbon, the tendency towards S_N1 reactions steadily increases, while the S_N2 mechanism is suppressed. Alkyl groups should therefore also favor the transition into the carbene, which is analogous to the S_N1 mechanism, in the case of α-substituted alkylmetal compounds (carbanions).

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Translated by Express Translation Service, London

[123] *E. J. Corey* and *M. Chaykovsky*, J. Amer. chem. Soc. *84*, 3782 (1962); Tetrahedron Letters *1963*, 169.

[124] *V. Franzen* and *H. E. Driessen*, Tetrahedron Letters *1962*, 661; Chem. Ber. *96*, 1881 (1963).

[125] *W. A. Johnson*, *V. J. Hruby*, and *J. L. Williams*, J. Amer. chem. Soc. *86*, 918 (1964).

Cyclopropenylium Compounds and Cyclopropenones

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The predictions of Hückel's rule gave the incentive to numerous investigations which led ultimately to a new definition of aromatic character, and which have added greatly to our knowledge of the properties and reactivity of aromatic compounds. Increasing use was made of physical measurements as criteria for the aromaticity of a compound. The first member (n = 0) in the series of Hückel's (4n + 2) π systems is the cyclopropenylium cation. The predictions regarding the stability of this system have been confirmed at least qualitatively by the synthesis of cyclopropenylium salts. Properties and reactions of cyclopropenylium compounds and cyclopropenones were investigated.

I. Introduction

Ever since the discovery of benzene by *Faraday* in 1825, the theory of the cyclic unsaturated systems has been of interest to organic chemists [1, 2]. The formulation of the (4n + 2)π-rule by *Hückel* [3] in 1931 was a milestone in this development. The (4n + 2)π-rule can be expressed as follows:

Planar monocyclic systems with trigonally hybridized atoms containing (4n + 2) π-electrons possess a characteristic electronic stability.

Not only did this rule provide an explanation on the basis of quantum theory of the special position of benzene, which was already known, but it also allowed predictions to be made regarding the stability of systems which had not yet been synthesized.

The validity of Hückel's rule for n = 1 was verified by the preparation of the tropylium cation [2, 4–5b] and by the agreement between the observed properties and

[1] Concerning the historical development of the theory of aromatic compounds, which is not discussed in detail in the present paper, see *e.g. C. K. Ingold*: Structure and Mechanism in Organic Chemistry. Cornell University Press, Ithaca 1953, pp. 156–196 and [2].

[2] *W. v. E. Doering* and *H. Krauch*, Angew. Chem. *68*, 661 (1956).

[3] *E. Hückel*, Z. Physik *70*, 204 (1931); *76*, 628 (1932).

[4] *P. L. Pauson*, Chem. Reviews *55*, 9 (1955).

[5a] *T. Nozoe* in *D. Ginsburg*: Non-Benzenoid Aromatic Compounds. Interscience, New York 1959, p. 339.

[5b] *T. Nozoe*: Progress in Organic Chemistry. Butterworths, London 1961, Vol. 5, p. 132.

those predicted by theory [6]. *Roberts, Streitwieser*, and *Regan* [7] were the first to point out the theoretically expected stability of the simplest aromatic system, *i.e.* the cyclopropenylium cation *(1)*, with n = 0. These predictions can be represented diagrammatically as shown in Fig. 1 [2,8].

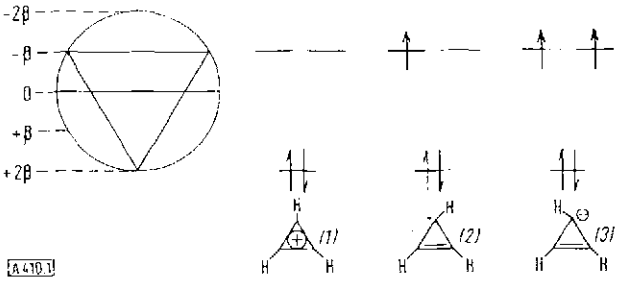
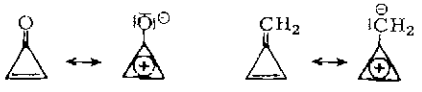


Fig. 1. Graphical representation of the energy levels for cyclopropenyl systems.

The delocalization energy, DE, of the cyclopropenylium cation *(1)* is found to be the difference in the π-electron energies of *(1)* and of ethylene; that is, DE = 4β − 2β = 2β. Similarly, the delocalization energies of the cyclopropenyl radical *(2)* and the cyclopropenyl anion *(3)* are found to be 1β and zero, respectively. Large delocalization energies were obtained in a similar manner for cyclopropenone *(4)* and for methylenecyclopropene *(5)*, and for their derivatives [7, 9, 10].



(4) *(5)*

Table 1. Delocalization energies DE for cyclopropenyl derivatives as calculated from the Hückel theory, and the increase ΔDE on phenyl substitution.

	Cation		Radical		Anion	
	DE [β]	ΔDE [β]	DE [β]	ΔDE [β]	DE [β]	ΔDE[β]
Cyclopropenyl	2.00		1.00		0.00 [*]	
Phenylcyclopropenyl	4.39	0.39	3.79	0.79	3.20	1.20
1,2-Diphenylcyclopropenyl	6.70	0.70	6.20	1.20	5.69	1.69
1,2,3-Triphenylcyclopropenyl	9.19	1.19	8.68	1.68	8.18	2.18
Cycloheptatrienyl	2.99		2.54		2.10 [*]	

[*] Triplet.

Table 2. Delocalization energies DE of some cyclopropenone derivatives as calculated from the Hückel theory, and the increase ΔDE on phenyl substitution [9].

	DE [β]	ΔDE [β]
Cyclopropenone	1.36	
Phenylcyclopropenone	3.75	0.39
Diphenylcyclopropenone	6.15	0.79
Methylenecyclopropene	0.96	
1-Phenylmethylenecyclopropene	3.37	0.41
1,2-Diphenylmethylenecyclopropene	5.79	0.83

The predicted stability of the three-membered ring cation *(1)* leads naturally to a comparison of it with the tropylium cation, $C_7H_7^{\oplus}$. In fact, the development of the chemistry of the cyclopropenylium compounds was completely analogous to that of the tropylium compounds. In comparing *(1)* to $C_7H_7^{\oplus}$, however, it should be noted that the calculated delocalization energy DE of an aromatic compound is not identical with the so-called empirical resonance energy RE which is experimentally determined from the heat of combustion or of hydrogenation. The reason for this is that the M.O. calculations take into account only the contribution of the delocalization of the π-electrons towards the stability of the molecules; no allowance is made for other factors such as ring strain, change in state of hybridization or in bond lengths, or, in certain cases, the electrostatic work of charge separation.

The ring-strain energy of the cyclopropenylium cation *(1)*, which can be estimated from the ring strain of cyclopropene [11,12] and the additional strain arising from the change in the hybridization in *(1)* [13], is about 74 kcal/mole, as compared with about 7 kcal/mole for the tropylium ion.

If we assume β=32 kcal/mole [14], the calculated delocalization energy 2β of the cyclopropenylium cation is overcompensated by the ring-strain energy. It is, therefore, impossible to foretell whether the high delocalization energy makes the cyclopropenylium system sufficiently stable to permit its isolation.

[6] In recent years, the validity of the Hückel rule has also been confirmed for n = 2 by synthesis of the cyclooctatetraene dianion and the cyclononatetraenyl anion: *A. R. Ubbelohde*, Chem. and Ind. *1956*, 153; *T. J. Katz*, J. Amer. chem. Soc. *82*, 3784, 3785 (1960); *H. P. Fritz* and *H. Keller*, Z. Naturforsch. *16b*, 231 (1961); *T. J. Katz* and *P. J. Garratt*, J. Amer. chem. Soc. *85*, 2852 (1963); *E. A. La Lancette* and *R. E. Benson*, ibid. *85*, 2853 (1963). Cyclodeca-1,3,5,7,9-pentaene appears to be unstable in comparison with 9,10-dihydronaphthalene for steric reasons: *E. E. van Tamelen* and *B. Pappas*, J. Amer. chem. Soc. *85*, 3296 (1963); *E. Vogel* and *H. D. Roth*, Angew. Chem. *76*, 145 (1964); Angew. Chem. internat. Edit. *3*, 228 (1964).

On the question of the aromatic character of higher conjugated cyclopolyolefins (n ≥ 3), particularly the [18]annulene, see: *W. Baker* and *J. F. W. McOmie* in *D. Ginsburg*: Non-Benzenoid Aromatic Compounds. Interscience Publishers, New York 1959, p. 477; *A. Streitwieser*: Molecular Orbital Theory for Organic Chemists. J. Wiley, New York 1961; *L. M. Jackman, F. Sondheimer, Y. Amiel, D. A. Ben-Efraim, Y. Gaoni, R. Wolovsky*, and *A. A. Bothner-By*, J. Amer. chem. Soc. *84*, 4307 (1962).

[7] *J. D. Roberts, A. Streitwieser*, and *C. M. Regan*, J. Amer. chem. Soc. *74*, 4579 (1952).

[8] *A. A. Frost* and *B. Musulin*, J. chem. Physics *21*, 572 (1953).

[9] *S. L. Manatt* and *J. D. Roberts*, J. org. Chemistry *24*, 1336 (1959).

[10] *D. A. Bochvar, I. V. Stankevich*, and *A. L. Chistyakov*, Izv. Akad. Nauk S.S.S.R., Otd. Khim. Nauk *1958*, 793; Chem. Abstr. *52*, 19424 (1958); Zhurn. fiz. Khim. *33*, 2712 (1959); Chem. Abstr. *55*, 15104 (1961); Zhurn. fiz. Khim. *34*, 2543 (1960); Chem. Abstr. *55*, 8324 (1961).

[11] *H. A. Staab*: Einführung in die theoretische organische Chemie. 3rd Edit., Verlag Chemie, Weinheim/Bergstr. 1962, pp. 54, 547.

[12] *K. B. Wiberg, W. J. Bartley*, and *F. P. Lossing*, J. Amer. chem. Soc. *84*, 3980 (1962).

[13] *R. Breslow* and *H. W. Chang*, J. Amer. chem. Soc. *83*, 2367 (1961).

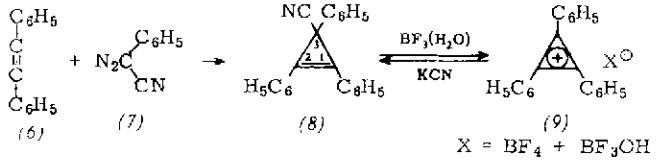
[14] For a discussion of the value of β in aromatic compounds, see *A. Streitwieser*: Molecular Orbital Theory for Organic Chemists. Wiley, New York 1961, and [13].

II. Cyclopropenylium Compounds

A. Preparation of Cyclopropenylium Compounds

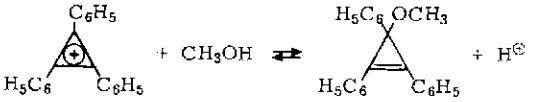
The starting materials for all syntheses were cyclopropenes which are generally obtained by addition of carbenes to substituted acetylenes.

Thus, by reacting phenyldiazoacetonitrile *(7)* with diphenylacetylene *(6)*, *Breslow* [15,16] obtained 1,2,3-triphenylcyclopropenyl cyanide *(8)* which yielded the mixed fluoroborate/hydroxofluoroborate of the 1,2,3-triphenylcyclopropenylium cation *(9)* on treatment with moist boron trifluoride etherate.



(6) *(7)* *(8)* *(9)*

X = BF_4 + BF_3OH

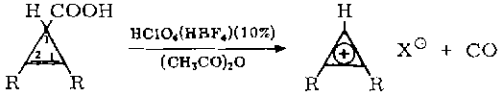


(10)

1,2,3-Triphenylcyclopropenyl methyl ether *(10)* was found to he a suitable starting material for the preparation of cyclopropenylium salts, giving 1,2,3-triphenylcyclopropenylium bromide on reaction with hydrogen bromide [16].

A number of other triaryl-substituted cyclopropenylium salts [13,17] and the diphenylcyclopropenylium cation [18] were synthesized directly by addition of arylchlorocarbenes to diarylacetylenes or to phenylacetylene.

Another method of preparing disubstituted cyclopropenylium salts, *e.g. (11)* and *(12)*, consists in the decarbonylation of 1,2-disubstituted cyclopropenecarboxylic acids with strong acids in acetic anhydride [19 to 21].

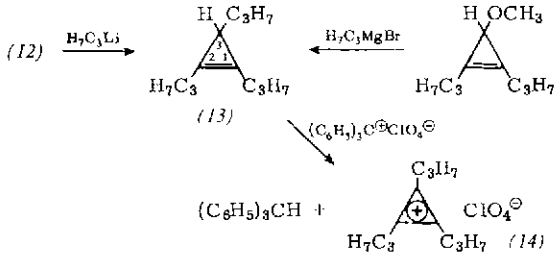


(11): R = C_6H_5

(12): R = C_3H_7

$X^{\ominus}$ = $ClO_4^{\ominus}$, $BF_4^{\ominus}$

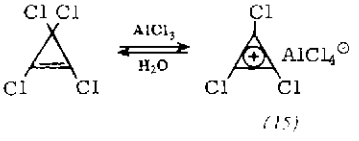
The reaction of *(12)* with propyl-lithium gave 1,2,3-tripropylcyclopropene *(13)* which was then converted to tripropylcyclopropenylium perchlorate *(14)* by hydride abstraction with the triphenylmethyl cation [21].



(13) *(14)*

A method based on hydride abstraction with 2,3-dichloro-5,6-dicyano-1,4-benzoquinone in the presence of acids had previously been used for the preparation of a number of triphenylcyclopropenylium salts from 1,2,3-triphenylcyclopropene [22].

Attempts to prepare the unsubstituted cyclopropenylium cation *(1)* by hydride abstraction from cyclopropene with the triphenylmethyl cation were unsuccessful [12]. Attempts to detect *(1)* in the gas phase and to determine its heat of formation by mass spectrometry also failed to yield any definite result, since it could not be decided whether the observed $C_3H_3^{\oplus}$ ion had the structure *(1)* or that of a propargyl cation [12,23]. On the other hand, the trichlorocyclopropenylium *(15)* [24] and tribromocyclopropenylium cations [25] were obtained as the tetrahalogenoaluminates by reaction of the corresponding tetrahalogenocyclopropenes with aluminum trihalides. Tetrachlorocyclopropene was reobtained on careful hydrolysis of *(15)*.



(15)

B. Proof of Structure and Physical Properties of Cyclopropenylium Compounds

Although many methods of preparation, such as the decarbonylation of the cyclopropenecarboxylic acids and hydride abstraction with triphenylmethyl perchlorate clearly pointed to the stability of the cyclopropenylium cation, final evidence for the symmetry of the cation was only provided by physical investigations.

1. Solubility

All cyclopropenylium compounds, both aromatic and aliphatic, are soluble only in highly polar solvents such as alcohols, acetonitrile, dimethylformamide, or aqueous acids, but insoluble in ether, chloroform, or benzene. On the other hand, covalent cyclopropene derivatives, such as *(8)*, are soluble in benzene. In contrast to the cyclopropenylium chlorides and bromides, *(8)* does not give a precipitate with ethanolic silver nitrate [15,16].

2. X-Ray Structural Analysis

An X-ray structural analysis carried out on triphenylcyclopropenylium perchlorate showed conclusively that the compound consists of triphenylcyclopropenylium

[15] *R. Breslow*, J. Amer. chem. Soc. *79*, 5318 (1957).

[16] *R. Breslow* and *C. Yuan*, J. Amer. chem. Soc. *80*, 5991 (1958).

[17] *A. S. Kende*, J. Amer. chem. Soc. *85*, 1882 (1963).

[18] *R. Breslow, J. Lockhart*, and *H. W. Chang*, J. Amer. chem. Soc. *83*, 2375 (1961).

[19] *D. G. Farnum* and *M. Burr*, J. Amer. chem. Soc. *82*, 2651 (1960).

[20] *R. Breslow* and *H. Höver*, J. Amer. chem. Soc. *82*, 2644 (1960).

[21] *R. Breslow, H. Höver*, and *H. W. Chang*, J. Amer. chem. Soc. *84*, 3168 (1962).

[22] *D. H. Reid, M. Fraser, B. B. Molloy, H. A. S. Payne*, and *R. G. Sutherland*, Tetrahedron Letters *1961*, 530.

[23] *G. P. Glass* and *G. B. Kistiakowsky*, J. chem. Physics *40*, 1448 (1964); *G. B. Kistiakowsky* and *J. V. Michael*, ibid. *40*, 1447 (1964).

[24] *S. W. Tobey* and *R. West*, J. Amer. chem. Soc. *86*, 1459 (1964).

[25] *R. West*, personal communication; *S. W. Tobey* and *R. West*, J. Amer. chem. Soc. *86*, 4215 (1964).

cations and perchlorate anions [26]. The three-membered ring and the three phenyl carbon atoms attached to it lie in the same plane. All the C–C distances in the three-membered ring are 1.40 Å, *i.e.* roughly the same as those in benzene (1.39 Å). The semicyclic C–C single bonds are 1.45 Å in length, and are thus shorter than the "normal" C–C single bond (1.54 Å), as is the central C–C bond in butadiene (1.48 Å) [27] or biphenyl (1.48 Å) [28].

Contrary to earlier belief [10, 13], the triphenylcyclopropenylium cation is not planar in structure, the phenyl groups being twisted out of the plane of the three-membered ring at an average angle of 21° owing to steric hindrance of the hydrogen atoms in the *ortho* position. Therefore the shortening of the semicyclic bonds can be attributed primarily to the change in hybridization, multiple-bond character resulting from mesomerism being only a secondary factor [29].

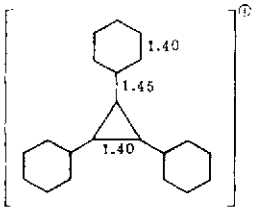


Fig. 2. Bond lengths in the triphenylcyclopropenylium cation (Å) [26].

3. Spectra

In contrast to cyclopropene [30], the cylcopropenylium compounds with only alkyl substituents do not absorb in the ultraviolet region above 185 mμ [21]. This agrees with the simple Hückel theory which predicts an excitation energy of 3β for the $\pi \rightarrow \pi^*$-transition (see Fig. 1). Since this excitation energy is much greater than that calculated for ethylene (2β), the $\pi \rightarrow \pi^*$-transition in the cyclopropenylium cation should occur at very short wavelengths (< 180 mμ).

With the exception of the triphenyl compound, the aryl-substituted cyclopropenylium compounds [13, 16–19] also give ultraviolet spectra which are quite different from those of the covalent cyclopropenes.

The similarity and simplicity of the infrared spectra of trichlorocyclopropenylium tetrachloroaluminate *(15)* and the hexachloroantimonate were accepted as evidence of the high symmetry of the $C_3Cl_3^{\oplus}$ cation [24]. Only one band in the IR spectrum, which occurs between 1400 and 1430 cm^{-1}, depending on the substitutents, has so far been assigned to the cyclopropenylium system itself [21, 31].

The nuclear magnetic resonance spectra give more information on the bonding in the cyclopropenylium cations [17, 20, 21] than the UV and IR spectra, since a linear relationship exists between the chemical shift of aromatic protons and the π-electron density per C-atom of the aromatic system in question [32]. This rule, which was established for the "classical" aromatic systems ($C_7H_7^{\oplus}$, C_6H_6, and $C_5H_5^{\ominus}$), has frequently been used as a test for aromatic character in a newly synthesized compound [6]. Fig. 3 shows that the value of −3.0 ppm (in relation to benzene) found for the ring proton of the dipropylcyclopropenylium cation [21] is in close agreement with the value expected from this rule.

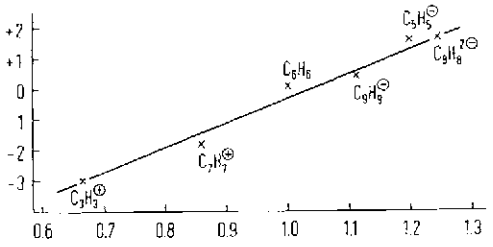


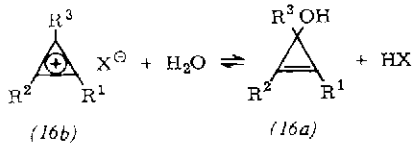
Fig. 3. Chemical shift of aromatic protons δ (in ppm in relation to benzene as a function of the π-electron density ρ_π per C-atom) [33].
Ordinate: δ [ppm]
Abscissa: ρ_π

The apparent reason for this agreement is that the effects of the ring current, which is smaller than in benzene, and of the changed hybridization in the three-membered ring on the position of the ^1H-resonance absorption just balance each other, so that only the influence of the π-electron density per C-atom is of any importance.

However, interesting conclusions can also be drawn from the NMR spectra of the substituents on the cyclopropenylium system. These show that all the propyl groups in the tri- and dipropylcyclopropenylium cations are equivalent, that all cyclopropenylium salts, irrespective of the nature of the substituents, have a similar charge distribution, and that, even in the phenyl-substituted cations, not much of the positive charge is distributed over the phenyl groups [21].

4. Cyclopropenylium-Cyclopropenol Equilibria

The influence of substituents on the stability of cyclopropenylium ions has been studied mainly by measurement of the pK-values [34] for the equilibrium *(16a)* ⇌ *(16b)*.



(16b) *(16a)*

The pK-value of the cations is determined by two factors: 1. The cations are better stabilized by propyl groups than by phenyl groups. 2. The covalent carbinols, on the other hand, are better stabilized by phenyl groups

[26] *M. Sundaralingam* and *L. H. Jensen*, J. Amer. chem. Soc. *85*, 3302 (1963).

[27] *A. Almenningen, O. Bastiansen*, and *T. Munthe-Kaas*, Acta chem. scand. *12*, 1221 (1958).

[28] *O. Bastiansen* and *M. Traetteberg*, Tetrahedron *17*, 147 (1962).

[29] Cf.: Epistologue on the Effect of Environment on the Properties of Carbon Bonds. Organised by *M. J. S. Dewar*, Tetrahedron *17*, 123–266 (1962).

[30] *K. B. Wiberg* and *B. J. Nist*, J. Amer. chem. Soc. *83*, 1226 (1961).

[31] *J. Chatt* and *R. G. Guy*, Chem. and Ind. *1963*, 212.

[32] *T. Schaefer* and *W. G. Schneider*, Canad. J. Chem. *41*, 966 (1963).

[33] *H. Spiesecke* and *W. G. Schneider*, Tetrahedron Letters *1961*, 468.

[34] The pK-value in this case is the pH-value at which 50% of the carbinol is ionized to the cation.

Table 3. pK-Values for some cyclopropenylium salts [13, 18, 20, 21]. (A = 50 % aqueous acetonitrile; B = 23 % aqueous ethanol; a = potentiometric titration; b = spectrophotometric titration).

Cyclopropenylium salt R^1, R^2, R^3	$X^{\ominus}$	Medium	Method of determination	pK [*]
2× Propyl	$ClO_4^{\ominus}$	A	a	2.7
3× Propyl	$ClO_4^{\ominus}$	A	a	7.2
2× Phenyl	$Br^{\ominus}$	B	b	−0.67
1× Propyl, 2× Phenyl	$BF_4^{\ominus}$	B	b	3.8
3× Phenyl	$Br^{\ominus}$	A	a	3.1
		B	b	2.8
2× Phenyl, 1× p-Anisyl	$Br^{\ominus}$	B	b	4.0
1× Phenyl, 2× p-Anisyl	$Br^{\ominus}$	A	a	5.2
		B	b	5.2
3× p-Anisyl	$Br^{\ominus}$	A	a	6.5
		B	b	6.4

[*] $K = \frac{[ROH]\,[H^{\oplus}]}{[R^{\oplus}]\,[H_2O]}$

than by propyl groups. Since the pK-value depends on the difference in the free energies of the cation and the carbinol, both factors are involved.

The propyl groups stabilize the cation by an inductive effect, just as a methyl group raises the pK value of the tropylium cation [35]; however, the stabilization is much more pronounced in the case of the cyclopropenylium cation, owing to the higher charge density. Phenyl groups also stabilize the cyclopropenylium cation, as shown by a comparison of the pK-values of the di- and triphenylcyclopropenylium cations, but by a mesomeric effect; an inductive effect, such as prevails *e.g.* in the phenyl [36] and heptaphenyltropylium cations [37], would lower the pK value in this case. However, a comparison with the corresponding free radicals [38, 39] and anions [40, 41] [*] shows that this resonance stabilization is not the only factor determining the stability of the phenyl-substituted cations.

The pK-values of some cyclopropenylium compounds were used as a test of the accuracy of the M.O. calculations. Good agreement was found between the calculated and experimentally determined pK-values within a series of very similar compounds, using suitable parameters [13].

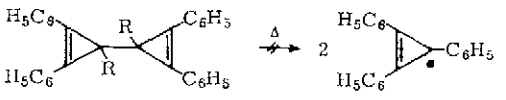
The pK-value of the triphenylcyclopropenylium cation was related to that of other cations by hydride abstraction. Competitive experiments gave the following order of stability:

tropylium > triphenylcyclopropenylium > perinaphthenylium > trianisylmethylium > triphenylmethylium [42].

C. The Cyclopropenyl Radical and Anion

The enhanced resonance stabilization of the cyclopropenylium cation compared to the free radical and, in particular, compared to the anion was the most important of the M.O. predictions regarding the unsaturated three-membered ring systems (see Introduction) [7, 9, 10, 41, 43, 44]. Since ring strain is comparable in these three systems, it should be possible to check the M.O. calculations on this point.

The properties of bis(triphenylcyclopropenyl) *(17a)* were as expected: even at high temperatures *(17a)* shows no tendency to dissociate into the radicals *(18)*



(17a): R = C_6H_5 *(18)*

(17b): R = H

[38]. This qualitative finding was also supported by a quantitative investigation, in which the difference in the free energies of triarylcyclopropenylium cations and the corresponding free radicals was determined polarographically from the reversible reduction potentials [39].

Table 4. Reversible one-electron reduction potentials of cyclopropenylium cations and of the triphenylmethyl cation.

Salt	Reversible reduction potential [V]
Triphenylcyclopropenylium-$ClO_4^{\ominus}$	−1.132
Diphenyl-*p*-anisylcyclopropenylium-$ClO_4^{\ominus}$	−1.24
Trianisylcyclopropenylium-$ClO_4^{\ominus}$	−1.49
Triphenylmethylium-$ClO_4^{\ominus}$	−0.090

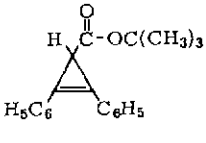
The difference of 1.04 eV (≈ 24 kcal/mole) between the triphenylcyclopropenyl and triphenylmethyl compounds roughly agrees with the result required by the simple Hückel theory, and evidently reflects the loss of resonance in the cyclopropenyl radical.

According to the predictions of the simple Hückel theory, the cyclopropenyl anion *(3)*, like cyclobutadiene, should possess no delocalization energy, and should exist as a triplet in the ground state; even the anion with three phenyl substituents has a delocalization energy which is lower by 1 β than that of the cation (see Introduction).

Attempts to prepare the 1,2,3-triphenylcyclopropenyl anion from 1,2,3-triphenylcyclopropene with alkali metal amides [41] or from 1,2,3-triphenyl-3-ethoxycyclopropene with potassium [45] were unsuccessful; undesired reactions occurred in every case.

When [3-^{3}H]-1,2,3-triphenylcyclopropene was treated with potassium t-butoxide in boiling t-butanol, there was no exchange of tritium for hydrogen, whereas [α-^{3}H]-triphenylmethane had lost 80 % of its activity after 8 hours under the same conditions [41]. All these results demonstrate the instability of the triphenylcyclopropenyl anion. It is possible, however, that cyclopropenyl anions can be stabilized by substituents in certain cases. For example, 1,2-diphenyl-3-t-butoxycarbonylcyclopropene *(19)* exchanges 5 % of the

(19)



[35] *K. Conrow*, J. Amer. chem. Soc. *83*, 2343 (1961).

[36] *C. Jutz* and *F. Voithenleitner*, Chem. Ber. *97*, 29 (1964).

[37] *M. A. Battiste*, J. Amer. chem. Soc. *83*, 4101 (1961).

[38] *R. Breslow* and *P. Gal*, J. Amer. chem. Soc. *81*, 4747 (1959).

[39] *R. Breslow*, *W. Bahary*, and *W. Reinmuth*, J. Amer. chem. Soc. *83*, 1763 (1961).

[*] See Section II.C.

[40] *R. Breslow* and *M. Battiste*, Chem. and Ind. *1958*, 1143.

[41] *R. Breslow* and *P. Dowd*, J. Amer. chem. Soc. *85*, 2729 (1963).

[42] *H. J. Dauben* and *L. M. McDonough*, Abstracts 142nd Meeting of the American Chemical Society, Atlantic City, September 1962. p. 55 Q.

[43] *A. Streitwieser*, J. Amer. chem. Soc. *82*, 4123 (1960).

[44] *A. Streitwieser*, Tetrahedron Letters *1960*, No. 6, 23.

[45] *P. L. Dowd*, Ph. D. Thesis, Columbia University, 1962; Ph. D. Thesis Abstracts *24*, 509 (1963).

hydrogen in the three-membered ring for deuterium on treatment with potassium t-butoxide in boiling deuterio-t-butanol; nevertheless, this exchange proceeds much more slowly than in the case of an ester of a cyclopropanecarboxylic acid, a fact which indicates that the double bond has a destabilizing influence [40].

D. Homocyclopropenylium Cations

According to the concept of homoaromaticity [46,47], the non-classical carbonium ions *(20)*, *(21)*, and *(22)* [and their derivatives, *e.g. (23)*], which have been postulated as intermediates in solvolytic reactions, were regarded as mono- [48], bis- [49–52], and trishomocyclopropenylium ions [47,53,54], and their relative stabilities were explained by their relationship to the cyclopropenylium system.

(20) *(21)* *(22)* *(23)*

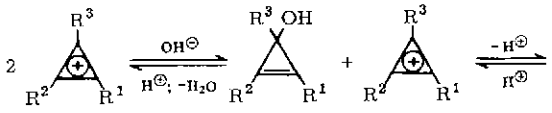
However, the evidence for the existence of these cations is the subject of the more general controversy regarding classical [55,56] and non-classical [52] carbonium ions.

E. Chemical Reactions of the Cyclopropenylium Salts

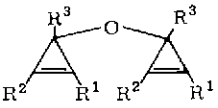
Owing to their integral positive charge, the cyclopropenylium compounds readily react with nucleophilic reagents. These reactions often constitute the first stage of a rearrangement, leading either to ethylene derivatives or to less strained five- or six-membered ring compounds.

1. Reactions with Bases

An equilibrium is set up between the cyclopropenylium cations *(16b)* and the covalent carbinols *(16a)* in aqueous or aqueous-alcoholic solution; the position of the equilibrium depends on the substitutents on the cation and on the pH of the solution (cf. Section II.B.4). However, the carbinols *(16a)* can also act as bases and react with a further cation to form the ethers *(24)*. Consequently, the carbinols, unlike the ethers, cannot be isolated [13,15,16,19,21].

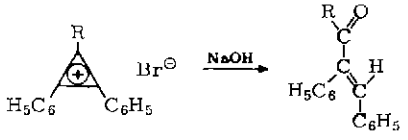


(16a)



(24)

In strongly alkaline solution (10 % NaOH), on the other hand, the ring is irreversibly opened; triphenylcyclopropenylium bromide *(25a)* gives 1,2,3-triphenylpropenone *(26a)* [16] *via* the ether as an intermediate, while the diphenyl derivative *(25b)* gives 2,3-diphenylpropen-1-al *(26b)* [18,19].



(25a): R = C_6H_5 *(26a)*: R = C_6H_5
(25b): R = H *(26b)*: R = H

The cyclopropenylium cation is also attacked by the anion of organometallic reagents (cf. Section II.A); thus, for example, the reaction of *(25a)* with methylmagnesium bromide yields 3-methyl-1,2,3-triphenylcyclopropene [41].

2. Reduction of the Cations

The reduction of *(25a)* with lithium aluminum hydride gave triphenylcyclopropene *(27)* in high yield [41]. This reaction is, therefore, formally the reverse of the preparation of cyclopropenylium salts by hydride abstraction [21,22,42].

(25a) *(27)*

The reaction of triphenyl- or dipbenylcyclopropenylium salts with zinc dust, like polarographic reduction (see Section II.C), gave the dimers *(17a)* and *(17b)* of the corresponding free radicals. These dimers rearrange at 130 °C to form benzene derivatives; 1,2,4,5- and 1,2,3,4-tetraphenylbenzenes have been isolated as products of the thermal rearrangement of bis-3,3'-(diphenylcyclopropenyl) *(17b)*, which may proceed *via* a prismane intermediate [*] [38,57,58].

[46] *S. Winstein*, J. Amer. chem. Soc. *81*, 6524 (1959).

[47] *S. Winstein* and *J. Sonnenberg*, J. Amer. chem. Soc. *83*, 3244 (1961).

[48] *E. F. Kiefer* and *J. D. Roberts*, J. Amer. chem. Soc. *84*, 784 (1962).

[49] *S. Winstein, M. Shatavsky, C. Norton*, and *R. B. Woodward*, J. Amer. chem. Soc. *77*, 4183 (1955).

[50] *S. Winstein* and *M. Shatavsky*, J. Amer. chem. Soc. *78*, 592 (1956).

[51] *W. G. Woods, R. A. Carboni*, and *J. D. Roberts*, J. Amer. chem. Soc. *78*, 5653 (1956).

[52] *S. Winstein, A. H. Lewin*, and *K. C. Pande*, J. Amer. chem. Soc. *85*, 2325 (1963).

[53] *S. Winstein* and *J. Sonnenberg*, J. Amer. chem. Soc. *83*, 3235 (1961); *T. Norin*, Tetrahedron Letters *1964*, 37.

[54] *R. R. Sauers*, Tetrahedron Letters *1962*, 1015.

[55] *H. C. Brown*, J. Amer. chem. Soc. *85*, 2324 (1963).

[56] *H. C. Brown, F. J. Chloupek*, and *M. H. Rei*, J. Amer. chem. Soc. *86*, 1246, 1247, 1248 (1964).

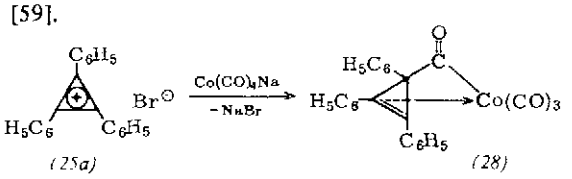
[*] For the reaction scheme, see *D. Seebach*, Angew. Chem., in the press.

[57] *R. Breslow* in *P. de Mayo*: Molecular Rearrangements. Interscience Publishers, New York-London 1963, Vol. 1, pp. 243–245.

[58] The photochemical dimerization of cyclopropenes to form tricyclohexanes is known: *H. H. Stechl*, Angew. Chem. *75*, 1176 (1963); Angew. Chem. internat. Edit. *2*, 743 (1963).

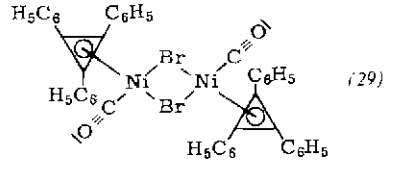
3. Reactions with Transition-Metal Complexes

Cobalt tetracarbonylate reacts with *(25a)*, with carbonylation of the cation, to form a π-complex which has been formulated as *(28)*; the desired symmetrical π-complex of the triphenylcyclopropenylium cation is not obtained [59].



(25a) *(28)*

Attempts to obtain this complex by reaction of *(25a)* with potassium trichloro(ethylene)platinate(II), followed by thermal elimination of ethylene from the resulting product, were also unsuccessful [31]. On the other hand, *(25a)* reacted with tetracarbonylnickel with evolution of CO to form a complex which was stable in the solid state, and which was assigned the structure *(29)* [60].

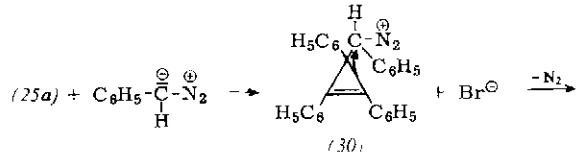


(29)

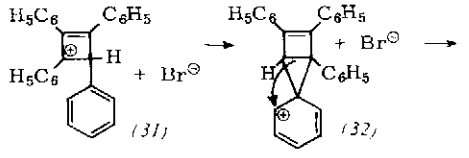
Compound *(29)* is regarded as a complex of formally zerovalent nickel with the triphenylcyclopropenylium cation. Each atom is tetrahedrallynickel surrounded by four pairs of electrons, two of which are supplied by the bromide anions, one by the carbon monoxide group, and one by the cyclopropenylium group. Recently a dipbenylcyclopropenone-nickel carbonyl complex has also been prepared [65].

4. Reactions with Diazo Compounds and Azides

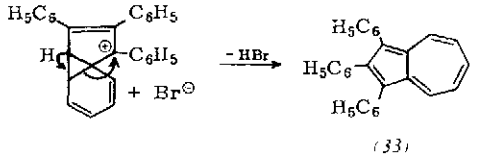
Compound *(25a)* reacts with phenyldiazomethane to form 1,2,3-triphenylazulene *(33)*. It is assumed that the diazonium compound *(30)* is first formed, and that this



(30)



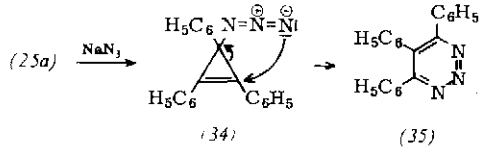
(31) *(32)*



(33)

loses nitrogen, with ring expansion, to form the cyclobutenyl cation *(31)*. The latter undergoes rearrangement, *via* the phenonium ion *(32)*, to form *(33)*. In the presence of excess phenyldiazomethane, the principal product is pentaphenylcyclopentadiene, formed by ring expansion of *(31)* [60a].

Sodium azide reacts with *(25a)* to form 1,2,3-triphenylcyclopropenyl azide *(34)*, which slowly rearranges, even at room temperature, to 4,5,6-triphenyltriazine *(35)* [60b, 60c]; this stabilization with ring expansion is typical of many similar cyclopropene derivatives [60d].

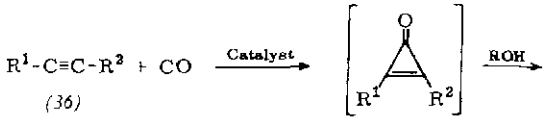


(34) *(35)*

III. Cyclopropenones

Whereas in the case of the seven-membered ring compounds tropone was synthesized before the tropylium cation [2], the first cyclopropenone, namely diphenylcyclopropenone *(37)* [61, 62] was only described after the first cyclopropenylium salt.

However, cyclopropenones had previously been postulated (although with no conclusive evidence) as intermediates [63], particularly in the catalytic carbonylation of acetylenes *(36)*, which, in the presence of water or alcohols, leads to acrylic acids or acrylates [64].



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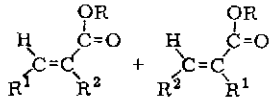


This assumption has been tested in recent years in the case of diphenylcyclopropenone *(37)*. The results indicate that no cyclopropenone intermediate occurs in the carbonylation of acetylenes [65].

Interest in the cyclopropenones was rekindled by the predictions of the M.O. calculations (see Introduction) and the preparation of cyclopropenylium salts. The validity of the M.O. calculations was clearly shown by the isolation of the stable cyclopropenones. According to classical concepts, the more highly strained cyclopropenones should be much less stable

[59] *C. E. Coffey*, J. Amer. chem. Soc. *84*, 118 (1962).

[60] *E. W. Gowling* and *S. F. A. Kettle*, Inorg. Chem. *3*, 604 (1964).

[60a] See [57], p. 276.

[60b] *R. Breslow, R. Boikess*, and *M. Battiste*, Tetrahedron Letters *1960*, No. 26, 42.

[60c] *E. Chandross* and *E. Smolinsky*, Tetrahedron Letters *1960*, No. 13, 19.

[60d] See [57], pp. 240–241.

[61] *R. Breslow, R. Haynie*, and *J. Mirra*, J. Amer. chem. Soc. *81*, 247 (1960).

[62] *D. N. Kursanov, M. E. Volpin*, and *Yu. D. Koreshkov*, Izv. Acad. Nauk S.S.S.R., Otd. Khim. Nauk *1959*, 560; Chem. Abstr. *53*, 21799 (1959); Zh. Obshch. Khim. (English translation) *30*, 2855 (1960).

[63] *L. Wolff*, Liebigs Ann. Chem. *260*, 79 (1890).

[64] *W. Reppe*, Liebigs Ann. Chem. *582*, 1 (1953).

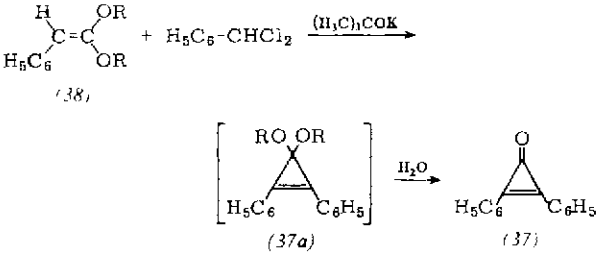
[65] *C. W. Bird* and *J. Hudec*, Chem. and Ind. *1959*, 570, *C. W. Bird* and *E. M. Hollins*, ibid. *1964*, 1362.

than the cyclopropanones, as is the case with the corresponding four-membered ring compounds [66]. However, cyclopropanones have so far only been detected as intermediates in a few reactions, but have not been isolated [67–71].

A. Preparation of Cyclopropenones

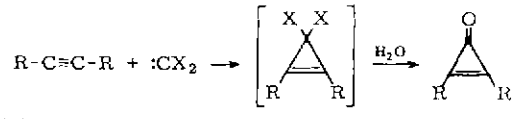
Of the four known syntheses of cyclopropenones, three proceed *via* substituted cyclopropenes which can be converted to cyclopropenones by hydrolysis; the fourth method is similar to the Favorskii reaction, the three-membered ring being formed only in the last step.

Diphenylcyclopropenone *(37)* was first prepared by the addition of phenylchlorocarbene to phenylketene acetal *(38)*, followed by elimination of HCl to form cyclopropenone ketal *(37a)* which is readily hydrolysed to *(37)* [61].



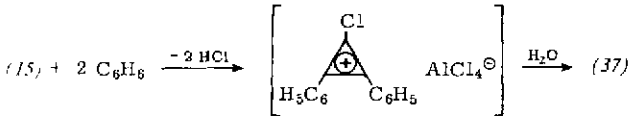
(38) *(37a)* *(37)*

A simpler synthesis of cyclopropenones is based on the addition of dichloro- or dibromo-carbenes to disubstituted acetylenes *(36a)* or *(36b)* and hydrolysis of the resulting product [62, 72, 73].

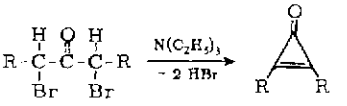


(36a): R = C_6H_5; X = Cl, Br
(36b): R = n-C_3H_7

Compound *(37)* is also formed from benzene and the trichlorocyclopropenylium cation *(15)* *via* a Friedel-Crafts reaction followed by hydrolysis [25].



A fundamentally different method uses α,α′-dibromoketones *(39)* as the starting materials; these lose 2 moles of hydrogen bromide to form cyclopropenones on treatment with triethylamine or other bases [74–77].



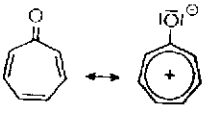
(39)

R = C_6H_5, n-C_4H_9
R + R = $(CH_2)_5$, $(CH_2)_9$

The unsubstituted cyclopropenone *(4)* has not yet been synthesized; however, this is due to its instability rather than to failure of the methods of preparation [62, 74].

B. Physical and Chemical Properties of the Cyclopropenones

The high stability of the cyclopropenylium cation suggests that, as in the case of tropone *(40)*, the zwitterionic form of *(4)* makes a considerable contribution to the ground state of the cyclopropenones; this should also be reflected in their properties.

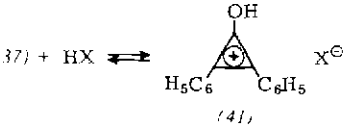


(40)

1. Basicity

Cyclopropenones are much more basic than other α,β-unsaturated ketones, with the exception of tropone [78–80]. Hammett's H_0-values (at which half of the ketone is protonated in aqueous solution) are -2.5 ± 0.3 (ca. 5.5 N $HClO_4$) for *(37)* and -0.4 ± 0.2 (ca. 1.3 N $HClO_4$) for *(40)* [80]. Dipropylcyclopropenone is more basic than diphenylcyclopropenone *(37)* [72, 73]; the substitutent effect in this case is therefore the same as in the case of the cyclopropenylium cations.

The high basicity of the cyclopropenones is often used in their separation and purification [62, 72–74]. The salts *(41)* of *(37)* can be obtained in crystalline form, and can be decomposed by heat or by weak bases to give cyclopropenone again [62].



(41)

The structure of the salts *(41)* is shown by the disappearance of the two typical cyclopropenone bands (see below) and the appearance of an OH band and of the cyclopropenylium band

[66] Cf. *E. Vogel* and *K. Hasse*, Liebigs Ann. Chem. *615*, 22 (1958).

[67] *P. Lipp, J. Buchkremer*, and *H. Seeles*, Liebigs Ann. Chem. *499*, 1 (1932).

[68] *R. B. Loftfield*, J. Amer. chem. Soc. *72*, 632 (1950); *73*, 4707 (1951).

[69] *D. A. Semenow, E. F. Fox*, and *J. D. Roberts*, J. Amer. chem. Soc. *78*, 3221 (1956); earlier work is also found there.

[70] *W. B. De More, H. O. Pritchard*, and *N. Davidson*, J. Amer. chem. Soc. *81*, 5874 (1959).

[71] *A. W. Fort*, J. Amer. chem. Soc. *84*, 4979 (1962).

[72] *R. Breslow* and *R. Peterson*, J. Amer. chem. Soc. *82*, 4426 (1960).

[73] *R. A. Peterson*, Ph. D. Thesis, Columbia University, 1962. Ph. D. Thesis Abstracts *23*, 1517 (1962).

[74] *R. Breslow, J. Posner*, and *A. Krebs*, J. Amer. chem. Soc. *85*, 234 (1963).

[75] *R. Breslow* and *J. Posner*, unpublished work.

[76] *R. Breslow* and *Th. Eicher*, unpublished work.

[77] *R. Breslow* and *A. Krebs*, unpublished work.

[78] *Yu. G. Borodka* and *Ya. K. Syrkin*, Dokl. Akad. Nauk S.S.S.R., *136*, 1335 (1961); Chem. Abstr. *55*, 19743 (1961).

[79] *B. E. Zaitsev, Yu. D. Koreshkov, M. E. Volpin*, and *Yu. N. Sheinker*, Dokl. Akad. Nauk S.S.S.R., *139*, 1107 (1961); Chem. Abstr. *56*, 344 (1962).

[80] *A. S. Kende*, personal communication.

(see Section II.B.3) in the IR spectrum. This change in the IR spectrum has been used for quantitative determination of the temperature dependence of the equilibrium *(37)* ⇌ *(41)*, and in this way the thermodynamic data were determined [78,79].

2. Spectra

The IR spectra of all cyclopropenones are characterized by two very intense bands at 1845–1865 and 1620 to 1645 cm^{-1} [61,62,72–79]. The authors are not in agreement as to the assignment of these bands; however, according to the solvent dependence of the positions of the bands, the band at 1850 cm^{-1} arises from the cyclopropene system with two substituents on the double bond, while that at 1640 cm^{-1} is due to the C=O stretching vibration [81]. The occurrence of the carbonyl band at this wave number, which is low for small-ring ketones [82], points to the high single-bond character of the C=O bond, and hence to the considerable contribution of the zwitterionic form of *(4)* to the ground state of the cyclopropenones. This is further supported by the high intensity of the carbonyl band and by the large dipole moments of 5.08 D and 5.3 D for dipbenyl- *(37)* and cycloheptenocyclopropenone *(42)*, respectively (cf. benzophenone 3.0 D; tropone 4.3 D; trimethylamine oxide 5.03 D) [62,81,83–85].

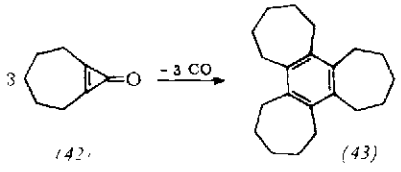
The nuclear magnetic resonance spectra of the cyclopropenones also agree with this structure. Thus the signals of the α-methylene protons occur at lower fields than those of the corresponding covalent cyclopropenes, but are not so strongly shifted as those of the cyclopropenylium salts [73,81]. In the case of the cyclopropenones, the differences Δ in the chemical shifts of the signals of the α- and β-CH_2 groups (which are proportional, in many cases, to the electronegativity of the substituents [21,86]) also lie between the values found for cyclopropenes and for cyclopropenylium salts [73,81].

C. Chemical Reactions of the Cyclopropenones

The reactions of the cyclopropenones can be subdivided into decarbonylations and additions. In the addition reactions, the reactant adds on either to the C=O or to the C=C double bond; this is often accompanied by rearrangements with opening of the three-membered ring [87].

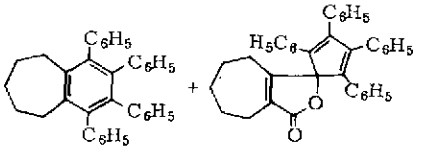
1. Decarbonylation

The thermal decomposition of the cyclopropenones at 130 – 250 °C leads to the formation of the corresponding acetylenes, with loss of carbon monoxide; the decarbonylation of dialkylcyclopropenones requires higher temperatures than that of diphenylcyclopropenones *(37)* [61,72–74,77]. Photolysis of *(37)* also yields diphenylacetylene and carbon monoxide [65,88]. Triscycloheptenobenzene *(43)* is formed on heating cycloheptenocyclopropenone *(42)* [74]. If *(42)* is decomposed in the



(42) *(43)*

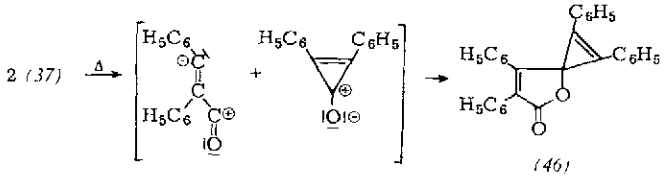
presence of tetraphenylcyclopentadienone, a small quantity of *(43)* (about 3 %) is formed, together with 1,2-cycloheptene-3,4,5,6-tetraphenylbenzene *(44)* (23 %) and *(45)* (21 %) as the principal products [77].



(44) *(45)*

Compounds *(43)* and *(44)* are probably formed *via* cycloheptyne as an intermediate [89]; however, addition of the strained C=C double bond of *(42)* to the tetraphenylcyclopentadienone, followed by elimination of 2 moles of carbon monoxide, cannot be excluded.

It is not yet certain whether the two C–C bonds are broken successively or simultaneously in the decarbonylation of cyclopropenones (which can be regarded as the reversal of a carbene addition). The dimer, which probably has the structure *(46)*, may be formed from *(37)* *via* an intermediate, since diphenylacetylene is the principal product of thermal decomposition of *(37)* only at high temperatures (> 160 °C). Between 145 and 150 °C, particularly in the presence of catalytic amounts of base, the main product is *(46)*, which cannot be thermally decomposed to give diphenylacetylene [77].



(46)

2. Addition Reactions

Additions to the carbonyl group can occur by electrophilic attack on the electron-rich oxygen atom, or by the attack of nucleophiles on the carbon atom which carries

[81] *A. Krebs*, unpublished work.

[82] Cyclopropanone has a band at 1825 cm^{-1} [70].

[83] *Yu. G. Borodko* and *Ya. K. Syrkin*, Dokl. Akad. Nauk S.S.S.R. *134*, 1127 (1960); Chem. Abstr. *55*, 12039 (1961).

[84] *B. E. Zaitsev, Yu. N. Sheinker*, and *Yu. D. Koreshkov*, Dokl. Akad. Nauk S.S.S.R. *136*, 1090 (1961); Chem. Abstr. *55*, 19480 (1961).

[85] *A. N. Shidlovskaja* and *Ya. K. Syrkin*, Dokl. Akad. Nauk S.S.S.R. *139*, 418 (1961).

[86] *J. R. Cavanaugh* and *B. P. Dailey*, J. chem. Physics *34*, 1094 (1961); *B. P. Dailey* and *J. N. Shoolery*, J. Amer. chem. Soc. *77*, 3977 (1955).

[87] None of the investigations carried out so far makes possible a decision as to whether, in a reaction of a cyclopropenone, the ring-opening takes place before, simultaneously with, or after the addition of a reactant.

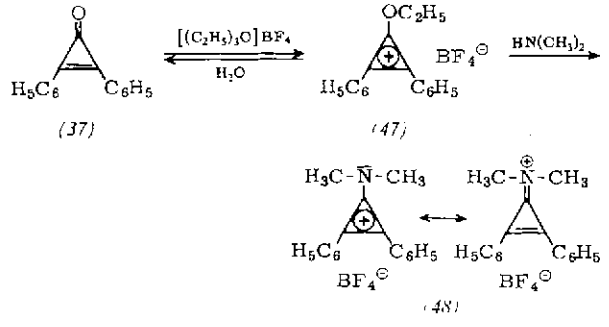
[88] *G. Quinkert, K. Opitz, W. W. Wiersdorff*, and *J. Weinlich*, Tetrahedron Letters *1963*, 1836.

[89] Cf. *G. Wittig* and *A. Krebs*, Chem. Ber. *94*, 3260 (1961); *G. Wittig* and *R. Pohlke*, ibid. *94*, 3276 (1961); *G. Wittig*, Angew. Chem. *74*, 479 (1962); Angew. Chem. internat. Edit. *1*, 415 (1962); *F. G. Willey*, Angew. Chem. *76*, 144 (1964); Angew. Chem. internat. Edit. *3*, 138 (1964).

a partial positive charge. However, nucleophilic addition to the carbonyl carbon atom is more difficult than in other α,β-unsaturated ketones, owing to the charge delocalization in the zwitterionic form of *(4)*.

α) Electrophilic Additions to the Carbonyl Group

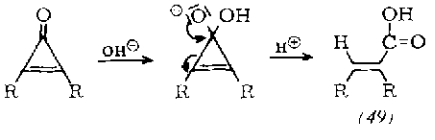
This group of reactions includes protonation of the cyclopropenones with strong acids (see Section III.B.1) and alkylation with triethyloxonium fluoroborate, which in the case of *(37)* leads [76, 89a] to ethoxydiphenylcyclopropenylium fluoroborate *(47)*. The enhanced reactivity of *(47)* as compared with *(37)* is shown in the reaction with dimethylamine; the product is dimethylaminodiphenylcyclopropenylium fluoroborate *(48)* whose stability towards boiling water can be explained by resonance [76].



(37) *(47)* *(48)*

β) Nucleophilic Additions to the Carbonyl Group

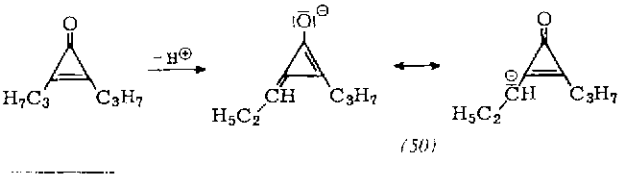
The hydrolysis of cyclopropenones with sodium hydroxide to yield α,β-unsaturated acids *(49)* [62, 72–74] probably begins with an addition of the $OH^{\ominus}$ ion to the C-atom of the carbonyl group; thus it proceeds in a manner similar to the ring-opening of the cyclopropanone intermediate in the Favorskii rearrangement [90].



(49)

The same gradation of reactivity is observed in this reaction as in the decarbonylation: the alkyl-substituted cyclopropenones are more stable than diphenylcyclopropenone [72–74]. This may be due either to the greater stabilizing action of the alkyl groups on the ketone (as suggested by basicity measurements) or to an increase in the stabilization of the transition state by the phenyl groups during ring-opening.

On the other hand, dipropylcyclopropenone reacts with other bases, such as sodium methoxide in methanol, to give the 2-propyl-3-propylidenecyclopropenolate anion *(50)*, as has been demonstrated by deuterium-exchange [80, 94].



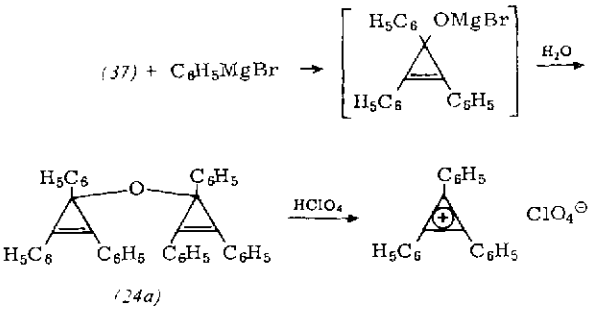
(50)

[89a] *B. Föhlisch*, personal communication.

[90] *A. Kende*, Organic Reactions *11*, 261 (1960).

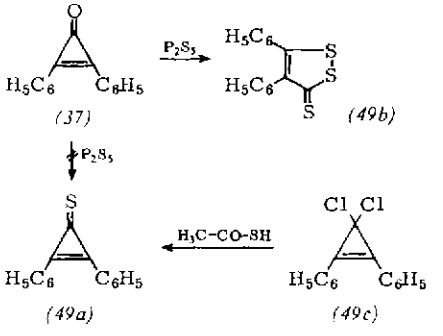
[90a] For a discussion of the mechanism of the reaction of *(37)* with hydroxylamine, see [73], pp. 42–44.

Grignard compounds also add in some cases to the carbonyl group of the cyclopropenones, whereas in the case of the tropones, this reaction occurs only to a very small extent, the principal reaction being 1,3-addition [91]. The different course taken by the reaction of *(37)* with phenylmagnesium bromide [73] is due either to steric factors or to the fact that the formation of a cyclopropanone is so difficult that the 1,3-addition is suppressed in favor of the formation of the ether *(24a)*.



(24a)

When it was attempted to convert *(37)* into the thioketone *(49a)* by reaction with phosphorus pentasulfide, only 4,5-diphenyltrithione *(49b)* was obtained [89a]. However, *(49a)* could be prepared from 3,3-dichloro-1,2-diphenylcyclopropene *(49c)* and thioacetic acid [91a].



(37) *(49b)* *(49a)* *(49c)*

Lithium aluminum hydride attacks the C=O and C=C double bonds of *(37)* to form 2,3-diphenylcyclopropan-1-ol [62], the structure of which, however, does not appear to be quite certain.

Even in the polarographic reduction of *(37)*, it could not be decided which of the two double bonds was first reduced [92].

Compound *(37)* forms a hydrazone with 2,4-dinitrophenylhydrazine [62]; the *p*-toluenesulfonylhydrazone, on the other hand, could only be obtained by the reaction of 3,3-dichloro-1,2-diphenylcyclopropene with *p*-toluenesulfonylhydrazine [93]. Hydrazine [93], semicarbazide, and hydroxylamine [62] did not yield the normal carbonyl derivatives with *(37)*. This inertia is evidently a result of the delocalization of the positive charge in the zwitterionic form of *(4)*.

[91] *G. L. Closs* and *L. E. Closs*, J. Amer. chem. Soc. *83*, 599 (1961); *T. Nozoe*, *T. Mukai*, and *T. Tezuka*, Bull. chem. Soc. Japan *34*, 619 (1961).

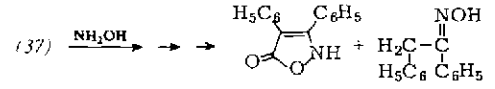
[91a] *Th. Eicher*, personal communication.

[92] *S. I. Zhdanov* and *M. K. Polievktov*, Zh. obshch. Khim. (English translation) *31*, 3607 (1961); Chem. Abstr. *57*, 10935 (1962).

[93] *W. M. Jones*, personal communication.

γ) Additions to the C=C Double Bond

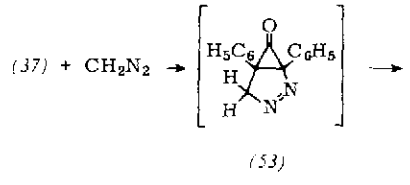
The reaction of *(37)* with hydroxylamine yields 3,4-diphenylisoxazolone *(51)* and desoxybenzoin oxime *(52)* [73].



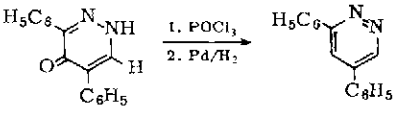
(51), 70% *(52)*, 11%

The first step is assumed to be a 1,4- or 1,2-addition (to the C=C double bond) of the hydroxylamine. The intermediates then undergo oxidation, or oxidation and decarboxylation, to form *(51)* or *(52)* [90a].

Diazomethane does not attack the carbonyl group, as it does in the case of saturated cyclic ketones, but adds as a 1,3-dipole (as in the case of normal α,β-unsaturated ketones) to the strained cyclopropene double bond of *(37)* [76,94] or dipropylcyclopropenone [94]. The cyclopropanone intermediate *(53)* isomerizes to 3,5-diphenyl-4-pyridazone *(54)*, the structure of which has been proved by reduction to *(55)* [76,94].



(53)



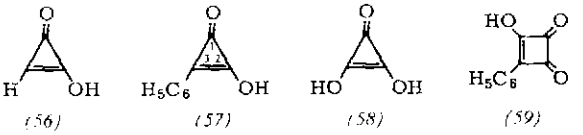
(54) *(55)*

The catalytic hydrogenation (Pt/H_2) of *(37)* gave dibenzyl ketone in one case [73]; other authors isolated 2,3-diphenylcyclopropan-1-ol as the sole product [62].

D. Cyclopropenone Derivatives

1. Hydroxycyclopropenones

The hydroxycyclopropenones are of interest on account of the analogy to the tropolone series and the high calculated delocalization energies of the anions of hydroxycyclopropenone *(56)* [95] and of 2-hydroxy-3-phenylcyclopropenone *(57)*, and of the dianion of dihydroxycyclopropenone *(58)* [96]. Thus *(56)*, *(57)*, and *(58)* should be very strong acids ($pK_a \approx 0$), as is 4-hydroxy-3-phenylcyclobutene-1,2-dione *(59)* [95].



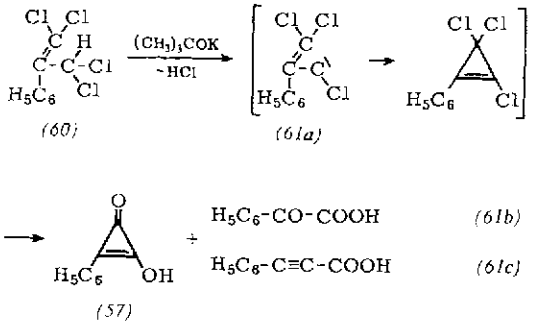
(56) *(57)* *(58)* *(59)*

[94] *P. T. Izzo* and *A. S. Kende*, Chem. and Ind. *1964*, 839.

[95] *E. J. Smutny*, *M. C. Caserio*, and *J. D. Roberts*, J. Amer. chem. Soc. *82*, 1793 (1960).

[96] *R. West* and *D. L. Powell*, J. Amer. chem. Soc. *85*, 2577 (1963).

However, of these compounds only *(57)* has been synthesized; the reaction of 1,1,3,3-tetrachloro-2-phenylpropene *(60)* with potassium t-butoxide, which probably proceeds *via* the vinylcarbene *(61a)*, led to *(57)*, phenylpyruvic acid *(61b)*, and phenylpropiolic acid *(61c)*. In accord with the predictions, *(57)* has $pK_a \approx 1$ [97].

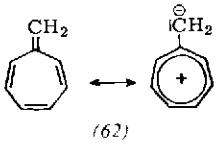


(60) *(61a)* *(61b)* *(61c)* *(57)*

Whereas the "aromatic" oxo-anions $C_4O_4^{2\ominus}$, $C_5O_5^{2\ominus}$, and $C_6O_6^{2\ominus}$ are known, the first member of this series, namely the dianion of *(58)* $C_3O_3^{2\ominus}$, has not yet been described [96]. Attempts to obtain *(58)* by hydrolysis of tetrachlorocyclopropene always led to ring-opening [98].

2. Methylenecyclopropenes (Triafulvenes)

Methylenecyclopropene *(5)* is the simplest cross-conjugated cyclic system. For this reason, and owing to its relationship with cyclopropenone on the one hand and 1-methylenecycloheptatriene (heptafulvene) *(62)* on the other hand, methylenecyclopropene *(5)* and its derivatives became the objects of theoretical studies at an early stage [7, 9, 99]. Despite the large calculated delocalization energy (see Table 2), the M. O. theory requires that *(5)* owing to the high free-valence index at the exocyclic methylene group should be readily polymerizable and should be highly reactive towards free radicals [*] [7]. In agreement with this, no derivatives of *(5)* without substituents on the exocyclic C-atom have as yet been isolated. On the other hand, substituents which can stabilize a negative charge on the exocyclic C-atom by inductive or mesomeric effects should increase the contribution of the zwitterionic form of *(5)* to the ground state, and so cause an increase in the chemical stability of the methylenecyclopropene.



(62)

The first synthesis of a stable methylenecyclopropene, namely 1,2-diphenyl-3,4'-(2',6'-dibromoquino)cyclopropene *(64)*, was achieved by thermal cleavage of the ether linkage in the cyclopropenylium salt *(63)*, bromination of the resulting diphenyl-(*p*-hydroxyphenyl)-

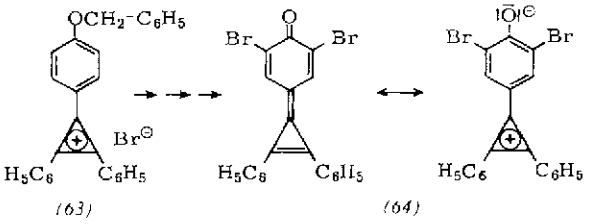
[97] *D. G. Farnum* and *P. E. Thurston*, J. Amer. chem. Soc. *86*, 4206 (1964).

[98] *S. W. Tobey* and *R. West*, Tetrahedron Letters *1963*, 1179.

[99] *J. Syrkin* and *M. Dyatkina*, Acta physicochem. (U.S.S.R.) *21*, 641 (1946); Chem. Abstr. *41*, 1648 (1947); *G. Berthier* and *B. Pullman*, Bull. Soc. chim. France *16 D*, 457 (1949); *A. Julg* and *P. Francois*, J. Chim. Physique *59*, 339 (1962); *O. Chalvet*, *R. Daudel*, and *J. J. Kaufman*, J. physic. Chem. *68*, 490 (1964).

[*] For a definition of the free-valence index, see *e.g. A. Streitwieser jr.*: Molecular Orbital Theory. Wiley, New York-London 1961, p. 56.

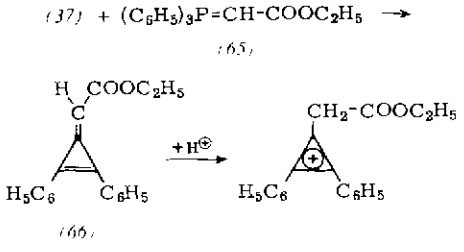
cyclopropenylium bromide with *N*-bromosuccinimide, and finally reversible elimination of HBr with a tertiary amine to yield *(64)* [17]. Compound *(64)* is much more



(63) *(64)*

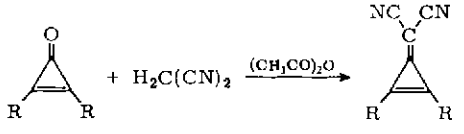
basic than diphenylcyclopropenone *(37)*. 10-(Diphenylcyclopropylidene)anthrone resembles compound *(64)* and was obtained [99a] by reacting diphenylcyclopropenylium perchlorate *(11)* with anthrone.

However, the simplest route to the methylenecyclopropenes is the Wittig olefination of cyclopropenones. Thus, 1,2-diphenyl-4-ethoxycarbonylmethylenecyclopropene *(66)* is obtained by the reaction of *(37)* with triphenylphosphine-ethoxycarbonylmethylene *(65)* [100].



(66)

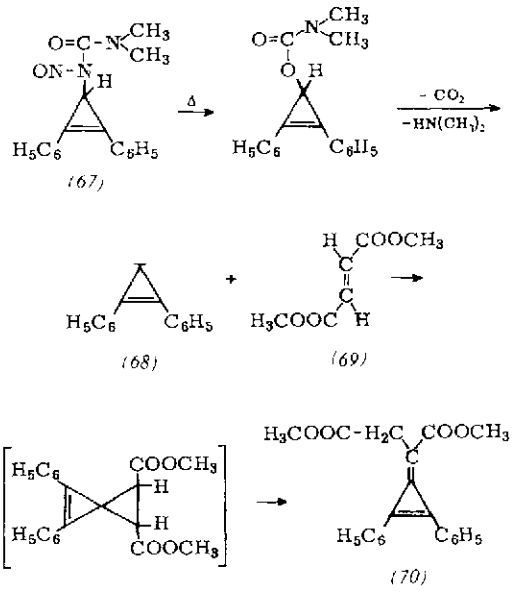
Condensation of *(37)* [100a] and dipropylcyclopropenone [100b] with malonodinitrile yields the correcponding 1,1-dicyanomethylenecyclopropenes *(66a)* and *(66b)*.



(66a) R = C_6H_5
(66b) R = C_3H_7

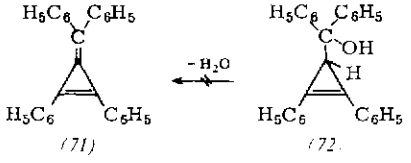
Another methylenecyclopropene, namely *(70)*, has been obtained during attempts to trap 1,2-diphenylcyclopropenylidene *(68)* with dimethyl fumarate *(69)*; *(68)* was formed on decomposition of the urea derivate *(67)* [93, 101].

Attempts to prepare tetraphenylmethylenecyclopropene *(71)* by elimination of water from *(72)* led to rearrangement with formation of 1,2,4-triphenylnaphtbalene and 1,2,3-triphenylazulene *(33)* [102].



(67) *(68)* *(69)* *(70)*

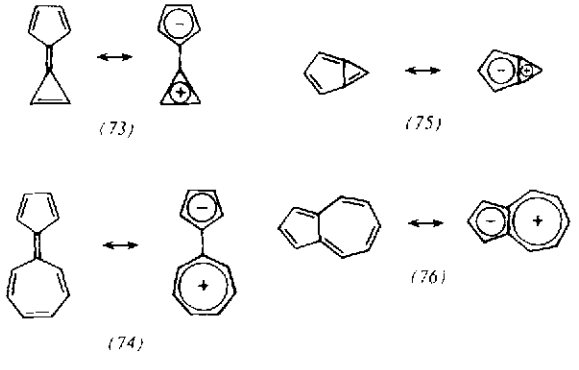
The NMR spectra of *(66)* [100] and of *(66b)* [100b], the high dipole moment of 7.9 D for *(66a)* [100a], the position of the carbonyl band in *(64a)* [99a], and also the strong solvent dependence of the ultraviolet spectra of



(71) *(72)*

(66) [100] and of *(66a)* [100a] prove how considerable the contribution is of the zwitterion form to the ground state of the methylenecyclopropene compounds: it was estimated to be almost 50 % in the case of *(66b)*. This also agrees with the fact that protons add preferentially to the exo-methylene carbon atom of *(66)* and *(70)* to form the cyclopropenylium system.

The formal combination of the cyclopropenylium cation with the cyclopentadienyl anion gives two interesting derivatives of methylenecyclopropene, namely calicene *(73)* and bicyclo[3,1,0]hexatriene *(75)*; these are the three-membered ring analogs of sesquifulvalene *(74)* and of azulene *(76)*.



(73) *(75)* *(74)* *(76)*

Although the considerably large values of 2.94 and 2.39 β have been obtained for the calculated delocalization energies of *(73)* and *(75)* [7], attempted syn-

[99a] *B. Föhlisch* and *P. Bürgle*, Angew. Chem. *76*, 784 (1964); Angew. Chem. internat. Edit. *3*, 699 (1964).

[100] *M. A. Battiste*, J. Amer. chem. Soc. *86*, 942 (1964).

[100a] *E. D. Bergmann* and *I. Agranat*, J. Amer. chem. Soc. *86*, 3587 (1964).

[100b] *A. S. Kende* and *P. T. Izzo*, J. Amer. chem. Soc. *86*, 3587 (1964).

[101] *W. M. Jones* and *J. M. Denham*, J. Amer. chem. Soc. *86*, 944 (1964).

[102] *R. Breslow* and *M. Battiste*, J. Amer. chem. Soc. *82*, 3626 (1960).

theses of these systems have so far been unsuccessful [103, 104].

Compound *(73)*, like *(74)*, may lack the postulated resonance stabilization, since the properties of *(74)* and its derivatives can be satisfactorily explained by the structure with substantially localized double bonds [105, 106]. In the case of *(75)*, the resonance energy is probably consumed by the enormous ring-strain energy; this is shown by the fact that *(75)* can also be described as a valence isomer of a *m*-dehydrobenzene.

IV. Conclusion

The chemistry of the cyclopropenylium compounds is only eight years old. In this short period, however, the important questions have already been answered, so that only a few problems of synthesis remain unsolved, *viz.* the unsubstituted cyclopropenylium cation *(1)*, the benzocyclopropenylium cation, and bicyclo[3,1,0]hexatriene *(75)*.

The preparation of the substituted cyclopropenylium salts, cyclopropenones, and methylenecyclopropenes has extended the number of the "Hückel aromatic" systems. The study of their properties and reactivities has impressively demonstrated the expected relationship with the "Hückel homologous" seven-membered ring compounds. If equality of the bond lengths and the existence of a ring current are accepted as criteria of aromatic character, the cyclopropenylium salts deserve to be called aromatic compounds.

I am indebted to Prof. R. Breslow for discussions and suggestions and also to Dr. Th. Eicher, Dr B. Föhlisch, Prof. W. M. Jones, Dr. A. S. Kende, Dr. H. Prinzbach, and Prof. R. West for making available unpublished results. Thanks are also due to Prof. H. A. Staab for suggestions made on perusal of the manuscript.

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[103] *H. Prinzbach* and *W. Rosswog*, Angew. Chem. *73*, 543 (1961); *H. Prinzbach*, personal communication.

[104] *B. Föhlisch*, Chem. Ber. *97*, 88 (1964).

[105] *H. Prinzbach*, Angew. Chem. *76*, 235 (1964); Angew. Chem. internat. Edit. *3*, 319 (1964).

[106] *T. Nakajima* and *S. Katagiri*, Bull. Chem. Soc. Japan *35*, 910 (1962).

Syntheses of Oxide Halides

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Knowledge of the oxide halides has made significant advances in recent years as a result of new methods of preparation. Moreover, the systematic study of older methods has led to versatile syntheses which permit the preparation of many new oxide halides. A brief outline of the scope, limitations, and difficulties of the various processes is given together with a number of examples.

I. Partial Hydrolysis of Halides

Although the method of partial hydrolysis of halides has been known for a very long time it can only be used in special cases to prepare definite anhydrous oxide halides. The reaction proceeds according to the General Equation (a).

$$MX_5 + H_2O = MOX_3 + 2\,HX \qquad (a)$$

However, the course of such hydrolyses is greatly complicated by the fact that other reactions, such as the formation of stable hydrates, oxyacids of the halides, hydroxo compounds, oxides, etc. are also formed in many cases. The method can, therefore, be succesful only if the reaction product is somehow stabilized or removed, *e.g.* by making use of its volatility. Examples are found in the preparations of $POCl_3$ [1] from PCl_5, of $P_2O_3Cl_4$ [2] from $POCl_3$, or of the silicon oxide halides of general formula $Si_nO_{n-1}Cl_{2n+2}$ which can be obtained by partial hydrolysis of $SiCl_4$, and of which the representatives up to n=10 have been isolated [3–7].

Oxide halides can also be stabilized in the crystal lattice. In such cases partial hydrolysis of the halide can even be carried out with excess water. This group includes certain oxide halides of mercury, *e.g.* $2HgCl_2 \cdot HgO$ [8]. In addition to the homopolar character of the Hg–X

[1] *C. A. Wurtz*, Ann. Chim. physique *20*, 472 (1847).

[2] *E. Fluck*, Angew. Chem. *72*, 752 (1960).

[3] *R. Rheinboldt* and *W. Wisfeld*, Liebigs Ann. Chem. *517*, 197 (1935).

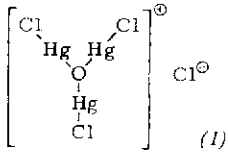
[4] *W. C. Schumb* and *D. F. Holloway*, J. Amer. chem. Soc. *63*, 2753 (1941).

[5] *W. C. Schumb* and *A. J. Stevens*, J. Amer. chem. Soc. *69*, 726 (1947); *72*, 3178 (1950); *75*, 1513 (1953).

[6] *J. Goubeau* and *R. Warncke*, Z. anorg. allg. Chem. *259*, 109 (1949).

[7] *F. K. Scholl*, Ph. D. Thesis, Technische Hochschule Stuttgart, 1960.

bond, the high symmetry of complex structural groups is also found to be a stabilizing factor in these compounds [cf. Formula *(1)*].



(1)

The method of partial hydrolysis of halides is particularly successful in the preparation of the oxide halides of the trivalent elements antimony, bismuth, indium, the rare earths, and some actinides. All these oxide halides are structurally related, and presumably the lattice is a stabilizing factor here, in that it prevents complete hydrolysis by steric effects.

The oxide fluorides of the rare earths, MOF, have been found to possess an unusually high thermal stability; they are prepared by partial hydrolysis of the trifluorides at 800 °C in a current of moist nitrogen [9–11]. The formation of higher oxides of cerium and praseodymium as by-products can be suppressed by admixture of a little hydrogen or ammonia with the carrier gas [10].

The oxide fluorides NbO_2F and TaO_2F can be prepared by simply drying solutions of niobium and tantalum pentoxides in hydrofluoric acid [12]. However, it should be pointed out that it is very difficult to obtain products which are completely free of OH^- ions by this method. For example, when a solution of Ti^{4+} in hydrofluoric acid is dried, the product is a "$TiOF_2$" [13] which can have an OH content of up to 50 % of the fluorine content, and which must, consequently, be formulated as TiO(OH)F [14]. This compound still retains the ReO_3-type lattice of $TiOF_2$ [15], owing to the practically equal ionic radii of OH^- and F^-.

Finally, the partial hydrolysis method still enjoys a certain importance in the preparation of a number of oxide chlorides, oxide bromides, and oxide iodides of the rare earths and actinides. Whereas ammonical hydrolysis is used in the preparation of the oxide chlorides and oxide bromides of these elements [16–19], the oxide iodides MOI (M = La, Sm, Tm, Y, Ac, Pu) can be prepared by simply heating the triiodides in moist air [20–22].

The extent to which halides can be subjected to partial hydrolysis has been explored in many directions. Mention is made only of the unsuccessful attempts to prepare $ZrOCl_2$ [23–25], or the surprising course of the hydrolysis of $TaCl_5$ [26,27], which – in contrast to $NbCl_5$, which yields $NbOCl_3$ – leads not to an oxide chloride, but exclusively to Ta_2O_5; this reaction can be used for the separation of niobium and tantalum [28].

II. Special Cases of the Partial Hydrolysis of Halides

A number of oxide halides can be obtained by controlled thermal decomposition of definite hydrates; it should be noted, in this connection, that hydration may be assumed to be a primary step in hydrolysis. For example, the thermal decomposition of $FeCl_3 \cdot 6H_2O$, after mixing with 5 moles of $FeCl_3$, leads to the elimination of HCl to yield FeOCl [29], as shown in Equation (b).

$$\frac{1}{6}\,(FeCl_3 \cdot 6\,H_2O + 5\,FeCl_3) = FeCl_3 \cdot H_2O + FeOCl + 2\,HCl \quad (b)$$

In special cases a partial hydrolysis can be combined with an oxidation or a reduction. In this way the oxide halides EuOI [30] and PuOF [31] are obtained by oxidizing hydrolysis of EuI_2 in an oxygen atmosphere, or reducing hydrolysis of PuF_4 with atomic hydrogen.

Instead of the controlled thermal decomposition of halide hydrates, it is possible in many cases to use the thermal decomposition of definite etherates. Thus the thermal decomposition of the monoetherates of $NbCl_5$, $NbBr_5$, and $TaCl_5$ starts at 90 °C with the elimination of ethyl halide to yield the solvate-free oxide halides $NbOCl_3$ [see Equation (c)], $NbOBr_3$, and $TaOCl_3$ [32].

$$NbCl_5 \cdot O(C_2H_5)_2 = NbOCl_3 + 2\,C_2H_5Cl \quad (c)$$

III. Commutation [*] of Oxides and Halides

By far the most important method for the preparation of oxide halides is the thermal combination of a halide with the corresponding oxide [see Equation (d)].

$$MO_2 + MCl_4 = 2\,MOCl_2 \quad (d)$$

[8] *A. Weiss, G. Nagorsen,* and *A. Weiss,* Z. anorg. allg. Chem. *273,* 151 (1953).

[9] *S. Fried, F. Hagemann,* and *W. H. Zachariasen,* J. Amer. chem. Soc. *72,* 772 (1950).

[10] *A. I. Popov* and *G. E. Knudson,* J. Amer. chem. Soc. *76,* 3921 (1954).

[11] *A. Zalkin* and *T. H. Templeton,* J. Amer. chem. Soc. *75,* 2453 (1953).

[12] *L. K. Frevel* and *H. W. Rinn,* Acta crystallogr. *9,* 626 (1956).

[13] *K. S. Vorres* and *F. B. Dutton,* J. Amer. chem. Soc. *77,* 2019 (1955).

[14] *K. Dehnicke,* unpublished work.

[15] *K. S. Vorres* and *J. Donohue,* Acta crystallogr. *8,* 25 (1955).

[16] *F. A. Bannister* and *M. H. Hey,* Mineralog. Mag. J. mineralog. Soc. *24,* 49 (1935).

[17] *L. G. Sillen,* Svensk. kem. Tidskr. *53,* 39 (1941).

[18] *W. H. Zachariasen,* Acta crystallogr. *2,* 388 (1949).

[19] *B. B. Cunningham,* Microchem. J., Symposium Issue, p. 69–93 (1961).

[20] *L. G. Sillen* and *A.-L. Nylander,* Svensk. kem. Tidskr. *53,* 367 (1941).

[21] *F. H. Kruse, L. B. Asprey,* and *B. Morosin,* Acta crystallogr. *14,* 541 (1961).

[22] *L. B. Asprey* and *F. H. Kruse,* J. inorg. nuclear Chem. *13,* 32 (1960).

[23] *P. Schmid,* Z. anorg. allg. Chem. *167,* 369 (1927).

[24] *E. Chauvenet,* C. R. hebd. Séances Acad. Sci. *154,* 821 (1912).

[25] *S. Takagi,* J. chem. Soc. Japan, Pure Chem. Sect. *75,* 637 (1954).

[26] *H. Schäfer* and *H. Bosch* (1952), unpublished work.

[27] *H. Schäfer,* Angew. Chem. *71,* 157 (1959).

[28] German patent 1017601 (1959), Inventor: *W. Schornstein* and *F. Kern.*

[29] *H. Schäfer,* Z. anorg. allg. Chem. *260,* 279 (1949).

[30] *H. Bärnighausen,* J. prakt. Chem. *14,* 313 (1961).

[31] *J. Karle,* cited by *W. H. Zachariasen,* Acta crystallogr. *4,* 231 (1951).

[32] *F. Fairbrother, A. H. Cowley,* and *N. Scott,* J. less-common Metals *1,* 206 (1959).

[*] It seems reasonable to use the term "commutation" to describe the reverse of a "dismutation" in which no redox reaction occurs.

$$MO_2 + MCl_4 \underset{\text{dismutation}}{\overset{\text{commutation}}{\rightleftharpoons}} 2\,MOCl_2$$

The term "comproportionation" will always be used to describe the reverse of a "disproportionation", in which a redox reaction is involved.

$$MO_2 + MCl_6 \underset{\text{disproportionation}}{\overset{\text{comproportionation}}{\rightleftharpoons}} 2\,MOCl_3$$

This method has recently gained considerably in importance and versatility, both practically and theoretically, as a result of the extensive studies by *Schäfer* [33] on chemical transport reactions. The limitation of this method is that the reaction of the halide with the oxide must proceed at a lower temperature than the decomposition of the expected oxide halide. Whereas the problems encountered in the preparation of oxide halides by partial hydrolysis are predominantly kinetic, thermodynamic effects come to the fore in this case. Most of the compounds involved have a high thermal stability.

The commutation method is very useful for the preparation of the oxide fluorides of the rare earths, MOF [11,34–38], the high thermal stability of which has already been seen from their preparation by partial hydrolysis at 800 °C.

The importance of the detailed study of the thermodynamic relationships in such oxide/halide systems can be clearly seen from thermal equilibrium measurements on the system $Ta_2O_5/TaCl_5$ which exists in equilibrium with gaseous $TaOCl_3$ at temperatures above 500 °C [39]. On cooling, the reverse reaction occurs and $TaOCl_3$ decomposes; however, the composition of $TaOCl_3$ can be confirmed by other methods [32,40]. In the case of niobium, $NbOCl_3$ [41] and Nb_3O_7Cl [42] can be obtained by simple commutation of the oxide and the halide, with preparatively useful results.

The commutation method can sometimes also be modified to give oxide halides of intermediate valence states. Thus TiOCl [43] is prepared by "comproportionation", either from TiO_2 and $TiCl_3$ according to Equation (e),

$$TiO_2 + 2\,TiCl_3 = 2\,TiOCl + TiCl_4 \qquad (e)$$

or by the addition of metallic titanium to a $TiO_2/TiCl_4$ mixture [Equation (f)].

$$2\,TiO_2 + TiCl_4 + Ti = 4\,TiOCl \qquad (f)$$

A completely analogous method can be used for the preparation of VOCl [44] and CrOCl [45], both of which crystallize in the same lattice as FeOCl which is rather less stable thermally, and consequently cannot be prepared by this method [44–46]. The comproportionation method can be used for the preparation of $NbOCl_2$ [42] and $TaOCl_2$ [42] by adding metallic niobium or tantalum in stoichiometric amounts to the oxide/halide mixture. It is possible to obtain $ReOCl_4$ [47] from Re_2O_7 and $ReCl_5$ at 70 °C by a particularly careful comproportionation, although excess Re_2O_7 leads to the formation of ReO_3Cl [47].

In the case of the elements of the main groups whose oxide halides can be prepared by the commutation method, the temperatures used are generally rather low, and furthermore, thermally unstable compounds are often encountered. However, low temperatures necessitate the use of reactive oxides, such as are found in the case of the elements boron, phosphorus, arsenic, sulfur, and selenium. Thus B_2O_3 dissolves in BCl_3 to form the cyclic trichloroboroxole $(BOCl)_3$ [48,49], and As_2O_3 dissolves in $AsCl_3$ to form the open-chain polymer $(AsOCl)_m$ [50]. BF_3 and BBr_3 can also be reacted with B_2O_3 above 250 °C and under pressure to form trimers, namely the trihalogenoboroxoles, the products decomposing again into the starting materials on slow cooling [48,49]. By rapid cooling, however, it is possible to obtain $(BOF)_3$ which is stable below −125 °C [51]. Owing to the low reactivity of Al_2O_3, a temperature of 440 °C is required for the preparation of AlOBr [52], while the corresponding gallium oxide halides, GaOX, with the exception of GaOF, can all be prepared from GaX_3 and Ga_2O_3 between 300 and 400 °C [53].

IV. Reactions of Halides with Oxides of Other Elements

In many cases where the temperatures required for reaction of the halide MX_{2n} with the oxide MO_n are too high to yield the oxide halide, a foreign oxide $M'O_m$ can be successfully used. This method has the disadvantage that it is often difficult to separate the foreign halide $M'X_{2m}$ which is also formed [54,55]. Suitable sources of oxygen are oxides yielding halides $M'X_{2m}$ which volatilize readily or which dissolve readily in inert solvents. On the other hand, the reaction can also be used in cases where a readily volatile or readily soluble oxide halide $MO_{n-x}X_{2x}$ is formed. Finally, when this method is used for the preparation of oxide halides of intermediate valence states, redox reactions can sometimes be carried out simultaneously. The wide variety of possible sources of oxygen make this reaction appear extremely susceptible to development; the example of VOCl [56,57] was described as early as 1911 [Equation (g)], but has only very recently become prominent again.

$$VCl_3 + CO_2 = VOCl + COCl_2 \qquad (g)$$

[33] *H. Schäfer*, Angew. Chem. *73*, 11 (1961); *H. Schäfer*: Chemische Transportreaktionen. Verlag Chemie, Weinheim/Bergstr. 1962.

[34] *F. Hund*, Z. anorg. allg. Chem. *265*, 62 (1951).

[35] *W. Klemm* and *H. A. Klein*, Z. anorg. allg. Chem. *248*, 167 (1941).

[36] *W. Finkelburg* and *A. Stein*, J. chem. Physics *18*, 1296 (1950).

[37] *W. H. Zachariasen*, Acta crystallogr. *4*, 231 (1951).

[38] *B. B. Cunningham, D. C. Feay*, and *M. A. Rollier*, J. Amer. chem. Soc. *76*, 3361 (1954).

[39] *H. Schäfer* and *E. Sibbing*, Z. anorg. allg. Chem. *305*, 341 (1960).

[40] *K. Dehnicke*, Angew. Chem. *73*, 535 (1961).

[41] *H. Schäfer* and *F. Kahlenberg*, Z. anorg. allg. Chem. *305*, 327 (1960).

[42] *H. Schäfer, E. Sibbing*, and *R. Gerken*, Z. anorg. allg. Chem. *307*, 163 (1961).

[43] *H. Schäfer, F. Wartenpfuhl*, and *E. Weise*, Z. anorg. allg. Chem. *295*, 268 (1958).

[44] *H. Schäfer* and *F. Wartenpfuhl*, J. less-common Metals *3*, 29 (1961).

[45] *H. Schäfer* and *F. Wartenpfuhl*, Z. anorg. allg. Chem. *308*, 282 (1961).

[46] *P. Ehrlich* and *H.-J. Seifert*, Z. anorg. allg. Chem. *301*, 282 (1959).

[47] *A. Brukl* and *K. Ziegler*, Ber. dtsch. chem. Ges. *65*, 916 (1932).

[48] *P. Baumgarten* and *W. Bruns*, Ber. dtsch. chem. Ges. *72*, 1753 (1939).

[49] *J. Goubeau* and *H. Keller*, Z. anorg. allg. Chem. *267*, 1 (1951).

[50] *E. Thilo* and *P. Flögel*, Angew. Chem. *69*, 754 (1957); Z. anorg. allg. Chem. *329*, 244 (1964).

[51] *H. D. Fisher, W. J. Lehmann*, and *I. Shapiro*, J. physic. Chem. *65*, 1166 (1961).

[52] *P. Hagenmuller, J. Rouxel*, and *B. LeNeidre*, C. R. hebd. Séances Acad. Sci. *252*, 282 (1961).

[53] *H. Hahn* and *H. Katscher*, Z. anorg. allg. Chem. *321*, 85 (1963).

[54] *P. Ehrlich* and *W. Engel*, Naturwissenschaften *48*, 716 (1961).

[55] *P. Ehrlich* and *W. Engel*, Z. anorg. allg. Chem. *317*, 21 (1962).

[56] *O. Ruff* and *H. Lickfett*, Ber. dtsch. chem. Ges. *44*, 506 (1911).

[57] *F. Wedekind* and *C. Horst*, Ber. dtsch. chem. Ges. *45*, 262 (1912).

This method has recently been used to prepare new oxide halides, and has also been used as a simplified method of preparing oxide halides which are already known.

As_2O_3, Sb_2O_5, Bi_2O_3, and SiO_2 are found to be particularly suitable as sources of oxygen, as are TiO_2, CrO_3, NO_2, and SO_3. Thus pure $TiOCl_2$ is obtained very readily by the dissolution of As_2O_3 in $TiCl_4$ [54, 55], while CrOCl can be prepared from Bi_2O_3 or TiO_2 and $CrCl_3$ at a somewhat higher temperature [45]. The preparation of $TaOCl_2$, described above [42], can be modified in such a way that the oxygen is supplied by the quartz wall of the reaction vessel in the reaction of $TaCl_5$ with Ta. Oxide halides of elements of the main groups have also been prepared: *e.g.* AlOCl [58] from $AlCl_3$ and Sb_2O_5, and AlOI [59] from AlI_3, preferably with As_2O_3. SOF_4 [61], which is of interest on account of its versatility as a reactant [60], can be obtained from SF_4 by the use of vigorous oxidizing agents such as CeO_2 or CrO_3. The oxidation can also be carried out with NO_2 at 200 °C, or with catalytic quantities of NO_2 using atmospheric oxygen as the oxidizing agent.

V. Preparation of Oxide Halides by Thermal Degradation

The preparation of oxide halides by thermal degradation is subject to two conditions. On the one hand, decomposition must proceed at temperatures at which the resulting oxide halide is stable. On the other hand, the products must be easily separated and should therefore exhibit, for example, wide differences in their volatilities or solubilities.

Some oxide halides are obtainable by thermal degradation of other oxide halides. Thus, the I_2 vapor pressure over $NbOI_3$ reaches 1 atm at 270 °C, and $NbOI_2$ [62] is formed, while $TiOI_2$ loses iodine at 120 °C in vacuo, with formation of TiOI [63]. When $NbOCl_3$ is heated in a sealed tube, Nb_3O_7Cl is formed together with NbO_2Cl [64]. Thermal treatment of the bismuth oxide halides also yields compounds of complicated composition. For example, when heated to 700 °C BiOCl gives $Bi_{24}O_{31}Cl_{10}$ [65, 66]; the unusual ratios of the atoms in the latter can be explained from the sequence of the layers in the lattice [66], and this also accounts for its high thermal stability.

Other starting materials for the preparation of oxide halides by thermal degradation are strontium and barium fluorosulfonates which give good yields of sulfuryl fluoride at 500 °C, in accordance with Equation (h) [67].

$$Sr(SO_3F)_2 = SrSO_4 + SO_2F_2 \quad (h)$$

[58] *H. Schäfer, F. E. Wittig,* and *W. Wilborn,* Z. anorg. allg. Chem. *297,* 48 (1958).

[59] *P. Hagenmuller, J. Rouxel, J. David,* and *A. Colin,* Z. anorg. allg. Chem. *323,* 1 (1963).

[60] *F. Seel* and *G. Simon,* Angew. Chem. *72,* 709 (1960).

[61] *W. C. Smith* and *V. A. Engelhardt,* J. Amer. chem. Soc. *82,* 3838 (1960).

[62] *H. Schäfer* and *R. Gerken,* Z. anorg. allg. Chem. *317,* 105 (1962).

[63] *K. Dehnicke,* Angew. Chem. *76,* 578 (1964); Angew. Chem. internat. Edit. *3,* 646 (1964).

[64] *K. Huber* and *J. Baunok,* Chimia *15,* 365 (1961).

[65] *A. E. Arppe,* Poggendorfs Ann. Physik Chem. *64,* 246 (1845).

[66] *L. G. Sillen* and *M. Edstrand,* Z. Kristallogr., Mineralog. Petrogr. Abt. *104,* 178 (1942).

[67] *E. L. Muetterties* and *D. D. Coffman,* J. Amer. chem. Soc. *80,* 5914 (1958).

VI. Preparation of Oxide Halides by Partial Halogenation of Oxides

Just as it is possible to replace part of the halogen in halides by oxygen, using an oxygen donor, oxides can be reacted with halogen donors. The particular problems of this method are very similar to those described in Sections III and IV. It has been found that halides which react to give readily volatile by-products are particularly suitable, *e.g.* BF_3, $COCl_2$, CCl_4, HF, HCl, HBr, F_2, Cl_2, certain interhalogen compounds, and, very recently, SeF_4.

On the other hand, it is also possible to use halides which do not give volatile reaction products if the resulting oxide halide itself is volatile or dissolves without decomposition. Of this group, particular mention should be made of $HOSO_2F$, SbF_3, AgF, KF, and CaF_2.

1. Chlorination with $SOCl_2$

Thionyl chloride has for some time been found to be a particularly easily manipulated reagent for the preparation of oxide chlorides. Thus $VOCl_3$ [68] can be prepared by simply heating V_2O_5 under reflux with the stoichiometric quantity of thionyl chloride. For the preparation of $NbOCl_3$ [69, 70] and $WOCl_4$ [69], on the other hand, the reaction must be carried out under pressure. However, the oxide chlorides are formed in a very pure state and in practically quantitative yield when the sulfur dioxide formed according to Equation (i) is removed.

$$WO_3 + 2\,SOCl_2 = WOCl_4 + 2\,SO_2 \quad (i)$$

2. Halogenation with CCl_4 and CBr_4

Some oxides can be partially halogenated with halides of carbon, generally at about 200 °C and therefore under pressure, with good results. To prevent complete halogenation of the oxide, stoichiometric quantities of the reactants are used. The carbon-halogen compounds must be free from carbon-hydrogen compounds, since reduction can otherwise occur. The reaction proceeds with formation of the readily volatile phosgene, *e.g.* according to Equation (j), and is particularly suitable

$$Nb_2O_5 + 3\,CCl_4 = 2\,NbOCl_3 + 3\,COCl_2 \quad (j)$$

for the preparation of $NbOCl_3$ [71], $NbOBr_3$ [72], and $WOCl_4$ [73]. The tungsten oxide bromides $WOBr_4$ and WO_2Br_2 [74] can be prepared by varying the quantity of CBr_4 used.

[68] *H. Hecht, G. Jander,* and *H. Schlapmann,* Z. anorg. allg. Chem. *254,* 255 (1947).

[69] *H. Hecht, G. Jander,* and *H. Schlapmann,* Z. anorg. allg. Chem. *254,* 260 (1947).

[70] *H. Hecht, G. Jander,* and *H. Schlapmann,* Z. anorg. allg. Chem. *267,* 213 (1952).

[71] *D. E. Sands, A. Zalkin,* and *R. F. Elson,* Acta crystallogr. *12,* 21 (1959).

[72] *M. Chaigneau,* C. R. hebd. Séances Acad. Sci. *248,* 3173 (1959).

[73] *A. Michael* and *A. Murphy,* J. Amer. chem. Soc. *44,* 382 (1910).

[74] *M. Pouraud* and *M. Chaigneau,* C. R. hebd. Séances Acad. Sci. *249,* 2568 (1959).

3. Halogenation with Halogens and Interhalogen Compounds

Among the halogens, only fluorine and interhalogen compounds containing fluorine can replace oxygen in oxides, owing to the electronegativity relationships. The replacement of bromine and iodine in oxide bromides and oxide iodides by chlorine and bromine, respectively, is of little interest, since it is easier in most cases to prepare the oxide chlorides directly. On the other hand, the replacement of chlorine in oxide chlorides by elementary fluorine is desirable in certain cases. The following may be used as fluorinating agents: F_2, ClF_3, BrF_3, IF_3, and IF_5.

The reaction proceeds more readily with the polar interhalogen compounds than with fluorine, and consequently lower temperatures can be used in the former case. Thus a temperature of 475 °C is required for the preparation of VOF_3 [75] from V_2O_5 and F_2, and even higher temperatures for the fluorination of MoO_3 with F_2. On the other hand, reactions with interhalogen compounds always proceed at lower temperatures; OsO_3F_2 [76] can be very easily obtained from OsO_4 and BrF_3. IF_3 and IF_5 are also occasionally used for the partial fluorination of oxides. CrO_3 and IF_3 react smoothly to give CrO_2F_2 [77], while IF_5 can be used to prepare MnO_3F from $KMnO_4$; similarly, $KReO_3$ reacts with IF_5 to yield ReO_3F [78]. VOF_3 [79] is very easily obtained by fluorination of $VOCl_3$ with ClF_3; this reaction proceeds even at room temperature

4. Fluorination with SF_4 and SeF_4

It has been found very recently that SF_4 and SeF_4 are particularly effective fluorinating agents in some cases. Their reaction products SOF_2 and $SeOF_2$ are highly volatile, and can, therefore, be easily removed.

The excellent fluorinating properties of SF_4 and SeF_4 are essentially due to their structure: they form trigonal bipyramids in which two fluorine atoms and the lone pair of electrons are arranged equatorially, and the remaining two fluorine atoms occupy the apices [80, 81]. The compounds are thus structurally similar to the interhalogen compounds which are known to be good fluorinating agents, and to certain fluoride chlorides of group V elements, *e.g.* SbF_3Cl_2 which also forms a trigonal bipyramid [82]. Such structural similarities are reflected in the chemistry of these compounds. Thus CrO_3 can be fluorinated to CrO_2F_2 [83] at 5 °C using SF_4. Also SeF_4 reacts very satisfactorily with CrO_3 or, more simply, with $K_2Cr_2O_7$, to form CrO_2F_2 [84, 85].

5. Halogenation with Hydrogen Halides and Halogenosulfonic Acids

In the reaction of hydrogen halides with oxides, the former are used in large excess; the reaction is carried out in the flowing gas to remove the water which is formed in accordance with Equation (k). For example,

$$MO_2 + 2\,HX = MOX_2 + H_2O \quad (k)$$

the oxide chlorides of the rare earths, MOCl, can be prepared by passing a current of moist HCl over the sesquioxides M_2O_3 at high temperatures [86]; this reaction can also be used for the preparation of AmOCl [87]. When halogenosulfonic acids are used as the halogenating agents, pyrosulfuric acid or alkali metal hydrogen sulfate is formed as a by-product [see Equations (l) and (m)].

$$CrO_3 + 2\,HOSO_2F = H_2S_2O_7 + CrO_2F_2\ [88] \quad (l)$$

$$KMnO_4 + HOSO_2F = KHSO_4 + MnO_3F\ [89] \quad (m)$$

It is necessary, for the separation of the products, that halogenation should yield a readily volatile oxide halide. In this way NO_2Cl [90, 91] can be prepared under very mild conditions at −60 °C from chlorosulfonic acid and HNO_3.

6. Special Halogenating Agents

In this section we shall mention a few less important halogenating agents which have, nevertheless, made possible the synthesis of certain oxide halides. This group includes acetyl bromide which reacts with CrO_3, as shown in Equation (n), and S_2Cl_2 which is the active

$$CrO_3 + 2\,CH_3COBr = CrO_2Br_2 + (CH_3CO)_2O \quad (n)$$

reagent for the chlorination of MoO_3/sulfur mixtures to give $MoOCl_4$ [93] [Equation (o)].

$$MoO_3 + S + 2\,Cl_2 = MoOCl_4 + SO_2 \quad (o)$$

Finally, BF_3 [94, 95], VF_5 [96] and CoF_3 [97] are also occasionally suggested as fluorinating agents for oxides.

[75] *L. E. Trevorrow*, J. physic. Chem. *62*, 362 (1958).

[76] *M. A. Hepworth* and *P. L. Robinson*, J. inorg. nuclear Chem. *4*, 274 (1957).

[77] *G. D. Flesch* and *H. J. Svec*, J. Amer. chem. Soc. *80*, 3189 (1958).

[78] *E. E. Aynsley* and *M. L. Hair*, J. chem. Soc. (London) *1958*, 3747.

[79] *K. Dehnicke* and *M. Afify*, unpublished work.

[80] *F. A. Cotton, J. W. George*, and *J. S. Waugh*, J. chem. Physics *28*, 994 (1958).

[81] *J. A. Rolfe, L. A. Woodward*, and *D. A. Long*, Trans. Faraday Soc. *49*, 1388 (1953).

[82] *K. Dehnicke* and *J. Weidlein*, Z. anorg. allg. Chem. *323*, 267 (1963).

[83] *H. L. Krauss* and *F. Schwarzbach*, Chem. Ber. *94*, 1205 (1961).

[84] *N. V. Sidgwick*: The Chemical Elements and their Compounds. Clarendon Press, Oxford 1950, pp. 718, 1044.

[85] *P. L. Robinson* and *N. Bartlett*, J. chem. Soc. (London) *1961*, 3549.

[86] *C. W. Koch* and *R. J. Borg*, cited by *D. H. Templeton* and *C. H. Dauben*, J. Amer. chem. Soc. *75*, 6069 (1953).

[87] *C. W. Koch*, cited by *D. H. Templeton* and *C. H. Dauben*, J. Amer. chem. Soc. *75*, 4560 (1953).

[88] *H. v. Wartenberg*, Z. anorg. allg. Chem. *247*, 135 (1941).

[89] *A. Engelbrecht* and *A. v. Grosse*, J. Amer. chem. Soc. *76*, 2042 (1954).

[90] *M. Schmeisser*, Z. anorg. allg. Chem. *255*, 33 (1948).

[91] *F. Seel* and *I. Nogrady*, Z. anorg. allg. Chem. *269*, 188 (1952).

[92] *H. L. Krauss* and *K. Stark*, Z. Naturforsch. *17b*, 1 (1962).

[93] *I. A. Glukhov* and *L. A. Tikhomirow*, Dokl. Akad. Nauk U.S.S.R. *3*, No. 2, 19 (1960); Chem. Abstr. *56*, 9690 (1962).

[94] *H. A. Lehmann* and *L. Kolditz*, Z. anorg. allg. Chem. *272*, 73 (1953).

[95] *A. Simon* and *R. Lehmann*, Z. anorg. allg. Chem. *311*, 224 (1961).

[96] *H. C. Clark* and *H. J. Emeléus*, J. chem. Soc. (London) *1958*, 192.

[97] *O. Ruff* and *H. Lickfett*, Ber. dtsch. chem. Ges. *44*, 2539 (1911).

VII. Transhalogenation of Oxide Halides

The most important transhalogenating agents are HBr and HF which are reacted with oxide chlorides [Equation (p)]. The reactions generally proceed to completion,

$$MOCl_2 + 2\ HX = MOX_2 + 2\ HCl \qquad (p)$$

since the HCl formed is more volatile then HF and HBr. In this way, it is possible to prepare VOF_2 [97] from $VOBr_2$, ReO_3F [89] from ReO_3Cl, or $SeOBr_2$ [98] from $SeOCl_2$.

Use is also made of the insolubility or the volatility of one of the reactants in the transhalogenation of oxide halides using other halogenating agents. Thus, $SOCl_2$ reacts very readily in liquid SO_2, with KBr dissolved in the latter, to yield $SOBr_2$ [99] which is deposited as a white precipitate. The volatility of $SeOF_2$ is utilized in the fluorination of $SeOCl_2$ by heating with KF [100]. In some cases, SbF_3 has also been found to be a good fluorinating agent for oxide chlorides, if a little $SbCl_5$ is added as a catalyst. Fluoride chlorides of Sb^{5+}, the particular fluorinating properties of which have already been mentioned, presumably occur as intermediates. In this way, high yields of COF_2 [101] can be prepared from $COCl_2$ in an autoclave.

VIII. Oxide Halides with Two Halogen Components

A number of oxide fluorochlorides can be prepared by reacting oxide chlorides with the theoretical amount of a fluorinating agent. Thus, SbF_3 is also suitable for partial fluorination of $COCl_2$ to give COFCl [101], or of $SOCl_2$ to give SOFCl [101]. To prepare CrO_2FCl [102], the oxide fluoride is combined with the oxide chloride in the molar ratio of 1:1.

An original preparation of sulfuryl fluoride chloride, SO_2FCl, involves controlled chlorination of an organically substituted oxide fluoride, namely benzenesulfonyl fluoride [see Equation (q)].

$$H_5C_6 \cdot SO_2F + Cl_2 = H_5C_6\text{-}Cl + SO_2FCl\ [101] \qquad (q)$$

IX. Oxide Halides from Halides and Oxygen

Just as fluorine can be used to replace part of the oxygen in oxides, part of the chlorine and bromine in chlorides and bromides can be replaced by oxygen, as shown in Equation (r).

$$MCl_4 + {}^1/_2\ O_2 = MOCl_2 + Cl_2 \qquad (r)$$

The lower reactivity of oxygen as compared to fluorine is compensated to some extent by the greater reactivity of chlorides and bromides as compared to the oxides. Thus VOCl [46] can be obtained by heating VCl_3 in a stream of oxygen, and UO_2Cl_2 [103] is formed from UCl_4 and oxygen at 300 °C. In other cases this method suffers from disadvantages, the most obvious of which are the heterogeneity (solid/gaseous) and the difficulty of metering the oxygen supply.

X. Oxide Halides by Oxidation of Lower Oxides or Oxide Halides with Halogens

This reaction, which has been known in principle for some time in the cases of NO and SO_2, was applied a few years ago to the preparation of ReO_3Cl [104] (from ReO_3 and chlorine at 160 °C) and ReO_2Br_2 [105] (from ReO_2 and Br_2).

The disadvantage of the low reactivity of many oxides can be avoided by reacting them, so the speak, in the nascent state with halides, *i.e.* by burning the element in gaseous halogen containing oxygen. In this way, for example, OsO_3F_2 [76] can be prepared from osmium in a current of O_2/F_2, or rhenium can be converted to $ReOF_5$ [106]. The required oxygen can also be formed in some cases by fluorination of the glass, as in the fluorination of ruthenium in a current of BrF_3/Br_2 to obtain $RuOF_4$ [107], or in the preparation of $CrOF_4$ [108] by direct fluorination of chromium. The method is still at a relatively early stage of its development and interesting variations are possible.

XI. Oxide Halides from Halides and Dichlorine Monoxide

The electropositive character of chlorine in dichlorine monoxide can be utilized for the preparation of oxide halides. Cl_2O reacts with many chlorides and bromides with partial replacement of chlorine or bromine by oxygen; hypochlorites occur as intermediates which cannot be isolated, and these spontaneously lose further halogen to form oxide chlorides [see Equation (s)].

$$MCl_4 + Cl_2O = [Cl_3MOCl] + Cl_2 = MOCl_2 + 2\ Cl_2 \qquad (s)$$

This reaction was discovered as early as 1875, during a study of the properties of Cl_2O which reacted with PCl_5 to yield $POCl_3$ [109]; however, the reaction was not studied further until recently.

[98] *G. Govaert* and *M. Hansens*, Natuurwetensch. Tijdschr. *20*, 77 (1938).

[99] *M. J. Frazer* and *W. Geraard*. Chem. and Ind. *1954*, 280.

[100] *R. Paetzold* and *K. Aurich*, Z. anorg. allg. Chem. *315*, 72 (1962).

[101] *H. J. Emeléus* and *J. F. Wood*, J. chem. Soc. (London) *1948* 2183.

[102] *A. Engelbrecht* and *A. v. Grosse*, J. Amer. chem. Soc. *74*, 5262 (1952).

[103] *H. A. Leary* and *J. F. Suttle* in: Inorganic Syntheses. McGraw-Hill, New York-Toronto-London 1957, Vol. V, p. 148.

[104] *C. J. Wolf*, *A. F. Clifford*, and *W. H. Johnston*, J. Amer.chem. Soc. *79*, 4257 (1957).

[105] *R. Colton*, J. chem. Soc. (London) *1962*, 2078.

[106] *E. E. Aynsley*, *R. D. Peacock*, and *P. L. Robinson*, J. chem. Soc. (London) *1950*, 1622.

[107] *J. H. Holloway* and *R. D. Peacock*, J. chem. Soc. (London) *1963*, 527.

[108] *A. J. Edwards*, Proc. chem. Soc. (London) *1963*, 205.

[109] *P. Spring*, Bull. Acad. Sci. Belgique 2, *39*, 895 (1875).

Oxide bromides can also be prepared by this method; however, when attempts are made to achieve higher yields, the chlorine liberated begins to form the oxide chloride. The reaction proceeds according to Equation (t).

$$MBr_4 + Cl_2O = MOBr_2 + Br_2 + Cl_2 \quad (t)$$

Owing to the oxidizing action of Cl_2O and Cl_2, only oxide chlorides in the highest valence states can be prepared by this method. The reactions proceed under very mild conditions at room temperature (and below), and, with the exception of the oxide bromides, are entirely free from side reactions. The only by-product formed is chlorine which can be easily removed. Cl_2O is very readily obtained by passing chlorine over mercuric oxide. It is not necessary to remove entrained chlorine, since this is formed as a by-product in any case; in the case of the oxide bromides, however, separation is recommended. The mildness of the conditions which can be achieved is shown particularly clearly in the case of $PbOCl_2$ [40, 109a] which is very sensitive to heat, and which is prepared from $PbCl_4$ and Cl_2O at $-10\,^{\circ}C$.

Thus it is possible, using the dichlorine monoxide method, to obtain thermally unstable oxide halides which cannot be prepared by commutation, and also oxide halides, the preparation of which (*e.g.* by partial hydrolysis of a halide) is subject to interference by by-products. Thus, it is also possible to prepare $SbOCl_3$ [110] and SbO_2Cl [111] from $SbCl_5$ and Cl_2O at room temperature, as well as VO_2Cl [112] from $VOCl_3$, $SnOCl_2$ [113] from $SnCl_4$, $TiOCl_2$ from $TiCl_4$ [113a], and AsO_2Cl [114] from $AsCl_3$.

The preparation of oxide chlorides is rather more difficult when it is necessary to use a solid chloride, *e.g.* $MoCl_5$, $TaCl_5$, or $ZrCl_4$, as the starting material. In this case, it may be helpful to add the theoretical amount of Cl_2O to a slurry of the chloride in CCl_4 cooled to $-30\,^{\circ}C$, and to warm slowly to room temperature with stirring. Good yields of $TaOCl_3$, $Ta_2O_3Cl_4$ [40], $ZrOCl_2$ [115], and $MoOCl_4$ [116] can be obtained in this way from the corresponding chlorides. The efficiency of the dichlorine monoxide method is shown especially clearly by the example of $ZrOCl_2$; all attempts to prepare this oxide chloride by other methods have failed.

The preparation of oxide bromides from metal bromides and Cl_2O can be achieved in the melt, using CCl_4, however, in the case of $TiBr_4$ to yield $TiOBr_2$ [117]; similarly, $SnOBr_2$ [117] is obtained from $SnBr_4$.

Oxide fluorides can also be prepared, in some cases, with the aid of Cl_2O. The starting materials must be definite fluoride chlorides, the chlorine of which is quantitatively replaced by the oxygen of Cl_2O, as shown in Equation (u). Thus $TiOF_2$ [118] is obtained by a

$$MF_2Cl_2 + Cl_2O = MOF_2 + 2\,Cl_2 \quad (u)$$

smooth reaction from TiF_2Cl_2, while $SbOF_3$ [119] is formed from SbF_3Cl_2, and SbO_2F [111] from $SbFCl_4$.

XII. Oxide Halides from Halides and Ozone

The reaction between certain halides and ozone is analogous to the reaction of oxide halides with chlorine monoxide. There is also some similarity between the structures of Cl_2O and O_3: the bond angle is $116\,^{\circ}$ in ozone, and is $109\,^{\circ}$ in Cl_2O. Ozone is rather less reactive than dichlorine monoxide [*]. Thus $TiCl_4$, $SnCl_4$, and $VOCl_3$ react only at their boiling points, but yield extremely pure oxide chlorides $TiOCl_2$, $SnOCl_2$, and VO_2Cl [120]. The reactions proceed in accordance with Equation (v).

$$TiCl_4 + O_3 = TiOCl_2 + O_2 + Cl_2 \quad (v)$$

Apart from the exceptional purity of all products, the main advantage of this method over that using Cl_2O is the reaction of ozone with bromides at low temperatures to yield oxide bromides. Thus, $TiOBr_2$ can be obtained easily and very cheaply by passing a current of ozone, diluted with oxygen, into titanium bromide; $SnOBr_2$ is obtained from $SnBr_4$, and $VOBr_3$ reacts with ozone to yield the thermally unstable $V_4O_9Br_2$ [120].

Finally, it has very recently become possible to prepare oxide iodides by the ozone method. Since the metal iodides have relatively high melting points, so that reactions in the melt cannot be considered, it is necessary to use solvents for the reactions, which must be carried out as far as possible in the homogeneous phase; cyclohexane has proved to be a particularly useful solvent. Less soluble iodides are stirred up; as the dissolved iodide reacts with ozone, the supply is replenished from the solid. In this way it has been possible to prepare the oxide iodides $TiOI_2$, $SnOI_2$ [63], and $Ge_2O_3I_2$ [14]. A remarkable point about this reaction

$$TiI_4 + O_3 = TiOI_2 + O_2 + I_2 \quad (w)$$

[109a] *K. Dehnicke*, Naturwissenschaften *51*, 535 (1964).

[110] *K. Dehnicke*, Z. anorg. allg. Chem. *312*, 237 (1961).

[111] *K. Dehnicke* and *J. Weidlein*, unpublished work.

[112] *K. Dehnicke* in *G. Brauer*: Handbuch der Präparativen Anorganischen Chemie. F. Enke-Verlag, Stuttgart 1962, Vol 2, p. 1107.

[113] *K. Dehnicke*, Z. anorg. allg. Chem. *308*, 72 (1961).

[113a] *K. Dehnicke*, Z. anorg. allg. Chem. *309*, 266 (1961).

[114] *K. Dehnicke*, Lecture at the XVII. IUPAC Congress, München (Germany) 1959, No. A 1042.

[115] *K. Dehnicke* and *K.-U. Meyer*, Z. anorg. allg. Chem. *331*, 121 (1964).

[116] *L. Dorn*, Ph. D. Thesis, Technische Hochschule Stuttgart, 1963.

[117] *K. Dehnicke*, Angew. Chem. *73*, 763 (1961).

[118] *K. Dehnicke*, Angew. Chem. *74*, 495 (1962).

[119] *J. Weidlein*, Diploma Thesis, Technische Hochschule Stuttgart, 1962.

[*] The reasons for the lower reactivity of O_3 towards MX_n as compared with that of Cl_2O may be the following: The greater bond angle of O_3 causes a decrease of donor properties of the central O-atom compared with that of Cl_2O. This renders more difficult the rate-determining primary step of adduct formation with the metal halides which act as Lewis acids. In addition, the polarity of the O–O bond of O_3 is less than that of the O–Cl-bond in Cl_2O (cf. *K. Dehnicke*, Chem. Ber., in the press).

[120] *K. Dehnicke*, Angew. Chem. *75*, 419 (1963); Angew. Chem. internat. Edit. *2*, 325 (1963).

(w) is that the iodine liberated does not react with the ozone to form iodine oxides until all the metal iodide has been consumed.

XIII. Preparation of Oxide Fluorides with the Aid of Chlorine Nitrate

A number of oxide fluorides cannot be prepared by the method using Cl_2O, owing to the low polarity of the M–Cl bonds in the fluoride chlorides which would be used, *e.g.* SnF_2Cl_2. However, using the more strongly polar chlorine nitrate, $ClONO_2$ [121, 122], definite oxide fluorides can be obtained by an indirect route.

The products of the primary reaction [Equation (x)] are the fluoride nitrates [127] which can generally be isolated [*].

$$MF_2Cl_2 + 2\ ClNO_3 \rightarrow MF_2(NO_3)_2 + 2\ Cl_2 \qquad (x)$$

Chlorine nitrate is easily obtainable from N_2O_5 and Cl_2O [125] which are condensed in succession onto the fluoride chloride. In a second reaction step (y) the fluoride nitrate

$$MF_2(NO_3)_2 \rightarrow MOF_2 + 2\ NO_2 + {}^1/_2\ O_2 \qquad (y)$$

is thermally decomposed to form the corresponding oxide fluoride. This method is used for the preparation of $AsOF_3$ [126] from AsF_3Cl_2, $SbOF_3$ [119] from SbF_3Cl_2, SbO_2F [127] from $SbCl_4F$, $SnOF_2$ [118] from SnF_2Cl_2, and Sn_2OF_6 [127] from SnFCl.

However, the fluoride chlorides required are only available in limited number and purity. It is, therefore, worth noting that lower fluorides also react with chlorine nitrate to yield the desired fluoride nitrates [see Equation (z)], the thermal decomposition of which

$$MF_2 + 2\ ClNO_3 = MF_2(NO_3)_2 + Cl_2 \qquad (z)$$

yields oxide fluorides, in accordance with Equation (y). Thus, the oxide fluorides $SbOF_3$, SbO_2F, and TlOF [127] can be prepared in this way from SbF_3, SbOF, and TlF, respectively.

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[121] *H. Martin* and *T. Jacobsen*, Angew. Chem. *67*, 524 (1955); Z. physik. Chem. NF *17*, 375 (1958).

[122] *M. Schmeißer*, *W. Fink*, and *K. Brändle*, Angew. Chem. *69*, 780 (1957).

[*] The reaction is possible owing to the pronounced electropositive character of chlorine in chlorine nitrate [123, 124].

[123] *K. Brändle*, *M. Schmeißer*, and *W. Lüttke*, Chem. Ber. *93*, 2300 (1960).

[124] *A. J. Arvia*, *L. F. R. Cafferata*, and *H. J. Schumacher*, Chem. Ber. *96*, 1187 (1963).

[125] *M. Schmeißer*, *W. Fink*, and *K. Brändle*, cited by *G. Brauer*: Handbuch der Präparativen Anorganischen Chemie. F. Enke-Verlag, Stuttgart 1962, Vol. 1, p. 298.

[126] *K. Dehnicke*, Angew. Chem. *76*, 385 (1964); Angew. Chem. internat. Edit. *3*, 448 (1964).

[127] *K. Dehnicke*, *J. Weidlein*, and *K. Krogmann*, Angew. Chem. *75*, 1110 (1963); Angew. Chem. internat. Edit. *3*, 142 (1964).

Empirical Parameters of the Polarity of Solvents

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The empirical parameters of the polarity of solvents which have been determined recently are reviewed: Y-values (Winstein, Grunwald), X-values (Gielen, Nasielski), Ω-values (Berson, Hamlet, Mueller), Z-values (Kosower), E_T-values (Dimroth, Reichardt, Siepmann, Bohlmann), R- and S-values (Brownstein). Their field of application and interrelationships are discussed. The theoretical principles of the solvent effect on the reaction rate and light absorption of organic compounds are briefly described, and mention is made of attempts to correlate the physical characteristics of the solvent with the empirical parameters.

I. Introduction

The influence of solvents on the course of chemical reactions has long been known, but has only recently received sufficient attention as a result of the more detailed study of reaction mechanisms. As early as 1890, *Menschutkin* wrote that a reaction cannot be separated from the medium in which it takes place [1]. This raised the problem of how the solvent affected the dissolved molecules, and the physical quantities by which this influence could be described in greater detail. *Menschutkin* postulated a relationship between the rate of reaction and the structure of the solvent. Most investigations were directed towards correlating the

[1] *N. Menschutkin*, Z. physik. Chem. *1*, 611 (1887); *5*, 589 (1890); *6*, 41 (1890).

equilibrium constants, the rate constants of the reactions, or the positions of ultraviolet and infrared absorption bands with the so-called "polarity" of the solvent. Attempts were made to express the polarity in terms of the dielectric constant, the dipole moment, the refractive index, or other properties of the solvent. Efforts to derive valid quantitative relationships were not very successful, owing to the simplifications used.

The "polarity" of a solvent [1a] is determined by its solvation behavior which in turn depends on the action of intermolecular forces (Coulomb, directional, inductive, dispersion, and charge-transfer forces, as well as hydrogen-bonding forces) between the solvent and the solute [2]. As has often been found (and as was to be expected owing to the complexity of the interactions), the macroscopic dielectric constant does not provide a direct measure of the interactions on the molecular scale, *i.e.* the solvating power of a solvent cannot be described by a single parameter.

Since the "polarity" of a solvent can, therefore, only be incompletely specified by individual physical characteristics of the solvent, attempts have recently been made to obtain such characteristics by experiment. It was sought to draw conclusions about the polarity of a solvent by working backwards from the effect of the solvent on a solvent-dependent standard process (the rate of a chemical reaction; the absorption of light by a solvatochromic dye [2a]), and to derive empirical parameters of the polarity of the solvent from the rate constants or absorption maxima determined in many solvents.

II. Basic Principles of the Solvent Effect

A. Influence of the Solvent on the Reaction Rate [3]

The qualitative influence of the solvent on aliphatic substitutions and eliminations has been investigated in detail by *Hughes* and *Ingold* [4], using a simple solvation model. According to these authors, the rates of reactions in which ionic charges arise or are compressed into a smaller space during passage through the transition state increase with the polarity of the medium surrounding the reactants and the activated complex. The reaction is retarded if ionic charges disappear or become distributed throughout a larger space. Reactions in which ionic charges are formed or disappear during passage through the transition state are much more strongly influenced by the solvent than those in which the activation process simply involves "charge diffusion". Thus, on replacing water by alcohol, the specific rate of substitution reactions is altered by a factor of 10^3 to 10^6 in the former case, but by a factor of between 3 and 10 in the latter case. A fundamental factor in assessing the effect of the solvent is therefore the charge type to which the reactants belong.

The reason for acceleration or retardation of the reaction is the difference in the stabilization of the starting materials and of the activated complex by solvation; this is more clearly illustrated by Fig. 1 (cf. [3c]). The two curves I represent the free enthalpy profile for a given reaction in a solvent in which neither the starting

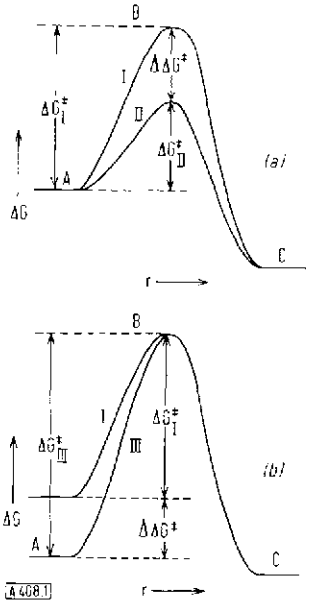


Fig. 1. The free enthalpy profile of a reaction with (a) an unsolvated (I) and a solvated (II) transition state, and (b) unsolvated (I) and solvated (III) starting materials.
$\Delta G_I^{\ddagger}$, $\Delta G_{II}^{\ddagger}$, $\Delta G_{III}^{\ddagger}$ = free enthalpies of activation,
A = starting materials;
B = transition state;
C = end products;
r = reaction coordinate.

[1a] The term "solvent polarity" is used throughout the paper to include the sum of all intermolecular interactions of which the solvent is capable. However, it excludes interactions which lead to definite chemical changes in the substrate as a result of protonation, oxidation, complex formation, etc.

[2] *O. Fuchs* in *Houben-Weyl-Müller*: Methoden der Organischen Chemie. Thieme, Stuttgart 1955, Vol. 3/2, p. 399; *O. Fuchs* in *W. Foerst*: Ullmanns Encyklopädie der technischen Chemie. Urban and Schwarzenberg, München-Berlin 1960, Vol. 12, p. 2.

[2a] Concerning similar efforts to obtain empirical polarity parameters from the effect of solvents on infrared frequencies, cf. *A. Allerhand* and *P. von R. Schleyer*, J. Amer. chem. Soc. *85*, 371 (1963).

[3] For summaries, see [3a]–[3l].

[3a] *M. Magat*, Z. physik. Chem. A *162*, 432 (1932).

[3b] *R. P. Bell*, J. chem. Soc. (London) *1943*, 629.

[3c] *S. Glasstone*, *K. J. Laidler*, and *H. Eyring*: The Theory of Rate Processes. McGraw-Hill, New York-London 1941, pp. 400–476.

[3d] *K. J. Laidler*: Chemical Kinetics. McGraw-Hill, New York-Toronto-London 1950, pp. 111–144.

[3e] *E. A. Moelwyn-Hughes*: The Kinetics of Reactions in Solution. Clarendon Press, Oxford 1947.

[3f] *S. W. Benson*: The Foundation of Chemical Kinetics. McGraw-Hill, New York-Toronto-London 1960, pp. 493–547.

[3g] *A. A. Frost* and *R. G. Pearson*: Kinetics and Mechanism. A Study of Homogeneous Chemical Reactions. 2nd Edition, Wiley, New York 1961, pp. 123–159.

[3h] *J. E. Leffler* and *E. Grunwald*: Rates and Equilibria of Organic Reactions. Wiley, New York-London 1963, pp. 263–314.

[3i] *Y. A. Ershov*, Dokl. Acad. Nauk. S.S.S.R. *139*, 922 (1961); Chem. Abstr. *56*, 12372 (1962).

[3k] *J. Ugelstad* and *P. Renolen*, Tidsskr. Kjemi, Bergves. Metallurgi *21*, 88 (1961); *J. Ugelstad* and *P. C. Mork*, ibid. *21*, 169 (1961).

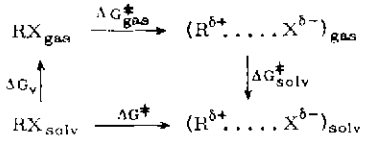
[3l] *K. B. Wiberg*: Physical Organic Chemistry. Wiley, New York London-Sydney 1964, pp. 374–396, 417.

[4] *E. D. Hughes* and *C. K. Ingold*, J. chem. Soc. (London) *1935*, 244; *K. A. Cooper*, *M. L. Dhar*, *E. D. Hughes*, *C. K. Ingold*, *B. J. MacNulty*, and *L. I. Woolf*, ibid. *1948*, 2043.

materials nor the activated complex are solvated. If only the activated complex is solvated in another solvent, then profile II in Fig. 1a is obtained. The free enthalpy of activation is reduced by an amount $\Delta_A G^{\ddagger}$, so that the reaction is accelerated. If, on the other hand, only the starting materials are solvated, curve III in Fig. 1b is obtained. The free enthalpy of activation is increased by the amount $\Delta_A G^{\ddagger}$, with the result that the reaction proceeds more slowly. The solvation of the end products does not affect the reaction rate directly. Since in reality both the reactants and the activated complex are solvated, the rate of the reaction will be determined by the difference between the two free enthalpies of solvation.

The situation is complicated by the fact that increased solvation leads to an increase in the order, and hence to a decrease in the entropy; this results in restriction of the freedom of movement, not only of the reactants, but also of the solvent molecules [4a]. Molecules of polar solvents exhibit a high degree of orientation, even in the absence of dissolved polar substances, owing to the strong interaction between the molecules, while those of non-polar solvents are only ordered to a smaller extent. If a polar transition state is formed from non-polar reactants, the greatest increase in the orientation associated with solvation, *i.e.* the greatest decrease in entropy, occurs in non-polar solvents. Thus the entropy of activation for the reaction of aniline with ω-bromoacetophenone is −56 cal/degree/mole in benzene, −39 in acetone, and −28 in ethanol [5]. A strongly negative entropy of activation slows down a reaction just as much as a high activation energy.

The effects of solvation can be illustrated for an ionization process by the cycle shown in Scheme 1 [6].



Scheme 1. The free enthalpy cycle in the solvation of RX.

The free enthalpy of activation $\Delta G^{\ddagger}$ in solution is thus the sum of the molar free enthalpy of vaporization ΔG_v of RX, the free enthalpy of activation of the reaction in the gas phase $\Delta G^{\ddagger}_{gas}$, and the free enthalpy of solvation of the activated complex $\Delta G^{\ddagger}_{solv}$:

$$\Delta G^{\ddagger} = \Delta G_v + \Delta G^{\ddagger}_{gas} + \Delta G^{\ddagger}_{solv} \qquad (1)$$

The change in the free enthalpy of activation $\Delta_A G^{\ddagger}$ on changing solvents is then

$$\Delta_A G^{\ddagger} = \Delta_A G^{\ddagger}_{solv} + \Delta_A G_v \qquad (2)$$

Thus the problem of the influence of the solvent on the rate of reaction can be essentially reduced to the determination of the free enthalpies of solvation of the starting materials and of the activated complex.

An accurate quantitative determination is difficult, owing to the complexity of the interactions between the solvent and the substrate [3g, 7]. Nevertheless, many authors have attempted, either empirically or on the basis of definite theories, to correlate rate constants or enthalpies of activation with a characteristic parameter of the solvent, in a form such as

$$k = f(\varepsilon, \mu, \ldots) \quad \text{or} \quad \Delta G^{\ddagger} = f(\varepsilon, \mu, \ldots) \qquad (3)$$

An early attempt in this direction was *Dimroth*'s relationship between the rate constant k and the solubilities of the reactants [8a]. During investigation of the intramolecular rearrangement of an ester of 5-hydroxy-1-phenyl-1,2,3-triazole-4-carboxylic acid in various solvents, this author found, in agreement with a rule formulated earlier by *van't Hoff* [8b], that the rate constant of the rearrangement reaction is inversely proportional to the solubility L of the isomer which is being transformed:

$$k = \text{const} \cdot \frac{1}{L} \qquad (4)$$

This and similar relationships have, however, only limited application [3d, 3e, 9].

For reactions between neutral non-polar molecules in dilute solutions, *Scatchard* [10] and *Hildebrand* [11] derived a relationship between the activity coefficient γ_2 of the solute in various solvents and the quantity $\delta = \sqrt{\Delta E/V}$ which is known as the internal pressure (or cohesive energy density):

$$RT \cdot \ln \gamma_2 = V_2(\delta_2 - \delta_1)^2 \qquad (5)$$

V_1 and V_2 are the molar volumes, ΔE_1 and ΔE_2 are the molar energies of vaporization of the pure solvent and the pure solute, γ_2 is the activity coefficient of the solute, referred to a standard state of the pure liquid solute, and δ is a measure of the cohesion forces acting on the molecular scale.

The use of this equation for the determination of the rate constant of a reaction

$$A + B \rightarrow C^{\ddagger} \rightarrow \text{products} \qquad (6)$$

leads to the following expression

$$\ln k = \ln k_0 + \frac{V_A}{RT}(\delta_1 - \delta_A)^2 + \frac{V_B}{RT}(\delta_1 - \delta_B)^2 - \frac{V_C}{RT}(\delta_1 - \delta_{C^{\ddagger}})^2 \qquad (7)$$

where k_0 is the rate constant in an ideal solution. The rate of reaction in a given solvent depends only on the difference between the internal pressures of the solvent and the reactants on the one hand and the activated complex on the other hand. Assuming that the activated complex is similar to the reaction products, the following rule, empirically derived by *Richardson* and *Soper* [12], applies: If the products of a reaction possess a

[4a] The change in the free entropy of activation $\Delta S^{\ddagger}$ on solvation is included in the free enthalpy of activation $\Delta G^{\ddagger}$ of Fig. 1, according to $\Delta G^{\ddagger} = \Delta H^{\ddagger} - T\Delta S^{\ddagger}$.

[5] *H. E. Cox*, J. chem. Soc. (London) *119*, 142 (1921); *E. S. Gould*: Mechanism and Structure in Organic Chemistry. Henry Holt and Co., New York 1959, p. 182.

[6] *S. Winstein* and *A. H. Fainberg*, J. Amer. chem. Soc. *79*, 5937 (1957); *R. E. Robertson, R. L. Heppolette*, and *J. M. W. Scott*, Canad. J. Chem. *37*, 803 (1959).

[7] *J. D. Bernal* and *R. H. Fowler*, J. chem. Physics *1*, 515 (1933); *J. L. Franklin*, Trans. Faraday Soc. *48*, 443 (1952); *R. Hümbelin*, Chimia *17*, 331 (1963); *R. F. Hudson*, Ber. Bunsenges. physik. Chem. *68*, 215 (1964).

[8a] *O. Dimroth*, Liebigs Ann. Chem. *377*, 127 (1910); *399*, 91 (1913).

[8b] *J. H. van't Hoff*: Vorlesungen über theoretische und physikalische Chemie. Vieweg, Braunschweig 1898, Part 1, p. 217.

[9] *H. Eyring* and *F. Daniels*, J. Amer. chem. Soc. *52*, 1472 (1930).

[10] *G. Scatchard*, Chem. Reviews *8*, 321 (1931); *10*, 229 (1932).

[11] *J. H. Hildebrand* and *S. E. Wood*, J. chem. Physics *1*, 817 (1933); *J. H. Hildebrand* and *R. L. Scott*: The Solubility of Nonelectrolytes. Reinhold Publ. Corp., New York 1950, p. 419.

[12] *M. Richardson* and *F. G. Soper*, J. chem. Soc. (London) *1929*, 1873.

higher internal pressure than the starting materials, the reaction is accelerated by solvents with high internal pressures. The concept of internal pressure is applicable only to reactions between non-polar molecules, since other properties of the solvent, such as its ability to form hydrogen bonds and its dielectric properties, are disregarded.

In a reaction between neutral, but polar molecules [12a], the electrostatic forces of attraction predominate, leading to an orientation polarization. Equation (8) was derived by *Kirkwood* [13] for the change in free enthalpy when a molecule with dipole moment μ and radius r passes from a medium of dielectric constant 1 into a medium of dielectric constant D.

$$\Delta G = -\frac{\mu^2}{r^3} \cdot \frac{D-1}{2D+1} \tag{8}$$

Taking into account the relationship arising from the theory of the transition state [3], application of Equation

$$k = \frac{RT}{N_L h} K^{\neq} = \frac{RT}{N_L h} \cdot e^{-\Delta G^{\neq}/RT} \tag{9}$$

(8) to Reaction (6) (where A, B, and $C^{\neq}$ represent polar compounds) leads to Equation (10).

$$\ln k = \ln k_0 - \frac{N_L}{RT} \frac{D-1}{2D+1} \left[\frac{\mu_A^2}{r_A^3} + \frac{\mu_B^2}{r_B^3} - \frac{\mu_{C^{\neq}}^2}{r_{C^{\neq}}^3} \right] \tag{10}$$

(k and k_0 are the rate constants in media with dielectric constants D and 1, respectively). This can be still further generalized to

$$\ln k = \ln k_0 - U \cdot \frac{D-1}{2D+1}, \tag{11}$$

where U is a constant which is independent of the solvent. The qualitative conclusion to be drawn from this equation is that a reaction which passes through a polar transition state is accelerated by a solvent of higher dielectric constant; quantitatively, a linear relationship is found between ln k and (D−1)/(2 D + 1).

Reasoning from different points of view, *Amis* [14] as well as *Laidler* and *Landskroener* [15] deduced a relationship between ln k and 1/D [15a]. In many reactions in binary solvent mixtures, the dielectric constants of which vary with the ratio of the components, a straight line is obtained on plotting ln k against (D−1)/(2 D + 1) [16, 17]. However, this relationship usually breaks down when reaction rates in different solvents of different dielectric constants are compared.

The deviations in solvent mixtures are essentially due to selective solvation as a result of the greater interaction between the molecules of the solute and those of the more highly polar components of the solvent mixture. Each solute molecule is thus surrounded by a medium having a dielectric constant which differs from the macroscopic value. Anions are preferentially solvated by solvents which form hydrogen bonds, and cations by solvents whose molecules possess free electron pairs, and hence have electron-donating properties [18].

In reactions between ions alone, or between ions and neutral molecules, electrostatic interactions clearly predominate. The equations derived for both types of reactions show a relationship between ln k and 1/D.

For a reaction between ions, the following relationship can be derived from *Coulomb*'s law [10]:

$$\ln k = \ln k_0 - \frac{N_L Z_A Z_B (e^2)}{DRT \cdot r^{\neq}} \tag{12}$$

$Z_A e$, $Z_B e$ = charges on the ions A and B; $r^{\neq}$ = equilibrium distance between the ions in the activated complex; k_0 = rate constant in a medium of infinite dielectric constant.

It follows from Equation (12) that, in reactions between two oppositely charged ions, ln k increases linearly with 1/D, while in the case of similarly charged ions ln k decreases with 1/D.

The influence of the solvent on a reaction between ions and neutral molecules can be described by Equation (13) [3c, 3g, 16] which is derived from *Born*'s equation [19] giving the free enthalpy for the transfer of an ion into a continuous dielectric.

$$\ln k = \ln k_0 + \frac{N_L (Ze)^2}{2 \cdot DRT} \cdot \left(\frac{1}{r} - \frac{1}{r^{\neq}} \right) \tag{13}$$

Ze = charge on the ion; $r, r^{\neq}$ = radii of the ion and of the activated complex, respectively; k_0 = rate constant in a medium of infinite dielectric constant.

Since $r^{\neq}$ is greater than r, the reaction rate should decrease with increasing dielectric constant.

All these relationships between the rate of reaction and the "polarity" of the solvent, which are derived from the classical electrostatic model with the dielectric constant of the continuum, take into account only some interactions, and disregard all specific effects, such as hydrogen-bonding. Consequently, they give only a rough picture of the effect of a solvent on a given reaction. Owing to the complexity of the situation, it seems very difficult to obtain a relationship similar to Equation (3) between the rate constants and one or more of the physical parameters of the solvent, in which all the relationships named above would be included. Indeed, according to *Popovici* and *Pop* [20], a general relationship of this type is impossible.

[12a] The term "polar molecules" includes molecules with a permanent dipole moment.

[13] *J. G. Kirkwood*, J. chem. Physics *2*, 351 (1934); *L. Onsager*, J. Amer. chem. Soc. *58*, 1486 (1936).

[14] *E. S. Amis*: Kinetics of Chemical Change in Solution. MacMillan and Co., New York 1949; J. chem. Educat. *30*, 351 (1953); Analytic. Chem. *27*, 1672 (1955).

[15] *K. J. Laidler* and *P. A. Landskroener*, Trans. Faraday Soc. *52*, 200 (1956).

[15a] Note that (D−1)/(2 D + 1) is approximately a linear function of 1/D, when D > 5.

[16] *K. J. Laidler* and *H. Eyring*, Ann. New York Acad. Sci. *39*, 303 (1940); Chem. Abstr. *35*, 2777 (1941).

[17] *A. Streitwieser jr.*: Solvolytic Displacement Reactions. McGraw-Hill, New York-San Francisco-Toronto-London 1962, pp. 31, 48.

[18] *A. J. Parker*, Quart. Rev. (chem. Soc., London) *16*, 163 (1962); *J. B. Hyne*, J. Amer. chem. Soc. *82*, 5129 (1960).

[19] *M. Born*, Z. Physik *1*, 45 (1920).

[20] *S. Popovici* and *M. Pop*, C. R. hebd. Séances Acad. Sci. *245*, 846 (1957); *250*, 1651 (1960).

B. Influence of the Solvent on the Absorption of Light [21]

It was observed long ago, during comparison of the absorption spectra of a substance in the gas phase and in solution, that the solvent causes a change in the position, intensity, and shape of the bands [22a–22d]. *Hantzsch* termed this phenomenon "solvatochromism" [22c]. Even then a relationship between the influence of the solvent and its properties was being sought (*e.g. Kundt*'s rule [22a]). The reason for the solvent-dependence of the wave number of the absorption and emission of light is the difference in the stabilization of the ground state and excited states by intermolecular forces, which can lead to an increase or decrease in the excitation energies [23].

This does not take into account spectral shifts due to fundamental alteration of the chromophore system by the solvent as a result of protonation, oxidation, complex formation, or equilibrium displacements.

The solvent effect depends primarily on the nature of the electron transition in question. The influence of a given solvent varies according to whether we are dealing with an $n\rightarrow\sigma^*$ [24], $n\rightarrow\pi^*$ [25], $\pi\rightarrow\pi^*$ [21], or a charge-transfer transition [26]. The ground state of the first two types is far more strongly influenced by solvents which form hydrogen bonds, and which therefore cause a particularly strong depression of the n-electron level, than are the other states [27a–27g]. The resulting hypsochromic shift is used as a criterion to distinguish between $n\rightarrow\pi^*$ and $\pi\rightarrow\pi^*$ transitions [28]. The following considerations are confined to $\pi\rightarrow\pi^*$ absorptions.

When a dipole-free compound (*e.g.* benzene) is dissolved in a non-polar solvent (*e.g.* n-hexane, CCl_4, CS_2), a shift of the absorption bands with respect to the positions in the gas spectrum is observed, this shift being always bathochromic. This is due to dispersion forces which depend on the polarizability and hence on the refractive index n of the solute and of the solvent. This relationship between the absorption shift and a function of the refractive index (using n_D at the frequency of the sodium D-line instead of $n_{\lambda\rightarrow\infty}$ at frequency 0) was also observed by *Lauer* and *Oda* [29] for benzene, by *LeRosen* and *Reid* [30] for lycopin, and by *Sheppard* [31] for cyanine dyes, all of which possess very readily polarizable π-electron systems.

Theoretical calculations, which take into account only the dispersion interactions, were carried out by *Bayliss* [32a], *Longuet-Higgins* and *Pople* [32b], *Weigang* [32c], and recently also by *Liptay* [21e]. It was found that dispersion interactions must always lead to a bathochromic shift of the absorption in solution in relation to that in the gas phase.

The equation derived by *Bayliss* [32a] is as follows:

$$\Delta\tilde{\nu}\ [\mathrm{cm}^{-1}] = \frac{3\,c^2}{8\pi^2 c^2 m}\cdot\frac{f}{\tilde{\nu}a^3}\cdot\frac{n^2-1}{2n^2+1} \qquad (14)$$

($\Delta\tilde{\nu}$ = band shift in relation to gas phase; f = oscillator strength; a = radius of the absorbing molecule, which is assumed to be spherical; $\tilde{\nu}$ = wave number of the transition; n = refractive index; the other symbols have the conventional meanings).

Experimental tests of Equation (14) and other relationships gave the required connection between $\Delta\tilde{\nu}$ and the refractive index only for a few solvents (hydrocarbons, aryl halides) [29–32c].

Yet other forces of interaction also occur between molecules with a permanent dipole in the ground state (μ_G) and non-polar or polar solvent molecules; the most important of these, apart from hydrogen bonding forces [33a, 33b], are polarization forces (electrostatic directional and inductive forces between dipoles and induced dipoles). The extent of the interaction, and hence of the spectral shift, depends both on the polarity of the dye

[21] For summaries, see [21a]–[21e].

[21a] *K. Dimroth*, Angew. Chem. *60*, 70 (1948); S.-B. Ges. Beförd. ges. Naturwiss. Marburg *76*, 3 (1953); Chem. Zbl. *1954*, 9481; Chimia *15*, 80 (1961); *K. Dimroth, G. Arnoldy, S. von Eicken*, and *G. Schiffler*, Liebigs Ann. Chem. *604*, 221 (1957).

[21b] *A. I. Kiprianov* and *W. J. Petrunkin*, Zh. obshch. Khim. *10*, 613 (1940); Chem. Zbl. *1940* II, 1876; *A. I. Kiprianov* and *E. S. Timoshenko*, Zh. obshch. Khim. *17*, 1468 (1947); Chem. Abstr. *42*, 8475 (1948); Ukrain. chem. J. *18*, 347 (1952); Chem. Abstr. *49*, 984 (1955); *A. I. Kiprianov*, Uspekhi Khim. *29*, 1336 (1960); Chem. Abstr. *55*, 7845 (1961).

[21c] *H. A. Staab*: Einführung in die theoretische Organische Chemie. Verlag Chemie GmbH., Weinheim/Bergstr. 1960, pp. 336, 385–393.

[21d] *H. Meier*: Die Photochemie der organischen Farbstoffe. Springer, Berlin-Göttingen-Heidelberg 1963, pp. 44.

[21e] *W. Liptay*, Lecture at the Second International Symposium on Dyestuffs, April 1964, Elmau Castle, Germany.

[22a] *A. Kundt*, Poggendorfs Ann. Physik. Chem. [N.F.] *4*, 34 (1878); Chem. Zbl. *1878*, 498.

[22b] *H. Kauffmann* and *H. Beisswenger*, Z. physik. Chem. *50*, 350 (1905).

[22c] *A. Hantzsch*, Ber. dtsch. chem. Ges. *55*, 953 (1922).

[22d] Review of earlier work: *S. E. Sheppard*, Rev. mod. Physics *14*, 303 (1942).

[23] Cf. *e.g. G. Scheibe, E. Felger*, and *G. Rößler*, Ber. dtsch. chem. Ges. *60*, 1406 (1927).

[24] *D. P. Stevenson* and *G. M. Coppinger*, J. Amer. chem. Soc. *84*, 149 (1962).

[25] Summary by *J. W. Sidman*, Chem. Reviews *58*, 689 (1958).

[26] For a summary, see [26a]–[26c].

[26a] *J. N. Murrel*, Quart. Reviews *15*, 191 (1961).

[26b] *G. Briegleb*: Elektronen-Donator-Akzeptor-Komplexe. Springer, Berlin-Göttingen-Heidelberg 1961, pp. 37–39.

[26c] *G. Briegleb*, Lecture at the Second International Symposium on Dyestuffs, April 1964, Elmau Castle, Germany.

[27a] *G. Scheibe*, Ber. dtsch. chem. Ges. *58*, 586 (1925); *59*, 2617 (1926).

[27b] *A. Burawoy*, J. chem. Soc. (London) *1939*, 1177; *W. A. Lees* and *A. Burawoy*, Tetrahedron *19*, 419 (1963).

[27c] *R. P. Mariella, R. R. Raube, J. Budde*, and *C. E. Moore*, J. org. Chemistry *19*, 678 (1954).

[27d] *G. J. Brealey* and *M. Kasha*, J. Amer. chem. Soc. *77*, 4462 (1955).

[27e] *G. C. Pimentel*, J. Amer. chem. Soc. *79*, 3323 (1957).

[27f] *N. Mataga* and *S. Tsuno*, Bull. chem. Soc. Japan *30*, 368 (1957); Chem. Zbl. *1960*, 1110.

[27g] *J.-E. Dubois* and *E. Goetz*, J. Chim. physique *60*, 1019 (1963).

[28] *M. Kasha*, Discuss. Faraday Soc. *9*, 14 (1950).

[29] *K. Lauer* and *R. Oda*, Ber. dtsch. chem. Ges. *69*, 851 (1936); cf. *e.g. B. J. Ferguson*, J. chem. Physics *24*, 1263 (1956) and *F. A. Bovey* and *S. S. Yanari*, Nature (London) *186*, 1042 (1960).

[30] *A. L. LeRosen* and *C. E. Reid*, J. chem. Physics *20*, 233 (1952).

[31] *S. E. Sheppard, P. T. Newsome*, and *H. R. Brigham*, J. Amer. chem. Soc. *64*, 2923 (1942).

[32a] *N. S. Bayliss*, J. chem. Physics *18*, 292 (1950).

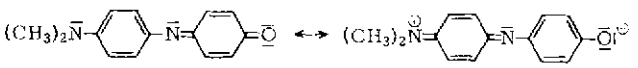
[32b] *H. C. Longuet-Higgins* and *J. A. Pople*, J. chem. Physics *27*, 192 (1957).

[32c] *O. E. Weigang*, J. chem. Physics *33*, 892 (1960).

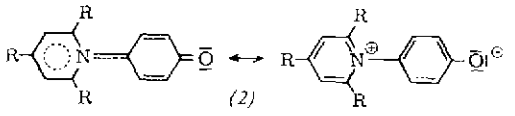
[33a] *E. Lippert*: The Influence of Hydrogen Bonding on Electronic Spectra. IUPAC-Symposium on Hydrogen Bonding, Ljubljana 1957, Pergamon Press London-New York-Paris-Los Angeles 1959, p. 217; Chem. Abstr. *54*, 19145 (1960).

[33b] *W. A. Ismailski* and *M. A. Mosstosslavski*, Dokl. Akad. Nauk S.S.S.R. *139*, 601 (1961); Chem. Zbl. *1963*, 20733.

and on that of the solvent, and is especially large in the case of intramolecularly ionic dyes, such as merocyanines [34a–34e] (*e.g.* phenol blue *(1)* [30–35]) or the pyridinium-*N*-phenol betaines (*e.g. (2)* [36]). In dyes of this type, an electron-donating group is joined to an



(1)



(2)

electron-accepting group *via* a conjugated system. The excitation is associated with a charge transfer between the two groups, resulting in an appreciable change in the magnitude and direction of the dipole moment in the excited state (μ_A) [37]. A qualitative differentiation is made between dyes with predominantly non-polar ground states [*(1)*; $\mu_G < \mu_A$], the long-wave absorption band of which undergoes a bathochromic shift as the polarity of the solvent increases (positive solvatochromism), and dyes with polar ground states [*(2)*; $\mu_G > \mu_A$], which exhibit the opposite absorption behavior (negative solvatochromism).

There are basically two theories regarding the mechanism of this interaction. Most theoretical calculations of the change in energy levels of dissolved molecules caused by the solvent are based on the fact that the effective electric field at the position of the dissolved molecule is replaced by the Onsager reaction field [13] for a polarizable point dipole in a spherical cavity. Calculations of this kind were carried out by *Ooshika* [38a], *Bayliss* and *McRae* [38b], *McRae* [38c], *Lippert* [38d], *Bakshiev* [38e], *Bilot* and *Kawski* [38f], and recently also by *Liptay* [21e]. These led to complicated relationships between the absorption shift and functions of the dielectric constant and refractive index of the solvent.

The model can be simplified by regarding the solute and solvent molecules as point dipoles surrounded by a homogeneous isotropic dielectric continuum and by disregarding all specific interactions such as hydrogen bonding and formation of electron donor-acceptor complexes; in such a case, however, the equations derived cannot agree exactly with the experimental findings.

A second line of reasoning is based on the fact that intramolecularly ionic dyes such as the merocyanines can be represented by a polar and a non-polar resonance structure, to which can be assigned the wave functions Ψ_1 and Ψ_2, according to the valence bond method. The linear combination of these ware functions

$$\Psi_G = a \cdot \Psi_1 + b \cdot \Psi_2 \qquad (15)$$

describes the electron distribution in the ground state. It was postulated by *Brooker* [34a], *Kiprianov* [21b], and *Dimroth* [21a], who independently carried out detailed investigations on the pronounced solvatochromism of the merocyanines, that a change of the solvent resulted in a displacement of the resonance position of the dye. The coefficients a and b should therefore depend on the solvent. According to the term diagram developed by *Förster* [39], the excitation energy is a minimum in the case of resonance structures of equal energy (a = b). In the case of polar dyes (a > b), the effect of increasing the polarity of the solvent is to increase the contribution of the polar resonance structure to the ground state; the symmetry of the π-electron system decreases further, and the result is a hypsochromic shift. Non-polar dyes (b > a) should exhibit the opposite absorption behavior for a similar change of solvent, since in this case the symmetry of the π-electron system increases with increasing participation of the polar resonance structure.

Quantitative calculations for the Brooker dyes have been carried out by *Simpson* [40a] and *Platt* [40b].

Recent investigations [41a], particularly by *Schweig* [41b] and *Liptay* [21e], indicate that the effect of dispersion and polarization interactions (which are essentially determined by the dipole moment in the ground state and its change on excitation) on the ground state and excited states probably makes a greater contribution to the total solvatochromism than the displacement of the resonance position of the dye. *Liptay* emphasized [21e] the fact that the concept of resonance change is equivalent to the concept of polarization (measured by the polarizability); consequently, the model developed to explain the solvatochromism by the effect of resonance implicitly corresponds to the model which considers the interaction between the solvent and the dye as the interaction between polarizable point dipoles in a homogeneous dielectric continuum.

Owing to the many possible interactions which can occur between the dye and the solvent, and owing to the simplified molecular model on which the calculations were based, attempts to discover generally valid quantitative relationships between macroscopic properties of the solvent and its effect on the spectra have met with only partial success [*].

[34a] *L. G. S. Brooker* et al., J. Amer. chem. Soc. *73*, 5326, 5332 (1951); Chimia *15*, 87 (1961).

[34b] *N. S. Bayliss* and *E. G. McRae*, J. Amer. chem. Soc. *74*, 5803 (1952); *E. G. McRae*, Spectrochim. Acta *12*, 192 (1958).

[34c] *E. Lippert* and *F. Moll*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *58*, 718, 853 (1954).

[34d] *S. Hünig* et al., Liebigs Ann. Chem. *587*, 132 (1954); *592*, 161 (1955); *599*, 131 (1956); *612*, 282 (1958); *617*, 210 (1958); *636*, 32 (1960).

[34e] *J. T. Leach* and *J. P. Phillips*, J. org. Chemistry *27*, 3309 (1962).

[35] *L. G. S. Brooker* and *R. H. Sprague*, J. Amer. chem. Soc. *63*, 3214 (1941).

[36] Review: *F. Kröhnke*, Angew. Chem. *65*, 605 (1953); cf. *e.g. W. Schneider*, *W. Döbling*, and *R. Cordua*, Ber. dtsch. chem. Ges. *70*, 1645 (1937).

[37] For determination of the dipole moment of excited molecules, see [38d] and *J. Czekalla*, Chimia *15*, 26 (1961).

[38a] *Y. Ooshika*, J. physic. Soc. Japan *9*, 594 (1954); Chem. Zbl. *1956*, 9083.

[38b] *N. S. Bayliss* and *E. G. McRae*, J. physic. Chem. *58*, 1002, 1006 (1954).

[38c] *E. G. McRae*, J. physic. Chem. *61*, 562 (1957).

[38d] *E. Lippert*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *61*, 962 (1957); Angew. Chem. *73*, 695 (1961).

[38e] *N. G. Bakhshiev*, Optika i Spektroskopiya *10*, 717 (1961); Chem. Abstr. *57*, 4194h (1962).

[38f] *L. Bilot* and *A. Kawski*, Z. Naturforsch. *17a*, 621 (1962).

[39] *Th. Förster*, Z. Elektrochem. angew. physik. Chem. *45*, 548 (1939).

[40a] *W. T. Simpson*, J. Amer. chem. Soc. *73*, 5359 (1951).

[40b] *J. R. Platt*, J. chem. Physics *25*, 80 (1956).

[41a] *J. Czekalla* and *G. Wick*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *65*, 727 (1961).

[41b] *A. Schweig*, Diploma Thesis, Universität Marburg (Lahn), 1964; *K. Dimroth* and *A. Schweig*, unpublished work.

[*] See, however, [21e, 41b].

III. Empirical Relationships for the Polarity of the Solvent

A. The Winstein-Grunwald Equation

Grunwald and *Winstein* [42] investigated solvolyses of aliphatic compounds proceeding by an S_N1 mechanism; from these investigations, they derived the "Y-values" as a quantitative measure of the ionizing power of a solvent. The relationship between Y and the rate of solvolysis is given by Equation (16).

$$\log \frac{k_A}{k_B} = m\,(Y_A - Y_B) \qquad (16)$$

k_A and k_B are the rate constants of an S_N1 solvolysis in solvents A and B, m is a constant at a given temperature, and is characteristic of the compound being solvolysed.

Since Equation (16) contains only differences between Y-values, the absolute values of Y can be arbitrarily fixed. The solvolysis of t-butyl chloride at 25 °C was chosen as the standard reaction, and Y was defined as

$$Y = \log k^{BuCl} - \log k_0^{BuCl} \qquad (17)$$

k^{BuCl} and k_0^{BuCl} being the rate constants of the solvolysis of t-butyl chloride at 25 °C in a given solvent and in a standard solvent (aqueous ethanol, 80 % by volume), respectively. By definition, the Y-value for 80 % ethanol is zero, and m for t-butyl chloride is 1.000. The general equation therefore reduces to the form (18)

$$\log \frac{k}{k_0} = m \cdot Y. \qquad (18)\ [*]$$

where k is the rate constant for the compound in question in a given solvent, k_0 is the rate constant in 80 % ethanol under the same conditions, and m is the sensitivity of this compound towards a change in the ionizing power of the solvent in relation to that of t-butyl chloride. Since according to the transition state theory, the logarithm of the rate constant is proportional to the free enthalpy of activation ΔG^+, Y bears a linear relationship to the free enthalpy [43].

A number of Y-values are listed in Table 1. These lie between +3.493 (water) and − 3.26 (t-butanol); the larger the value of Y, the greater is the ionizing power of the solvent. Y-values are also known for a series of solvent mixtures (mixtures of ethanol, methanol, acetone, dioxane, acetic acid, formic acid, and formamide with water, as well as acetic acid/formic acid and dioxane/formic acid mixtures). Experimental difficulties have prevented extension of the Y-scale to include other solvents.

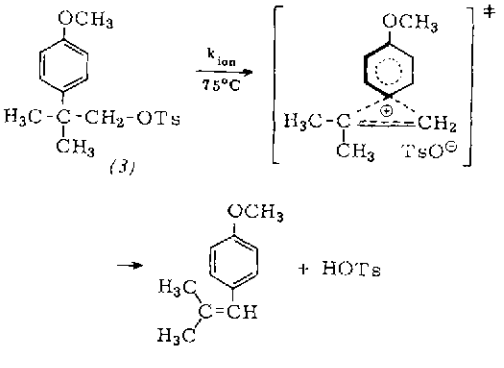
The Y-values are an empirical measure of the ability of a solvent to solvate ions, and in many cases give better correlations with the logarithms of the rate constants of solvent-dependent reactions than do the dielectric constants [42, 17]. Equation (18) is satisfactorily obeyed by the rates of solvolysis of certain tertiary halides and secondary sulfonates, but it can be successfully applied to primary derivatives (which react by an S_N2 mechanism) and secondary derivatives (which exhibit borderline behavior) only if the solvents to be compared differ in polarity and nucleophilic character to an equal extent.

If, for example, Y is plotted against log k for the solvolysis of benzhydryl chloride or neophyl chloride (1-chloro-2-methyl-2-phenylpropane) in various binary mixtures, each mixture (dioxane, acetic acid, or ethanol with water) gives a different straight line, although, if Equation (18) were strictly valid, all the points should lie on the same straight line. Thus parameter m, which is supposed to be independent of the solvent, must contain another factor which is a measure of the nucleophilic character of the solvent. Compounds which react by an S_N mechanism undergo nucleophilic attack by the solvent during the formation of ions in the transition state; the reactivity of the compounds therefore also depends on the nucleophilic character of the solvent, and cannot be measured by Y.

The range of application of Equation (18) can be extended if each compound is given a series of m-values, each of which is valid for one pair of solvents [44]. As an example, the following m-values have been found for t-butyl bromide: 0.941 for ethanol/water, 1.067 for glacial acetic acid/water, and 0.921 for dioxane/water mixtures.

In this connection, mention must be made of *Swain*'s relationship [45], which accounts for these deviations of the m-values in terms of nucleophilicity and electrophilicity parameters of the solvent.

In a recent paper, *Smith*, *Fainberg*, and *Winstein* [46] introduced another standard reaction for characterizing the polarity of solvents, namely the ionization of *p*-methoxyneophyl *p*-toluenesulfonate *(3)*. The ($\log k_{ion}$)-values (for a selection see Table 1) of *(3)* were determined in sixteen solvents (particularly those containing



[42] *E. Grunwald* and *S. Winstein*, J. Amer. chem. Soc. *70*, 846 (1948); *S. Winstein*, *E. Grunwald*, and *H. W. Jones*, ibid. *73*, 2700 (1951); *A. H. Fainberg* and *S. Winstein*, ibid. *78*, 2770 (1956).

[*] Note the formal analogy between this equation in the form $\log k = \log k_0 + mY$ and Equation (11).

43] Reviewed by *P. R. Wells*, Chem. Reviews *63*, 171 (1963).

[44] *S. Winstein*, *A. H. Fainberg*, and *E. Grunwald*, J. Amer. chem. Soc. *79*, 1597, 1602, 1608, 4146, 5937 (1957).

[45] *C. G. Swain*, J. Amer. chem. Soc. *70*, 1119 (1948); *C. G. Swain* and *C. B. Scott*, ibid. *75*, 141 (1953); *C. G. Swain*, *R. B. Mosely*, and *D. E. Bown*, ibid. *77*, 3727, 3731 (1955); cf. also *J. O. Edwards* and *R. G. Pearson*, ibid. *84*, 16 (1962).

[46] *S. G. Smith*, *A. H. Fainberg*, and *S. Winstein*, J. Amer. chem. Soc. *83*, 618 (1961).

Table 1. Empirical parameters of the polarity of solvents, arranged in order of decreasing E_T-values.

Solvents	Dielectric constant (25 °C) [a]	E_T [55] [kcal/mole] (25 °C)	Z [52] [kcal/mole] (25 °C)	Y [42] (25 °C)	log kion [46] [sec^{-1}] (75 °C)	Ω [50] (30 °C)	S [59] (25 °C)
H_2O	78.5	63.1	94.6	3.493	−1.180		0.1540
HCOOH	57.9 [f]			2.054	−0.929		0.1139
$HCONH_2$	109.5 [b]	56.6	83.3	0.604			0.0463
$HOCH_2$–CH_2OH	37.7 [c]	56.3	85.1				0.0679
CH_3OH	32.6	55.5	83.6	−1.090	−2.796	0.845	0.0499
HCO–$NHCH_3$	182.4 [b]	54.1					
C_2H_5OH/H_2O 80:20		53.6	84.8	0.000	−2.505		0.0650
$HOCH_2$–CH_2OCH_3	15.95 [d]	52.3					
CH_3–CH_2OH	24.3	51.9	79.6	−2.033	−3.204	0.718	0.0000
CH_3–COOH	6.19	51.9 [e]	79.2	−1.639	−2.772	0.823	0.0050
C_6H_5–CH_2OH	13.6 [f]	50.8					
CH_3–CH_2–CH_2OH	19.7	50.7	78.3				−0.0158
CH_3–CH_2–CH_2–CH_2OH	17.7	50.2	77.7				−0.0240
CH_3–CHOH–CH_3	18.3	48.6	76.3	−2.73			−0.0413
$(CH_3)_2CH$–CH_2–CH_2OH	15.2	47.0					
Propylene carbonate [n]	65.1 [g]	46.6					
CH_3NO_2	38.57 [f]	46.3			−3.921	0.680	−0.134
CH_3CN	37.5 [f]	46.0	71.3		−4.221	0.692	−0.1039
CH_3SOCH_3	48.9 [f, h]	45.0	71.1		−3.738		
$C_6H_5NH_2$	6.98	44.3					0.001
Sulfolane	44.0 [d, i]	44.0					
$(CH_3)_3COH$	12.2	43.9 [d]	71.3	−3.26			−0.1047
HCO–$N(CH_3)_2$	36.71 [b]	43.8	68.5		−4.298	0.620	−0.1416
CH_3–CO–CH_3	20.5	42.2	65.7		−5.067	0.619 [f]	−0.1748
$C_6H_5NO_2$	34.6	42.0					−0.218
C_6H_5CN	25.2	42.0					
$ClCH_2$–CH_2Cl	10.37	41.9				0.600	−0.151
C_6H_5–CO–CH_3	17.4	41.3					
CH_2Cl_2	8.9	41.1	64.2				−0.1890
$(H_3C)_2N$–CO–$N(CH_3)_2$	23.1 [k]	41.0					
Pyridine	12.3	40.2	64.0		−4.670	0.595	−0.1970
Quinoline	9.22	39.4					
$CHCl_3$	4.70	39.1	63.2				−0.2000
α-Picoline	9.94 [f]	38.3					
CH_3OCH_2–CH_2OCH_3	3.5-6.8 [a, l]	38.2	62.1 [50]			0.543	
CH_3–$COOC_2H_5$	6.03	38.1			−5.947		−0.210
C_6H_5Br	5.39	37.5					−0.164
C_6H_5Cl	5.61	37.5					−0.182
Tetrahydrofuran	7.39	37.4			−6.073		
$C_6H_5OCH_3$	4.30	37.2					−0.214
2,6-Lutidine	7.23 [m]	36.7					
1,4-Dioxane	2.21	36.0					−0.179
$C_6H_5OC_6H_5$	3.68 [d]	35.3 [d]					
$C_2H_5OC_2H_5$	4.22	34.6			−7.3		−0.277
C_6H_6	2.27	34.5					−0.215
C_6H_5–CH_3	2.38	33.9					−0.237
CS_2	2.64	32.6					−0.240
CCl_4	2.23	32.5					−0.245
n-Hexane	1.90	30.9					−0.337
iso-Octane	1.94 [f]		60.1				

[a] *Landolt-Börnstein*: Zahlenwerte und Funktionen. 6th Edition, Springer, Berlin-Göttingen-Heidelberg 1959, Vol. II/6, p. 613.

[b] *G. R. Leader*, J. Amer. chem. Soc. *73*, 856 (1951); *G. R. Leader* and *J. F. Gormley*, ibid. *73*, 5731 (1951).

[c] *A. R. Tourky*, *H. A. Rizk*, and *J. M. Elanwar*, Z. physik. Chem. N. F. *31*, 161 (1962).

[d] Value at 30 °C.

[e] Interpolated with the aid of Z [52].

[f] Value at 20 °C.

[g] *P. L. Kronick* and *R. M. Fuoss*, J. Amer. chem. Soc. *77*, 6114 (1955).

[h] *H. L. Schläfer* and *W. Schaffernicht*, Angew. Chem. *72*, 618 (1960).

[i] *R. L. Burwell* and *C. H. Langford*, J. Amer. chem. Soc. *81*, 3799 (1959); *E. M. Arnett* and *C. F. Douty*, ibid. *86*, 409 (1964).

[k] *T. Gäumann*, Helv. Chim. Acta *41*, 1956 (1958); *A. Lüttringhaus* and *H. Dirksen*, Angew. Chem. *75*, 1059 (1963); Angew. Chem. internat. Edit. *3*, 260 (1964).

[l] *G. Wittig* and *E. Stahnecker*, Liebigs Ann. Chem. *605*, 69 (1957); *J. L. Down*, *J. Lewis*, *B. Moore*, and *G. Wilkinson*, J. chem. Soc. (London) *1959*, 3767.

[m] *R. Ladenburg*, Z. Elektrochem. angew. physik. Chem. *7*, 816 (1901).

[n] 4-Methyl-1,3-dioxol-2-one.

no OH-groups), and in some solvent mixtures. These values provide a measure of the solvating power of a solvent as good as that provided by the Y-values for solvents containing OH-groups. The (log k_{ion})-values show good correlation with the Y-values (although each pair of solvents gives a different straight line), with the Z- and E_T-values described below, and with the (log k)-values for a number of rearrangements [46]. They are only roughly related to the dielectric constants, disagreement being particularly marked in the case of solvents containing protons and forming hydrogen bonds.

B. The X-Values

Equation (16) makes it possible to measure the ionizing action of a solvent for electrophilic aliphatic substitutions on a saturated carbon atom [47]. This was recently

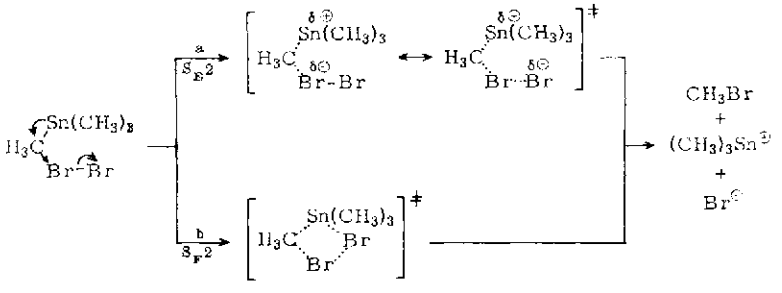
[47] Review by *G. Köbrich*, Angew. Chem. *74*, 453 (1962); Angew. Chem. internat. Edit. *1*, 382 (1962).

shown by *Gielen* and *Nasielski* [48] in the case of the reaction of halogen with tetraalkyltin compounds,which proceeds by an S_E2 mechanism. The relationship given by these authors is as follows

$$\log \frac{k}{k_0} = p \cdot X \qquad (19)$$

k and k_0 are the rate constants of an electrophilic aliphatic substitution on an organometallic compound in a given solvent or in glacial acetic acid which is used as the standard solvent (X = 0), p is a constant which depends on the electrophile and on the organometallic compound, and X is proportional to the polarity of the solvent.

As a standard reaction (for which p is assumed to be equal to unity), the authors chose the reaction of bromine with tetramethyltin (see Scheme 2) which in polar solvents probably passes through a non-cyclic polar transition state (Route a). On stepwise reduction of the polarity of the solvent, a cyclic transition state (Route b) gains importance.



Scheme 2. Transition states of the reaction of tetramethyltin with bromine.

X-Values are at present known for only four solvents (CH_3OH 0.91; DMF: 0.8; C_6H_5Cl: −1.9; CCl_4: −4.8), and no correlation is observed on comparison with the dielectric constants. The solvent series obtained from the X- and Y-values do not quite agree, since the reaction rate is again influenced not only by the stabilization of the polar transition complex as a result of solvation, but also by the electrophilic and nucleophilic character of the solvent. The electrophilic substitution is probably supported by a nucleophilic "pull" of the solvent on the leaving group (−SnR_3). The coupling constants $J(^{117}Sn-^1H)$ obtained from the NMR spectrum of $(CH_3)_3SnBr$ in various solvents, which can be taken as a measure of the nucleophilic character of the solvent with respect to tin, show a correlation with the X-values, in agreement with this assumption [48].

C. The Ω-Values

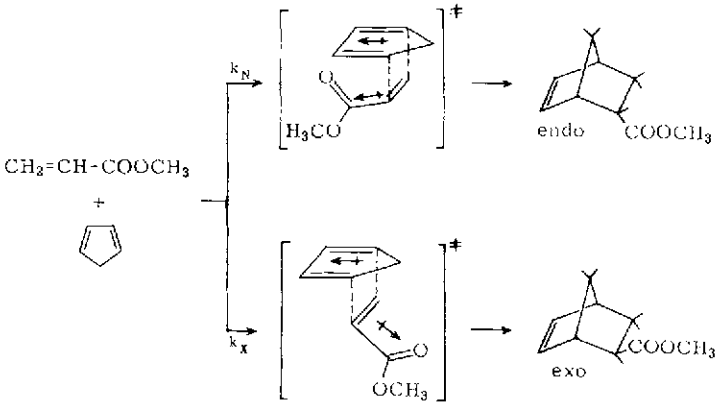
The fact that the rate of Diels-Alder reactions is affected, although only slightly, by the solvent [49] was used by *Berson*, *Hamlet*, and *Mueller* [50] in setting up a polarity scale. These authors found that, in the Diels-Alder addition of cyclopentadiene to methyl acrylate, the ratio of the endo-product (N) to the exo-product (X) depends on the solvent. Since the reaction is kinetically controlled, the product ratio N/X equals the ratio of the specific rate constants. The authors define

$$\log \frac{k_N}{k_X} = \log \frac{N}{X} \equiv \Omega \qquad (20)$$

where Ω is proposed as a new empirical parameter of the polarity of the solvents

The values of Ω at 30 °C lie between 0.445 (triethylamine) and 0.845 (methanol), and are known for twelve solvents (for a selection see Table 1). Owing to the low solubility of the reactants in polar media, the extension of this scale is subject to narrow limits.

The increase in Ω with increasing polarity of the solvent corresponds to an increase in the difference of the free enthalpies of activation, $\Delta G_X^{\ddagger} - \Delta G_N^{\ddagger}$, and is readily understandable, if it is assumed that the total dipole moment of the endo-transition state is greater than that of the exo-transition state. The resulting better solvation of the endo-transition state lowers the enthalpy of activation to a greater extent, in accordance with Fig. 1a, and so leads to preferential endo-addition (see Scheme 3).



Scheme 3. Endo- and exo-products in the Diels-Alder reaction between cyclopentadiene and methyl acrylate. (The arrows indicate the directions of the dipole moments).

The Ω-values show a good correlation with log(N/X)-values of other dienophiles, the (log k_{ion})-values, and the Z- and E_T-values; a satisfactory relationship with the dielectric constants, on the other hand, exists only for aprotic solvents.

D. The Z-Values

The first suggestion that solvatochromic dyes should be used as indicators for the polarity of solvents was made by *Brooker* et al. [51], but *Kosower* was the first to set

[48] *M. Gielen* and *J. Nasielski*, Recueil Trav. chim. Pays-Bas *82*, 228 (1963); J. organomet. Chemistry *1*, 173 (1964).

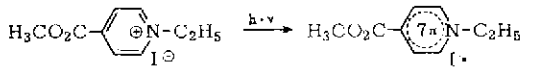
[49] *A. Wassermann*, J. chem. Soc. (London) *1942*, 623; Mh. Chem. *83*, 543 (1952); *W. Rubin*, *H. Steiner*, and *A. Wassermann*, ibid. *1949*, 3046.

[50] *A. Berson*, *Z. Hamlet*, and *W. A. Mueller*, J. Amer. chem. Soc. *84*, 297 (1962).

[51] *L. G. S. Brooker*, *G. H. Keyes*, and *D. W. Heseltine*, J. Amer. chem. Soc. *73*, 5350 (1951).

up a comprehensive solvent scale in this way [52]. The latter author found that the charge-transfer absorption of 1-alkylpyridinium iodides exhibited a pronounced negative solvatochromism, and chose 1-ethyl-4-methoxycarbonylpyridinium iodide *(4)* as a test dye. *Kosower* termed the molar transition energies E_T [see Eq. (21)] calculated from the position of the absorption maximum [$\tilde{\nu}$ in cm^{-1}] "Z values".

$$E_T\,[\text{kcal/mole}] = h \cdot c \cdot \tilde{\nu} \cdot N_L = 2.859 \cdot 10^{-3} \cdot \tilde{\nu} \equiv Z \qquad (21)$$



(4)

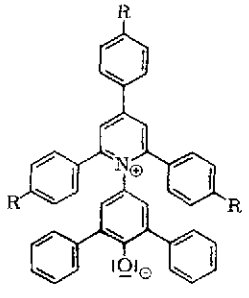
High Z-values correspond to a high transition energy. The stronger the stabilizing effect of the solvent on the ion-pair in the ground state as compared with that on the less polar excited state, the lower the wavelength of the intermolecular charge-transfer band [52, 53]. The experimental Z-values therefore provide a direct empirical measure of the solvation behavior of a solvent towards *(4)*.

The Z-values lie between 94.6 (water) and 60.1 (iso-octane), and have been determined for 23 pure solvents and for a number of aqueous solvent mixtures (for a selection see Table 1) [*]. The Z-value could be obtained by direct measurement only over the range from chloroform ($Z = 63.2$; $\lambda = 452$ mμ) to 70 % ethanol ($Z = 86.4$; $\lambda = 331$ mμ), corresponding to a ΔE_T range of 23.2 kcal/mol ($\Delta\lambda = 121$ mμ). Higher Z-values could not be determined directly, since the specific absorption of the pyridinium cation masks the low-intensity short-wave charge-transfer band. However, the excellent linear correlation with the Y-values of suitable binary solvent mixtures (*e.g.* $Y = 0.41632\,Z - 35.877$ for methanol/water) permits determination of Z for polar solvents by extrapolation.

Owing to the insolubility of *(4)* in non-polar solvents, pyridine 1-oxide was used as a second standard dye; in this case, however, the maximum shift of the solvatochromic band, namely 28 mμ ($\lambda = 254$ mμ in water; $\lambda = 282$ mμ in iso-octane), is very small and the correlation between Z and the E_T-values of pyridine 1-oxide is only moderately good. No relationship exists between Z and the dielectric constants. However, *Kosower* has shown [54a–54l] that Z exhibits an excellent correlation with other solvent-sensitive absorptions, such as the $n \rightarrow \sigma^*$ absorption of alkyl halides [54h], the $n \rightarrow \pi^*$ and $\pi - \pi^*$ absorption of mesityl oxide [54a], the $\pi \rightarrow \pi^*$ absorption of phenol blue [54a], and the charge-transfer absorption of tropylium iodide [54l], as well as with kinetic data (Menschutkin reaction, Finkelstein reaction, etc. [54a]).

E. The E_T-Values of Pyridinium N-Phenolbetaines

Probably the most comprehensive solvent scale to date is that determined by *Dimroth, Reichardt, Siepmann* and *Bohlmann* [55a–55c]. The E_T-values calculated from Equation (21) for the pyridinium *N*-phenolbetaine *(5)* used as the test substance provide an excellent characterization of the polarity of solvents, owing to the extraordinarily large displacement of the solvatochromic band. This displacement of a solvatochromic band observed in the case of *(5)* is the largest so far known: the long-wave band is situated at 810 mμ ($E_T = 35.3$ kcal/mole) in diphenyl ether and at 453 mμ ($E_T = 63.1$ kcal/mole) in water corresponding to a hypsochromic



(5): R = H
(6): R = CH_3

shift of 357 mμ ($\Delta E_T = 27.8$ kcal/mole). Since the solvatochromic band lies in the visible region of the spectrum, it is even possible to make a visual estimation of the polarity of a solvent (CH_3OH: red; $CH_3-CHOH-CH_3$: blue; $CH_3-CO-CH_3$: green). Compound *(5)* is protonated at the oxygen atom by acids and the long-wave band disappears, so that no E_T-value can be found for solvents such as glacial acetic acid. Compound *(5)* is insoluble in aliphatic and aromatic hydrocarbons. However, the solvent scale could be extended to these solvents with the aid of alkylated, more soluble betaines, *e.g. (6)*. Owing to the excellent correlation of the E_T-values of *(5)* with those of *(6)*, E_T-values of *(5)* in solvents in which its solubility is too low can be obtained by extrapolation [55c].

Thus E_T-values are known for 62 pure solvents and five solvent mixtures (for a selection see Table 1). The

[52] *E. M. Kosower*, J. Amer. chem. Soc. *80*, 3253 (1958); *E. M. Kosower*: Molecular Biochemistry. McGraw-Hill, London 1962, p. 180; *E. M. Kosower*, J. Chim. physique *61*, 230 (1964).

[53] *G. Briegleb, W. Jung*, and *W. Herre*, Z. physik. Chem. N. F. *38*, 253 (1963).

[*] Recently *C. Walling* and *P. J. Wagner*, J. Amer. Soc. *86*, 3368 (1964), have determined Z-values for another six solvents: $Z = 58.0$ (C_6H_5Cl); 59.2 (C_6H_5Br); 60.0 (o-$C_6H_4Cl_2$); 60.2 (C_6H_5F); 63.9 (cis-$C_2H_2Cl_2$); 65.0 (C_6H_5CN).

[54a] *E. M. Kosower*, J. Amer. chem. Soc. *80*, 3261, 3267 (1958).

[54b] *E. M. Kosover* and *D. C. Remy*, Tetrahedron *5*, 281 (1959).

[54c] *E. M. Kosower* and *B. G. Ramsay*, J. Amer. chem. Soc. *81*, 856 (1959).

[54d] *E. M. Kosower* and *G.-S. Wu*, J. Amer. chem. Soc. *83*, 3142 (1961).

[54e] *E. M. Kosower, G.-S. Wu*, and *T. S. Sorensen*, J. Amer. chem. Soc. *83*, 3147 (1961).

[54f] *E. M. Kosower, D. Hofmann*, and *K. Wallenfels*, J. Amer. chem. Soc. *83*, 3314 (1961); *84*, 2755 (1962).

[54g] *E. M. Kosower* and *M. Ito*, Proc. chem. Soc. (London) *1962*, 25.

[54h] *E. M. Kosower, M. Ito*, and *P.-K. Huang*, Trans. Faraday Soc. *57*, 1662 (1961).

[54i] *E. M. Kosower*, J. chem. Physics *38*, 2813 (1963).

[54k] *W. D. Closson, S. F. Brady, E. M. Kosower*, and *P. C. Huang*, J. org. Chemistry *28*, 1161 (1963).

[54l] *E. M. Kosower*, J. org. Chemistry *29*, 956 (1964).

[55a] *K. Dimroth* and *C. Reichardt*, Palette No. 11, p. 28 (1962), Publication by Sandoz AG. (Basel), Switzerland.

[55b] *K. Dimroth, C. Reichardt, T. Siepmann*, and *F. Bohlmann*, Liebigs Ann. Chem. *661*, 1 (1963).

[55c] *K. Dimroth* and *C. Reichardt*, unpublished work.

E_T-values change on addition of an electrolyte and decrease with increasing temperature, owing to the pronounced thermochromism of the pyridinium *N*-phenolbetaines [56].

It should be noted that solvents such as formamide (D = 109.5), methylformamide (D = 182.4), and dimethylsulfoxide (D = 48.9), which are described as "highly polar" on account of their dielectric constants and their good solvent power towards salts, are by no means so polar in their behavior towards *(5)*. Methylformamide, the solvent with the highest dielectric constant, is in fact no more polar than methanol, while dimethylsulfoxide has an E_T-value similar to that of t-butanol. Protonic solvents always exhibit more highly polar behavior than aprotic solvents of the same dielectric constant (cf. *e.g.* n-butanol and acetophenone). When the OH-groups are shielded by bulky substituents, alcohols become more like aprotic solvents (cf. benzyl alcohol → t-butanol → pyridine). Increasing steric hindrance is also always associated with decreasing E_T-values in aprotic solvents (cf. pyridine → picoline → 2,6-lutidine).

There is a good linear correlation between the E_T-values and the other empirical parameters for the solvent polarity; this correlation can be expressed by Equation (22):

$$y = a \cdot E_T + b \qquad (22)$$

where a and b were determined by the method of least squares and have the values given in Table 2.

Table 2. Correlation of the E_T-values [pyridinium *N*-phenolbetaine *(5)*] with Z, log k_{ion}, Ω, and S according to Equation (22).

y	a	b
Z	1.259	13.76
log k_{ion}	0.179	−12.35
Ω	0.0154	−0.0389
S	0.0134	−0.704

The E_T-values also exhibit a good, generally linear correlation with a large number of solvent-sensitive absorption bands and with a number of kinetic data [57].

F. Brownstein's Linear Free Enthalpy Relationship

By formal analogy with *Hammett*'s linear free enthalpy relationship [58] for the reactions of substituted benzene derivatives, *Brownstein* formulated the following equation [59]:

$$\frac{\log k_S}{\log k_E} = S \cdot R \qquad (23)$$

k_S is the rate constant, equilibrium constant, or the function of a spectral shift in various solvents at 25 °C, and k_E is the corresponding parameter in absolute ethanol. S is a constant which depends on the solvent (S = 0.00 for absolute ethanol), while R is a measure of the sensitivity of the system in question towards a change of solvent.

As a reference system, *Brownstein* chose the standard dye *(4)* used by *Kosower*, and assigned to it an R-value of 1.00. This choice is just as arbitrary as the choice of the dissociation of benzoic acid in water at 25 °C as the reference reaction for the *Hammett* equation (ρ = 1).

Having chosen a standard solvent and a standard reaction, it is now possible to calculate R- and S-values for every reaction and every solvent. From *Kosower*'s work 58 S-values were used to determine R-values for 9 reactions. In continuation of this process, 158 S-values and 78 R-values were deduced, including R-values for solvent-dependent ultraviolet, infrared, and nuclear resonance absorptions, rates of reactions, and positions of equilibria. The *Brownstein* relationship brings together a large number of experimental data, and the S-values represent an empirical generalization of the special solvent parameters.

IV. Conclusion

All these empirical parameters constitute a more comprehensive measure of the polarity of a solvent than the dielectric constant or any other single physical characteristic, since they reflect more faithfully the complete picture of all the intermolecular forces acting in solutions. The solvent-dependent standard processes may be regarded as probes which permit a purely empirical investigation of the solvent effect. In applying these parameters, however, it is tacitly assumed that the contribution of intermolecular forces in the interaction between the solvent and the standard substance is the same as in the interaction between the solvent and a substrate. This is probably true only in very few cases, so that the use of these parameters for characterizing the solvating action of any solvent and conclusions as to the solvation of any organic molecules appear to be very restricted. However, until the theory of solutions leads to the development of generally applicable laws for the influence of the solvent on rates of reaction and absorption of light, these parameters are of practical value.

With the aid of the *Hammett* equation [58], it is possible, knowing the empirical σ-values for any given substituted aromatic compound, to calculate the approximate effect of the substituents on the equilibrium or on the rate of a reaction (the reaction constant ρ of which has been found from the reactions of other members of the same series of compounds). In the same way, the polarity parameters make possible the semi-quantitative estimation of the effect of solvents on the rate of substitution reactions or the position of absorption bands of solvatochromic dyes, and so lead to conclusions regarding the reaction mechanism or the nature of the light absorption.

In view of the wide variation in the energies of the standard processes, the good agreement found for all the

[56] *K. Dimroth, C. Reichardt*, and *A. Schweig*, Liebigs Ann. Chem. *669*, 95 (1963).

[57] *K. Dimroth* and *C. Reichardt*, unpublished work.

[58] *L. P. Hammett*: Physical Organic Chemistry. McGraw-Hill, New York-London 1940, pp. 184–199; *H. H. Jaffé*, Chem. Reviews *53*, 191 (1953).

[59] *S. Brownstein*, Canad. J. Chem. *38*, 1590 (1960).

parameters is surprising. One always obtains substantially similar orders for the solvents: Z changes by about 24 kcal/mole in the solvent range from iso-octane to methanol, E_T of *(5)* by about 25 kcal/mole between n-hexane and methanol, $-2.3\ RT \log k_{ion}$ by 7 kcal/mole between ether and methanol, while $-2.3\ RT\,\Omega$ changes by only 0.5 kcal/mole between decalin and methanol.

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Protonic States and the Mechanism of Acid-Catalysed Esterification

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Protons can be very mobile in condensed phases; the length of time they are present in any one place is minute. The significance of proton mobility in the course of chemical reactions is considered in the case of acid-catalysed esterification by the normal carbonyl addition mechanism. – The properties of the protons in the carboxylic acid/alcohol system can be discussed on the basis of a semiconductor term diagram. The high mobility of the catalysing protons in the semiconductor system suggests that formation of the esterification intermediates occurs in two reaction steps which proceed at different rates. In the first rapid step the transition state is reached by proton transfers via hydrogen bridges. The proton rearrangement involved proceeds so rapidly that the heavy molecular skeletons retain their mutual spatial positions (Franck-Condon principle for proton-catalysed reactions). In the second slower step, the intermediate is formed by rearrangement of the groups of atoms. – Decomposition of the intermediate, with formation of either the starting materials or the end products, proceeds via a mechanism similar to that for the formation.

I. Introduction

The proton is of fundamental importance in being an elementary particle. Its radius is some five orders of magnitude smaller than those of the atoms and ions of other elements. The proton can therefore possess appreciable mobility in condensed phases, in contrast to heavier atoms, ions, and molecules, and so it remains in any given place for only a very short time; this is one main source of difficulty encountered in the discussion of proton-catalysed reactions.

In general, during an acid-catalysed reaction, a proton becomes attached to a molecule A, with formation of a cation $AH^{\oplus}$. The cation then interacts with a co-reactant B, and the reaction product $ABH^{\oplus}$ is converted into the final product AB with loss of a proton:

$$A \xrightarrow{+H^{\oplus}} AH^{\oplus} \xrightarrow{+B} ABH^{\oplus} \xrightarrow{-H^{\oplus}} AB$$

The life-time of $AH^{\oplus}$ is generally very short because of the high mobility of the proton; contrasted with this the time required for reaction between $AH^{\oplus}$ and B is much longer, since the heavy molecules must approach each other until they are separated only by the bond distance in $ABH^{\oplus}$. Since the mobility of the heavy particles is much less than that of the proton [**], the formation of the reaction product $ABH^{\oplus}$ is not completed in the time during which the proton remains in the vicinity of the reaction center. The catalysing proton initiates the reaction, but does not complete it. Using proton-catalysed esterification as an example, it will be shown below that, in spite of the short time during which the proton remains in the reaction complex, catalysis is possible, provided certain conditions affecting the course of the reaction are fulfilled.

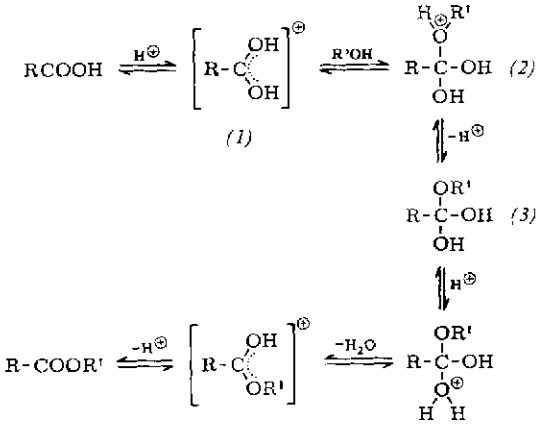
The mechanism of esterification has been investigated in detail by many workers [1]. According to these investigations, proton-catalysed esterification usually proceeds by carbonyl addition, via an intermediate which can be regarded as the monoester of the ortho-carboxylic acid. This mechanism may be symbolized as in Scheme 1. Evidence for this mechanism will not be discussed in detail here, since it is generally known [1], but instead an attempt will be made to explain the reaction from the point of view of protonic states.

Protonic states are discussed here by analogy with electronic states [2]. Protons and electrons are ele-

[*] Extract from the Ph. D. Thesis on "Protonic States in Chemistry" by *J. Rudolph*, Technische Hochschule München (Germany), 1964.

[**] Detailed discussion in Section IV.

[1] For a summary see *M. L. Bender*, Chem. Reviews *60*, 53 (1960). Cf. Textbooks on theoretical organic chemistry, *e. g. J. Hine:* Physical Organic Chemistry. McGraw-Hill, New York 1962.



Scheme 1. Mechanism of proton-catalysed esterification according to *Bender* [1].

mentary particles which are subject to wave-particle dualism and can be described by wave mechanics; they differ quantitatively but not qualitatively; thus it seemed worthwhile to apply the results obtained for electronic states qualitatively to the behavior of protons in chemical reactions.

II. Protonic Semiconductors

The reaction medium of esterification contains mobile protons derived from the carboxyl group of the acid, the hydroxyl group of the alcohol, and the catalyst. The protons occupy states of definite energy. To characterize these, it is convenient to draw up a term diagram. An energy diagram has already been used by *Gurney* [3] in his discussion of prototropic reactions. We shall extend *Gurney*'s considerations and apply them in a modified form to the protonic states of esterification. An auto-dissociating substance AH may be considered first.

$$2\,AH \rightleftharpoons A^{\ominus} + AH_2^{\oplus} \qquad (1)$$

The proton of a molecule AH occupies a state with an energy characterized by term I (Fig. 1a). The energy of the free proton p was chosen as the zero point on the energy scale (Term III, Fig. 1a). If the molecule AH is supplied with the dissociation energy D_1, the proton is

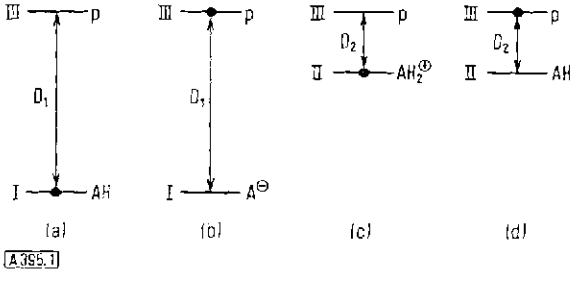


Fig. 1. Proton transitions between states in the term diagram of a molecule AH.

[2] *H. Zimmermann*, Angew. Chem. *76*, 1 (1964); Angew. Chem. internat. Edit. *3*, 157 (1964).

[3] *R. W. Gurney*: Ionic Processes in Solution. McGraw Hill, New York 1953, p. 132ff.

transferred from I to III (Fig. 1b). Chemically, this excitation of the proton corresponds to dissociation of the molecule:

$$AH \rightarrow A^{\ominus} + H^{\oplus} \qquad (2)$$

After the excitation there remains an empty term I; this should evidently be allocated to a molecule formed by removal of a proton from AH, *i.e.* the anion $A^{\ominus}$. Term I has thus two meanings: when occupied, it corresponds to the molecule AH, when empty it corresponds to the ion $A^{\ominus}$. It may be assigned therefore to a conjugate acid-base pair.

Free protons cannot exist in condensed phases. Consequently, the proton in term III formed by dissociation is either recaptured by the anion $A^{\ominus}$ or transferred to a second molecule AH.

$$AH + H^{\oplus} \rightleftharpoons AH_2^{\oplus} \qquad (3)$$

In the latter process it moves into a state II which can be assigned to the molecule $AH_2^{\oplus}$ (Fig. 1c). If we supply this molecule with energy D_2, a proton passes from II to III, with dissociation of $AH_2^{\oplus}$. The empty term II corresponds to AH, the conjugate base of $AH_2^{\oplus}$ (Fig. 1d). A proton can be more readily separated from the cation $AH_2^{\oplus}$ than from the neutral molecule AH. D_2 is therefore smaller than D_1, and term II lies above term I.

The molecule AH can react in two ways. As a proton donor, it can be assigned to the occupied term I (Fig. 1a), and as a proton acceptor, it corresponds to the empty term II (Fig. 1d). Since each molecule simultaneously possesses both acidic and basic properties, it should have both terms I and II assigned to it. The complete term diagram of a molecule is reproduced in Figure 2. The terms are characterized by the conjugate acid-base pair.

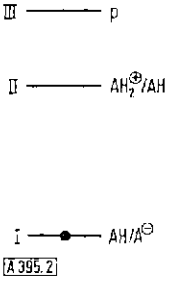


Fig. 2. Term diagram of the protonic states of a molecule AH in the ground state.

Intermolecular proton transfers between acid-base pairs can therefore be described as proton transitions between an occupied term of the donor and an unoccupied term of the acceptor. Let us consider two adjacent molecules AH with position coordinates R_1 and R_2. The term diagram of the molecule pair in the ground state is shown in Figure 3a. If the system is supplied with excitation energy, intermolecular proton transfer from I to II can occur, according to Equation (1). The result of the excitation is an ion-pair $A^{\ominus}/AH_2^{\oplus}$ with the position coordinates R_1 and R_2 (Fig. 3b). The anion $A^{\ominus}$ contains no mobile protons, and accordingly, terms I and II are empty. The cation $AH_2^{\oplus}$ possesses two mobile protons. Dissociation of the first proton (for-

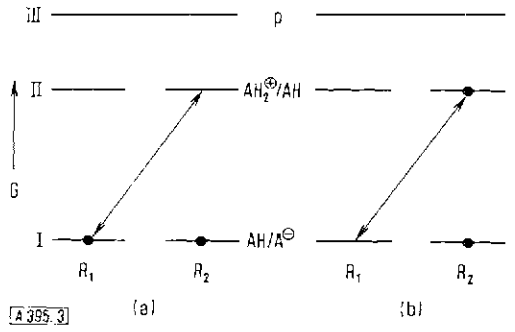


Fig. 3. Term diagram of two adjacent molecules AH. (a) Ground state; (b) ion-pair (G = free enthalpy).

mation of AH) occurs more readily than subsequent removal of the second proton (formation of $A^{\ominus}$).

In prototropic reactions it is convenient to use the free enthalpy $\Delta G = -RT\ln K$ as a measure of the energy in the term diagram in question. The energy difference between the donor term and the acceptor term is then a direct measure of the position of the reaction equilibrium.

Let us now consider a system of several AH molecules; it can be shown that such a system behaves as a protonic semiconductor. In order to understand this approach more fully the properties of electronic semiconductors will first be reviewed briefly for purposes of analogy [4].

A semiconductor is generally a solid which behaves as an insulator at low temperatures, but whose conductivity increases with rising temperature. Semiconductor properties can be understood with the aid of a band model. The semiconductor may consist of atoms, ions, or molecules. The highest doubly occupied and the lowest unoccupied electron term of a constituent unit are represented in Figure 4a. In a semiconductor, the states of different units are in mutual interaction. The terms are split into energy bands (Fig. 4b). In the

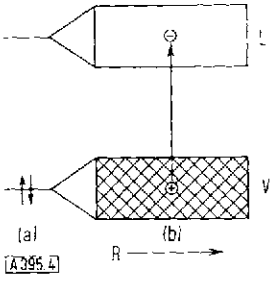


Fig. 4. Band model of an electronic semiconductor (R = position coordinate).

ground state, the band of lower energy (valence band V) is fully occupied; the band of higher energy (conductivity band L) is empty. The system behaves as an insulator, since the prerequisite for conductivity is that electrons can be accelerated in the applied external electric field, and here in the fully occupied valence band there is no room for electrons with increased energy.

If thermal energy is supplied, electrons can be raised from the valence band into the conductivity band. Both energy bands are then only partly occupied and conductivity occurs. From a purely formal standpoint, the electron transition from V to L results in the formation of a "charge pair", *i.e.* an electron in the conductivity band and a positive hole, *i.e.* a defect electron, in the valence band (Fig. 4b). Both the electron in L and the defect electron in V can migrate in an electric field, giving rise to charge transport. Since the electron transition from the valence band to the conductivity band is favored by an increase in temperature, the conductivity increases with rising temperature.

Since the individual AH molecules of a protonic semiconductor can act as both proton donors and proton acceptors, they are mutually linked by hydrogen bridges. This results in coupling of the protonic states of many molecules, although this is extremely weak compared to the interaction of electronic states. In principle, however, energy bands are also formed here, although the band width is only very small and the individual molecules largely retain their individuality. In place of the broad energy bands of electronic semiconductors, protonic semiconductors contain quasi-degenerate energy bands.

In the ground state of a protonic semiconductor, the band of lower energy (valence band V) is completely filled. Each protonic state of V is occupied by a proton. The band of higher energy (conductivity band L) is empty. The system contains only AH molecules. Like an electronic semiconductor, the protonic semiconductor is also non-conducting in the ground state, since no charge carriers exist (Fig. 5a).

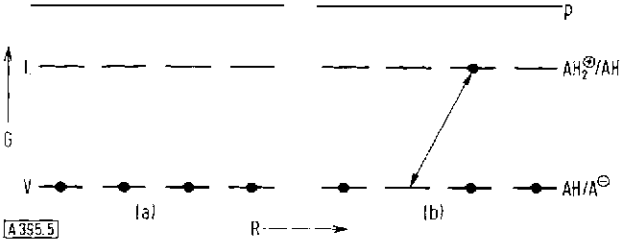


Fig. 5. Term diagram of a protonic semiconductor. (a) Ground state; (b) excited state (G = free enthalpy; R = position coordinate).

When thermal energy is supplied, intermolecular proton transfers can occur with promotion of a proton from the valence band to the conductivity band (Figure 5b). Just as for an electronic semiconductor, conductivity now occurs, since a proton in L and a negative hole, a defect proton in V, are produced (Fig. 5b). The "charge pair" formed, $AH_2^{\oplus}$ and $A^{\ominus}$, assumes the function of current transport. Since the proton transition from V to L is facilitated by heating, with the result that more charge pairs are produced, the conductivity of protonic semiconductors increases with rising temperature.

Electronic and protonic semiconductors differ in the mechanism of charge transport. In the energy bands of an electronic semiconductor, there are states which extend over the whole solid. A given electron can move throughout the entire semiconductor and so give rise to conductivity. On the other hand, the protons in a protonic semiconductor can move primarily only within hydrogen bonds between adjacent molecules. Charge

Conductivity band:

$$\cdots H\text{-}A^{\oplus}\text{-}H\cdots A\text{-}H\cdots A\text{-}H\cdots A\text{-}H\cdots \longrightarrow \cdots H\text{-}A\cdots H\text{-}A\cdots H\text{-}A\cdots H\text{-}A^{\oplus}\text{-}H\cdots$$

Valence band:

$$\cdots A^{\ominus}\cdots H\text{-}A\cdots H\text{-}A\cdots H\text{-}A\cdots \longrightarrow \cdots A\text{-}H\cdots A\text{-}H\cdots A\text{-}H\cdots A^{\ominus}\cdots$$

[4] *W. Finkelnburg:* Einführung in die Atomphysik. Springer, Berlin-Göttingen-Heidelberg 1962.

transport over long distances is not effected by one single proton, but by mutual cooperation of many protons. The mechanism of charge transport in the conductivity and valence bands is represented below for the sake of completeness.

The charge can be rapidly transported in the energy bands (with the enthalpy of reaction $\Delta G = 0$); it is delocalized over the entire semiconductor.

The proton transitions in the hydrogen bridges take place between conjugate acid-base pairs:

$$\cdots H-A^{\oplus}-H\cdots A-H\cdots \overset{p}{\leftrightarrow} \cdots H-A\cdots H-A^{\oplus}-H\cdots$$

$$\cdots A^{\ominus}\cdots H-A\cdots \overset{p}{\leftrightarrow} \cdots A-H\cdots A^{\ominus}$$

During this transition, the protons move in potential fields with symmetrical double minima. Their presence is equally possible in both potential troughs, and consequently they oscillate across the hydrogen bridges. Rapid transposition of the protons in bridge bonds with double minima has been detected experimentally in favorable cases [5–7].

The transposition of protons in a hydrogen bond with a symmetrical double minimum can take place in two ways: *via* proton jumps or *via* a tunnel effect. The tunnel effect depends on the height and width of the potential wall between the two troughs. The potential field in which the proton moves within the bridge bond can be estimated. It can be shown that, unless the hydrogen bridges present are very weak, the tunnel effect should occur very often. Protonic states are then formed which extend over the region of both potential troughs and in which the protons are delocalized. In the wave mechanical picture, the two protonic states ψ can be described by protomerism between the limiting states of the bridge bond [2].

$$\psi = (1/\sqrt{2})[\psi(H-A^{\oplus}-H\cdots A-H)] \pm [\psi(H-A\cdots H-A^{\oplus}-H)]$$

$$\psi = (1/\sqrt{2})[\psi(A^{\ominus}\cdots H-A)] \pm [\psi(A-H\cdots A^{\ominus})]$$

The interaction of protomeric limiting states is slight. The energy difference ΔE between symmetrical and asymmetrical linear combinations is therefore small, and the band width in protonic semiconductors can be neglected.

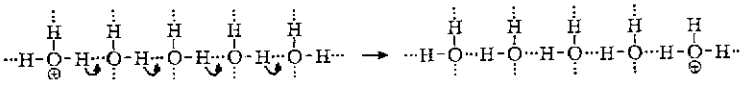
From the corpuscular approach protomerism corresponds to the oscillation of a proton between the two potential troughs of the bridge bond. The average life-time τ of the proton in one of the potential minima [8] and hence the life-time of the ions $AH_2^{\oplus}$ and $A^{\ominus}$ is very short:

$$\tau = 1/2c\Delta E$$

where c = velocity of light; ΔE = term splitting [cm^{-1}].

For very strong hydrogen bridges of the type $H-A^{\oplus}-H\cdots A-H$, term-splitting may be assumed to be at least 1 cm^{-1}. This corresponds to an average life-time of less than 10^{-11} sec. It therefore follows, for example, that an acid-catalysed reaction between co-reactants AH and B must be initiated during the very short time while the catalysing protons are in the vicinity of AH, *i.e.* during the life of the species $AH_2^{\oplus}$.

However, the mechanism of proton transport is not fully described by the foregoing discussion. Let us examine briefly the conditions in ice. *Eigen* and *DeMaeyer* [9] have shown that ice is a protonic semiconductor. The crystal consists of a three-dimensional network of water molecules linked together by hydrogen bridges. Ice exhibits conductivity towards direct current. The charge carriers may be assumed to be $OH_3^{\oplus}$ and $OH^{\ominus}$ ions formed by dissociation of the water. Charge can be transported through the crystal in the normal manner by proton jumps in hydrogen bridges in an electrical field [*(4)* → *(5)*].



(4) *(5)*

Conductivity for direct current requires that charge transport should always be possible in the same direction. However, after a single passage of charge, the chain of water molecules is in a condition *(5)* unsuitable for further transport of charge. To explain conductivity for direct current, therefore, it must be assumed that a state which makes the chain suitable for renewed proton-passage will be brought about by rotation of water molecules in the crystal.

By combination of proton jumps in hydrogen bridges and reorientations of water molecules, a proton can migrate as an individual through the entire ice crystal. This mechanism for proton transport may be generally valid for protonic semiconductors.

According to investigations by *Eigen*, *DeMaeyer*, and *Spatz* [9–11], the rate-determining step of the conductivity in ice is the proton transition in hydrogen bonds. Here proton transfer follows a "non-classical" mechanism, probably involving a tunnel effect. The mobility of the proton is only one or two orders of magnitude less than that of electrons in metals [9–11].

Semiconductors are generally solids. However, it is not absolutely essential to restrict the concept in this sense. We shall therefore apply the term semiconductor generally to any system which, independently of the state of aggregation and nature of the charge carrier, possesses a conductivity which is zero at very low temperatures and increases with rising temperature. It is thus possible to include liquid systems.

[5] *H. Zimmermann*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *65*, 821 (1961).

[6] *N. Joop* and *H. Zimmermann*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *66*, 440 (1962).

[7] *N. Joop* and *H. Zimmermann*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *66*, 541 (1962).

[8] *G. Herzberg*: Molecular Spectra and Molecular Structure II, Infrared and Raman Spectra of Polyatomic Molecules. Van Nostrand, New York 1962, p. 222.

[9] *M. Eigen* and *L. DeMaeyer*, Proc. Roy. Soc. (London), Ser. A *247*, 505 (1958).

[10] *M. Eigen*, Angew. Chem. *75*, 489 (1963); Angew. Chem. internat. Edit. *3*, 1 (1964).

[11] *M. Eigen*, *L. DeMaeyer*, and *H.-Ch. Spatz*, Ber. Bunsenges. physik. Chem. *68*, 19 (1964).

III. Protonic States in Carboxylic Acid/Alcohol Systems

Nuclear magnetic resonance measurements on carboxylic acid/alcohol systems have shown that the protons of the carboxyl and hydroxyl groups are mobile. Instead of two separate signals for the carboxyl and hydroxyl groups, one common signal is always observed. Thus the protons cannot be distinguished in nuclear magnetic resonance experiments, a fact which indicates rapid proton exchange.

The chemical shift of the signal is generally a monotonic function of the mole-fraction. By way of example, the findings for the acetic acid/ethanol system are reproduced in Figure 6; an approximately linear function is obtained. This shows that the proton exchange must extend over a range so large that it encompasses the

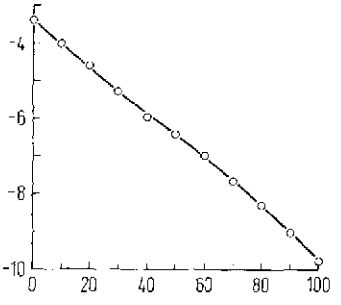


Fig. 6. Concentration dependence of the chemical shift of the OH signal in the NMR spectrum of the acetic acid/ethanol system.
Standard: CH_3 signal of acetic acid
Ordinate: Chemical shift δ[ppm].
Abscissa: Concentration of acetic acid [mole-%].

carboxylic acid and the alcohol in a ratio which corresponds to the "macromolecular" mole-fraction of the overall system. The protons can thus migrate over large distances and enter randomly into interaction with various molecules. A single signal with an average chemical shift is then observed in the NMR spectrum.

The kinetics of proton exchange in alcohols and alcohol/carboxylic acid mixtures have been investigated by other authors [12, 13]. In agreement with our views, the protons are exchanged *via* the ions present in the system.

As explained above, proton migration is possible over large distances in protonic semiconductors. It can be shown that carboxylic acid/alcohol systems also possess semiconductor properties. This explains the proton mobility shown by the NMR experiments.

The conductivity of the acetic acid/ethanol system was measured by *Drutman* [14] (Fig. 7); it depends on the mole-fraction and on the temperature. At a given mole-fraction, it always increases with rising temperature. Extrapolation to absolute zero gives extremely low values for the conductivity. The system thus behaves as a semiconductor.

[12] *E. Grunwald, C. F. Jumper,* and *S. Meiboom,* J. Amer. chem. Soc. *84,* 4664 (1962).

[13] *E. Grunwald* and *C. F. Jumper,* J. Amer. chem. Soc. *85,* 2051 (1963).

[14] *S. S. Drutman,* Zhur. Obshch. Khim. *25,* 30 (1955).

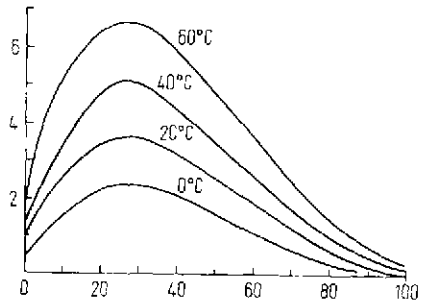


Fig. 7. Concentration dependence of conductivity in the acetic acid/ethanol system at various temperatures [14].
Ordinate: Conductivity $\varkappa \cdot 10^6$ [ohm^{-1} cm^{-1}].
Abscissa: Concentration of acetic acid [mole-%].

The semiconductor term diagram of the acetic acid/ethanol system is shown in Figure 8. It was derived from the normal affinities of the prototropic reactions:

$$2\,C_2H_5OH \rightleftharpoons C_2H_5O^{\ominus} + C_2H_5OH_2^{\oplus} \qquad \Delta G_{25\,°C} = 29.6\ \text{kcal/mole}$$

$$2\,CH_3COOH \rightleftharpoons CH_3COO^{\ominus} + CH_3C(OH)_2^{\oplus} \qquad \Delta G_{25\,°C} = 20.5\ \text{kcal/mole}$$

$$CH_3COOH + C_2H_5OH \rightleftharpoons CH_3COO^{\ominus} + C_2H_5OH_2^{\oplus} \qquad \Delta G_{25\,°C} = 15.8\ \text{kcal/mole}$$

The free enthalpies ΔG were calculated from the known equilibrium constants for dissociation and autoprotolysis, taking the molarity into account [15–17]. The energy of the conductivity band of water (system

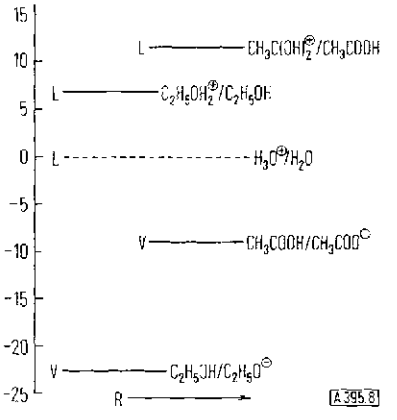


Fig. 8. Term diagram of the protonic semiconductor acetic acid/ethanol.
Ordinate: Free enthalpy G [kcal/mole].

$OH_3^{\oplus}/OH_2$) was arbitrarily chosen as the zero point of the term diagram. The position of the term can be established [17] by the reaction:

$$CH_3COOH + H_2O \rightleftharpoons CH_3COO^{\ominus} + OH_3^{\oplus} \qquad \Delta G_{25\,°C} = 8.9\ \text{kcal/mole}$$

In acetic acid/ethanol mixtures, the above free enthalpies of the prototropic reactions are only approximately valid, owing to solvation. However, solvation occurs in all systems predominantly *via* hydrogen bridges. Since the bond energies of bridge bonds differ only slightly from one another, the molecules and ions should possess similar solvation energies in different media. The position of the terms then depends only

[15] *S. Kilpi* and *M. Puranen,* Ann. Acad. Sci. fennicae, Ser. A *57,* Nr. 10, 3 (1941).

[16] *G. Brière* and *N. Félici,* C. R. hebd. Séances Acad. Sci. *251,* 1004 (1960).

[17] *E. Grunwald* and *B. J. Berkowitz,* J. Amer. chem. Soc. *73,* 4939 (1951).

slightly on the ratio of acid to alcohol in the mixture. It is therefore sufficient in a qualitative discussion to consider terms of constant energy.

At very low temperatures the valence bands of the acetic acid and of the ethanol are fully occupied. The system then exhibits no conductivity. At higher temperatures, protons pass from V to L to form charge pairs, and conductivity occurs. Dissociation of either acetic acid or ethanol alone requires more energy than dissociation of the acid in alcoholic solution (see ΔG values). In acetic acid/ethanol mixtures, therefore, more charge pairs are formed than in the pure components, and it is plausible that the conductivity – as a function of the mole-fraction – passes through a maximum (Fig. 7). However, detailed discussion of the position of the maximum is possible only if the mobilities of the protons in the energy bands are known. Knowledge of the temperature dependence of the mobility would also be necessary to explain completely the temperature dependence, and hence the activation energy, of the conductivity.

In the esterification of carboxylic acids with alcohols, mineral acids are added as catalysts. Since strong acids are practically completely dissociated in water, the valence band of the acid lies above the conductivity band of water, and hence certainly in the vicinity of the conductivity band of alcohol. It is therefore easy for this conductivity band to become occupied. In the absence of a catalyst, appreciable occupation of the term is not possible owing to the high excitation energy of this state. The conductivity bands of acetic acid and ethanol lie energetically close together (see Fig. 8). Proton transfer between the two bands is therefore readily possible. In chemical notation it corresponds to the reaction:

$$C_2H_5OH_2^{\oplus} + CH_3COOH \rightleftharpoons C_2H_5OH + CH_3C(OH)_2^{\oplus}$$
$$\Delta G_{25\,^{\circ}C} \approx 5 \text{ kcal/mole}$$

If the conductivity band of the alcohol becomes appreciably occupied owing to the presence of the catalysing mineral acid, $CH_3C(OH)_2^{\oplus}$ ions can be formed in large numbers. It is generally assumed that these ions are of vital importance to the course of esterification. However, it must be realized that the $CH_3C(OH)_2^{\oplus}$ ion corresponds to a proton in the conductivity band of the acetic acid. The proton can pass through the system very rapidly, and the ion is consequently very short-lived. The charge is delocalized, and the ion simply represents one of the possible protomeric limiting forms.

In concluding this section, further discussion of the reaction medium in which the esterification takes place seems appropriate: in the solution, the heavy molecules form a three-dimensional lattice held together by hydrogen bridges. The protons oscillate rapidly in the bridge bonds. Moreover, the bridge bonds are continuously being reoriented. It is therefore possible for the protons to move between the molecular skeletons throughout the entire lattice. Whereas the heavy molecules change their positions only relatively slowly, a swarm of rapidly moving protons streams between the molecules. The protons thus behave like electrons in metals, and one is tempted to formulate a "proton gas" in analogy to the electron gas.

IV. Short-Range Structure and Franck-Condon Principle in Proton-Catalysed Reactions

According to the conventional views on the mechanism of proton-catalysed esterification [1], the intermediate *(2)* is formed by addition of an alcohol molecule onto the protonated carboxylic acid *(1)*.

As shown in Section III, the cation $RC(OH)_2^{\oplus}$ is only very short-lived, owing to the mobility of the protons in the conductivity band of the carboxylic acid. For a reaction to occur, therefore, the alcohol and acid molecules must be present in the reaction medium in such a steric arrangement that the reaction can be initiated immediately after addition of the catalysing proton onto the carboxyl group. The short-range structure of the molecules is therefore particularly important for the occurrence of the reaction.

During the very short time within which the catalysing proton is in the reaction complex the reaction must overcome the activation barrier. It is now generally assumed that the protonated form of the carboxylic acid *(1)* is sufficiently long-lived to permit reaction with the alcohol molecule to give the intermediate *(2)*. The monoester of the orthoacid *(3)* is finally formed by elimination of a proton from *(2)*.

However, it is difficult to imagine how the reaction proceeds in the manner described. During the very short life-time of $RC(OH)_2^{\oplus}$ it would be necessary not only for the heavy, inert carboxylic acid and alcohol molecules to approach to within bonding distance of each other, but also for the bonds to be formed with a change in the hybridization of the carboxyl carbon atom, *i.e.* again with rearrangement of heavy groups of atoms [*]. These difficulties can be avoided if it is assumed that, simultaneously with the separation of the catalysing proton from the reaction complex, the activation barrier of the reaction is overcome. The reaction has then progressed so far, even with extremely short residence times of the catalysing proton, that it proceeds of its own accord to form the end product after separation of the proton. The mechanism of esterification will be discussed below in more detail. In this context, the problem of short-range structure shall be considered first.

The short-range order in liquids is due to secondary valence forces acting between the molecules. In the esterification medium, the secondary valence forces to

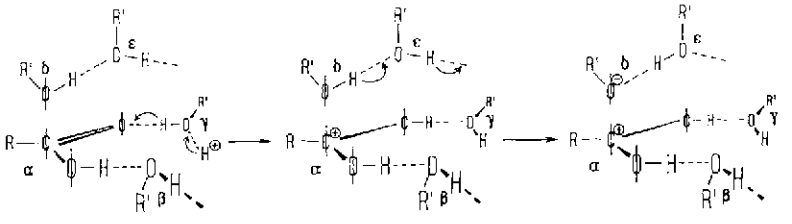
[*] These considerations can be taken even further. It is known from infrared spectroscopic investigations that the life of an $OH_3^{\oplus}$ ion in aqueous solutions is about 10^{-13} sec [18, 19]; it may be assumed that the life of $R'OH_2^{\oplus}$ or $RC(OH)_2^{\oplus}$ is not appreciably longer, since the ions correspond to protons in the conductivity bands of water, the alcohol, or the carboxylic acid ($\tau < 10^{-11}$ sec). From photochemical reactions it follows that higher excited singlet states with a life of 10^{-11} to 10^{-12} sec are generally incapable of reacting with heavy molecules. Such reactions are possible only for the lowest excited singlet or triplet state with lives of about 10^{-3} or 10^{-8} sec, respectively. It is likely, therefore, that the life of $RC(OH)_2^{\oplus}$ is too short to undergo a reaction with R'OH with formation of *(2)* under these conditions.

[18] *Th. Ackermann*, Z. physik. Chem. NF *27*, 253 (1961).

[19] *M. Eigen* and *L. DeMaeyer*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *60*, 1073 (1956); *61*, 856 (1957).

be considered are hydrogen bridges and electrostatic interactions between molecules.

For the sake of simplicity, let us examine a carboxylic acid molecule in a dilute alcoholic acid solution. The carboxyl group can act both as a proton donor and as a proton acceptor. Accordingly, the acid molecule is linked to two alcohol molecules by hydrogen bridges. The charge distribution of the carboxyl group of an acid molecule was calculated by the simple Hückel LCAO-MO procedure (see Fig. 13). The parameters on which the calculation is based are presented in SectionV. The partial charges on the oxygen atoms of the carboxyl group are involved in hydrogen bonding. The remaining partial charge on the carbon must be compensated by the lone-pair of electrons from another alcohol molecule. For steric reasons it can be assumed that the oxygen atom of this third alcohol molecule is situated above the positive carbon atom of the carboxyl group. The arrangement of molecules within the immediate vicinity of a carboxylic acid molecule in the reaction medium is shown schematically in Figure 9a [**].



(a) (b) (c)

Fig. 9. Short-range structure about an acetic acid molecule in dilute alcoholic acid solution (a). Formation of the ion $RC(OH)_2^{\oplus}$ (b) and of the ion pair $RC(OH)_2^{\oplus}/R'O^{\ominus}$ (c) by proton transfers in hydrogen bridges.

The conductivity band L of the alcohol is partially occupied by the catalysing mineral acid. As already mentioned, a proton can be transferred easily from L to an acid molecule. This results in the formation of the ion $RC(OH)_2^{\oplus}$ which is solvated by alcohol molecules (Fig. 9b). This complex will rapidly release a proton again into the conductivity band of the alcohol, owing to charge delocalization. Three routes are possible:

1. A proton is transferred from molecule α to molecule γ by reversal of the formation of $RC(OH)_2^{\oplus}$, the initial state in the reaction medium being restored.

2. A proton is transferred from molecule α to molecule β. The resulting atomic arrangement is the mirror image of the original state. Carbonyl and hydroxyl groups are interchanged. However, the original and final states are physically equivalent.

3. A proton is transferred from molecule δ to ε with formation of the ion pair $RC(OH)_2^{\oplus}/R'O^{\ominus}$ (Fig. 9c).

It is immediately noticeable that proton transfers according to Routes (1) and (2) make no contribution to esterification. On the other hand, the ion-pair formation by Route (3) is of interest. Let us first examine the energy relationships in the reaction medium with the aid of a term diagram. Figure 10 shows the protonic

[**] The various molecules are designated by Greek letters. The axes of the p-functions are also shown in the diagram.

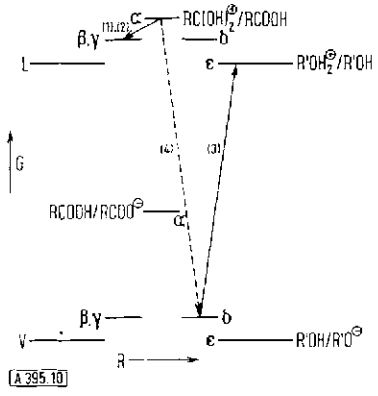


Fig. 10. Term diagram of protonic states in the reaction complex during formation of the intermediate (3) from carboxylic acid and alcohol (G = free enthalpy; R = position coordinate).

states of the ion $RC(OH)_2^{\oplus}$ and of the alcohol molecules surrounding it. Owing to the polarizing action of the cation, it must be expected that the alcohol molecules β, γ, and δ of the first solvation shell are better proton donors and poorer proton acceptors than molecules which remain at a greater distance from the cation, such as molecule ε. Consequently, the donor and acceptor terms of the molecules of the first solvation shell will be raised, as illustrated diagrammatically in Figure 10. As can be seen from Figure 10, proton transfers by Routes (1) and (2) are energetically easy, but ion-pair formation by Route (3) can occur only when energy is supplied.

The donor term of the alcohol molecule δ is raised with respect to that of molecule ε. Proton transfer by Route (3) is then facilitated compared to dissociation of the pure alcohol. Since alcohol is already appreciably dissociated under normal conditions, elimination of a proton from molecule δ by Route (3) at a higher temperature, *i.e.* under esterification conditions, will certainly be possible. Ion pairs $RC(OH)_2^{\oplus}/R'O^{\ominus}$ can thus be formed occasionally in the reaction medium. This only requires proton transfer in hydrogen bridges.

The ion pairs are stabilized on account of the electrostatic interaction. They are of high energy and are therefore metastable in the reaction medium. Deactivation by direct proton transfer from $RC(OH)_2^{\oplus}$ to $R'O^{\ominus}$ is not possible [Fig. 10, Route (4)], since there is no hydrogen bridge between the molecules α and δ (see Fig. 9). However, a lower energy state can be reached by electronic interaction, *i.e.* if the ions become linked by a covalent bond. The ion pair can then undergo deactivation by direct transformation into the esterification intermediate (Fig. 11). As will be shown in the following section, electronic interaction is possible. The bond is

formed without necessitating any great activation energy. The ion pair becomes stabilized spontaneously with formation of the esterification intermediate *(3)*.

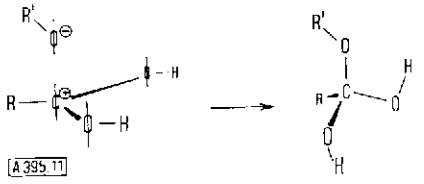


Fig. 11. Formation of the esterification intermediate *(3)* from the ion pair

The reaction course following from the above conclusions corresponds to the one described in Scheme 1. Initial addition of a proton onto the carboxyl group of the acid is immediately followed by elimination of a proton from the alcohol molecule δ of the solvation shell with formation of an ion pair. This reaction step involves participation of a catalysing proton in the reaction complex and is extremely fast. Energy must be supplied for the separation of the proton by Route (3) (see Figs. 9 and 10). The activation energy barrier of the reaction is reached and the transition state can be approximately described by the ion pair $RC(OH)_2^{\oplus}/R'O^{\ominus}$. Deactivation now takes place in a slower reaction step, and the esterification intermediate is formed in the absence of the catalysing proton. The heavy molecules thus have sufficient time to move into their new equilibrium positions.

The ion pair is therefore formed only by rapid proton transfers in hydrogen bridges. The transition state is thereby reached without appreciable change in the position coordinates of the molecules. Thus, the arrangement of the atoms in the transition state of a proton-catalysed reaction is given approximately by the short-range structure in the reaction medium.

A similar situation is encountered in the excitation of electronic states in molecules. The electron distribution in a molecule can be very rapidly changed by absorption of light. According to the Franck-Condon principle, the atoms, which are comparatively heavy, do not have sufficient time at the instant of excitation by light to change their positions. The equilibrium position of the atoms corresponding to the new electronic state is therefore only reached by a subsequent slower reaction step.

The Franck-Condon principle can be applied directly to proton-catalysed reactions. Proton transfers across hydrogen bridges can result in such a rapid change in proton distribution in the reaction complex that the heavy molecules do not have time to take up their new equilibrium positions. An atomic arrangement compatible with the new proton distribution is only reached in a subsequent slower step with formation of the reaction product. Thus, even in chemical reactions, we observe an analogy in the behavior of electrons and protons.

V. Interactions between Electronic States of the Coreactants

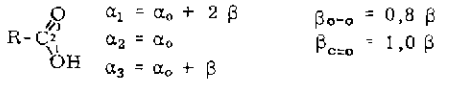
We concluded from the protonic states in the carboxylic acid/alcohol system that the esterification intermediate is formed by interaction of the ion pair $RC(OH)_2^{\oplus}/R'O^{\ominus}$. We shall now show, by consideration of the pertinent electronic states, that the interaction in this ion pair is much greater than that in the molecule pairs RCOOH/R'OH or $RC(OH_2)^{\oplus}/R'OH$, so that the reaction proceeds practically exclusively *via* the ion pair.

The vital step leading to the esterification intermediate is the formation of a σ-bond between the oxygen atom of the alcohol and the carbon atom of the carboxyl group of the acid. The carbon atom changes from trigonal to tetrahedral hybridization. The carboxyl group offers resistance to the change in hybridization, since the resonance energy of its π-electron system must be overcome. However, the energy balance is compensated by the newly formed σ-bond.

Formation of the σ-bond is initiated by mutual approach of the co-reactants. The π-electron system of the carboxyl group of the acid and the lone pair of electrons on the oxygen atom of the alcohol then mutually overlap. Interaction of the electronic states produces the energy ΔE, which can be used to break down the π-electron system, and so make it possible for change of hybridization and formation of a σ-bond to occur. It is likely that the reaction proceeds more readily as the energy gain ΔE resulting from the mutual approach of the co-reactants increases. ΔE has been evaluated for a few simple cases by the Hückel LCAO-MO method [*].

[*] The eigenfunctions were formed in the usual manner by linear combination of orthogonally normalized atomic eigenfunctions. The Coulomb and resonance integrals, α and β, were based on the following values [20]:

For



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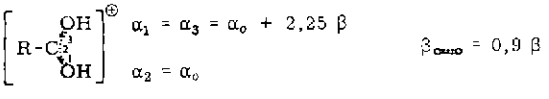
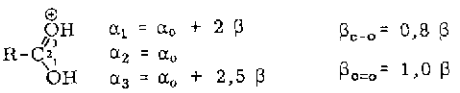


α_1, α_3, and $\beta_{C\ O}$ were assumed in the calculation to be mean values of the corresponding Coulomb and resonance integrals of a limiting structure of the protonated carboxyl group. For



The lone pair of electrons on the oxygen atom of the alcohol molecule (cf. Fig. 9) was approximated by a p-function. The Coulomb integrals of the oxygen atom are

for R'OH $\alpha = \alpha_0 + 2\beta$

for $R'O^{\ominus}$ $\alpha' = \alpha_0 + 0{,}5\beta$

The Coulomb integral α' was estimated by the ω-rule [21]:

$$\alpha' = \alpha + \xi\,\omega\,\beta$$

α corresponds to the Coulomb integrals of the oxygen atom in the absence of an excess charge ($\alpha = \alpha_0 + 2\beta$); ξ represents the excess charge at the oxygen atom, ($\xi = -1$); ω is a constant factor with a value of 1.5; thus, α' is found to be $\alpha' = \alpha_0 + 2\beta - 1.5\beta = \alpha_0 + 0.5\beta$.

The resonance integral γ between the oxygen atom of the alcohol molecule δ and the carbon atom of the carboxyl group of the acid was varied between $\gamma = 0$ and $\gamma = \beta$ in order to account for the increase in interaction as the co-reactants approach each other.

[20] *A. Streitwieser jr.*: Molecular Orbital Theory. Wiley, New York-London 1961, p. 135.

[21] *A. Streitwieser jr.*, [20], p. 115.

The gain in energy ΔE when the co-reactants approach each other is represented in Figure 12 as a function of the intermolecular interaction integral γ.

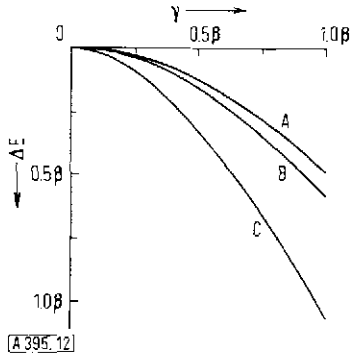


Fig. 12. Increase in the energy of interaction ΔE on mutual approach of co-reactants RCOOH/R'OH (A), $RC(OH)_2^{\oplus}/R'OH$ (B), and $RC(OH)_2^{\oplus}/R'O^{\ominus}$ (C).
Abscissa: resonance integral γ between co-reactants.

The interactions between

A. RCOOH and R'OH
B. $RC(OH)_2^{\oplus}$ and R'OH
C. $RC(OH)_2^{\oplus}$ and $R'O^{\ominus}$

were investigated.

The interaction energy in the ion pair $RC(OH)_2^{\oplus}/R'O^{\ominus}$ is about twice as great for all values of γ as that in the molecule pairs RCOOH/R'OH and $RC(OH)_2^{\oplus}/R'OH$. On the other hand, the interaction energies of RCOOH/R'OH and $RC(OH)_2^{\oplus}/R'OH$ differ only slightly. Since experience has shown that no reaction occurs between RCOOH and R'OH, it does not appear plausible that the slight increase in the energy of interaction between $RC(OH)_2^{\oplus}$ and R'OH should be responsible for bringing about the reaction. It is more likely that the increased interaction in the ion pair $RC(OH)_2^{\oplus}/R'O^{\ominus}$ makes the reaction possible.

The interaction energy also serves in part to compensate for the electrostatic repulsion between the reactants. Charge distributions and π-bond orders of the molecules RCOOH and $RC(OH)_2^{\oplus}$ are shown in Figure 13. The electrostatic interaction is determined primarily by the charges on the carbon

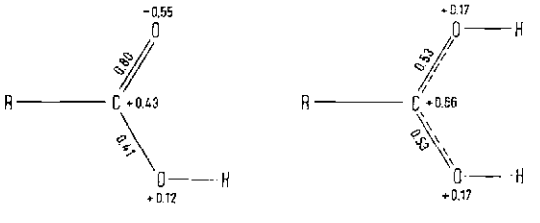


Fig. 13. Charge distribution and π-bond orders in the RCOOH molecule and in the $RC(OH)_2^{\oplus}$ ion.

atom of the carboxyl group and on the oxygen atom of the alcohol molecule δ. The charge on the carbon atom of the $RC(OH)_2^{\oplus}$ ion is rather higher than that in RCOOH; consequently, the electrostatic repulsion of the alcohol molecule is reduced. However, an appreciable greater reduction of the repulsive forces is to be expected in the ion pair $RC(OH)_2^{\oplus}/R'O^{\ominus}$, since in this case the oxygen atom of the alcohol molecule carries an excess negative charge. Thus, in the ion pair, the reactants can come together more closely, and the interaction energy ΔE increases correspondingly.

According to our conclusions, therefore, the reaction conditions in the ion pair $RC(OH)_2^{\oplus}/R'O^{\ominus}$ are much more favorable than those in other molecule pairs. Consequently, it appeared reasonable to assume that, during esterification, the intermediate *(3)* is in fact formed *via* the ion pair. The ions can only be formed if energy is supplied. On the other hand, reaction of the ion pair to form the intermediate has a comparatively low activation energy. The transition state in the formation of the intermediate *(3)* from $RC(OH)_2^{\oplus}$ and R'OH is then – as mentioned above – approximately described by the ion pair.

For the ion pair $RC(OH)_2^{\oplus}/R'O^{\ominus}$ to be formed, a proton must be given up by the alcohol molecule δ of the solvation shell around the cation $RC(OH)_2^{\oplus}$ to the conductivity band L of the alcohol. The ability of the ion pair to exist depends essentially on the fact that this proton in the conductivity band of the semiconductor can be removed very rapidly. If this were not possible, the ion pair could be immediately deactivated by proton capture, and the formation of the intermediate would be inhibited. Moreover, the intermediate itself would also be sensitive to acid and would decompose on addition of a proton. This could lead to either the original acid and alcohol or to the end products, namely ester and water.

Decomposition of the solvated intermediate *(3)* into ester and water is represented in Figure 14. According to the Franck-Condon principle for proton-catalysed reactions, the energy-rich transition state *(6)* is reached

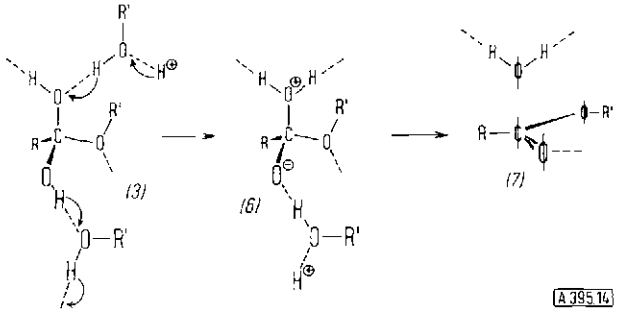


Fig. 14. Proton-catalysed decomposition of the intermediate *(3)* during esterification.

by a rapid change in proton distribution in the reaction medium. The final product *(7)* is formed in a subsequent slower reaction step, with rearrangement of the heavy groups of atoms. The formation of the π-electron system favors this step.

On formation of the intermediate *(3)*, the energy-rich ion pair $RC(OH)_2^{\oplus}/R'O^{\ominus}$ is converted into a neutral molecule with equalization of charge. On decomposition of the intermediate, the zwitterion *(6)* is converted into the neutral molecule pair, again with equalization of charge. In both reaction steps the polar transition state is reached by rapid proton jumps in hydrogen bridges. The subsequent deactivation of the transition state is reserved for a slower later step involving rearrangement of heavy groups of atoms.

According to our considerations, the reaction proceeds *via* a polar transition state; this also readily explains the

increase in the rate of reaction with increasing dielectric constant of the solvent found in the acid-catalysed hydrolysis of esters [1,22].

VI. Concluding Remarks

Discussion of the importance of the mobility of protons in the course of chemical reactions has been attempted in this paper, using acid-catalysed esterification as an example. Conditions are considered which are significant, not only in esterification, but in proton-catalysed reactions generally. Our observations are necessarily incomplete and have the character of an approximation. However, we believe that the great importance of protons in chemistry justifies our attempted interpretation.

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Translated by Express Translation Service, London

[22] *K. J. Laidler* and *P. A. Landskroener*, Trans. Faraday Soc. 52, 200 (1956).

Eliminations from Olefins

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Eliminations from olefins are very often initiated by bases, and usually lead to formation of acetylene derivatives. In view of the numerous side-reactions and subsequent additions or rearrangements observed, the nature of the base used is of considerable significance. Organometallic bases are very versatile. In addition to dehydrohalogenation, dehalogenation by metals, and also thermolytic and photolytic eliminations (e.g. the retrodiene reaction with exchange of substituents) are discussed. Elimination from low-membered cyclic olefins yields cycloalkynes having strained ring-systems, and the existence of these can be demonstrated by trapping them. The mechanisms known for β-elimination (E2, E1 and E1cB) occur also in the case of olefins; however – due to the sp^2-hybridization of the carbon atoms taking part – they are realized with different rates of reaction relative to saturated compounds. α-Eliminations from olefines having aryl residues in the β-position lead to formation of arylacetylenes by rearrangement of the carbon skeleton. The mechanism of this reaction, which is known as the Fritsch-Buttenberg-Wiechell rearrangement, is discussed in considerable detail, and several variations of the reaction are considered. According to present-day knowledge carbenes are involved in α-eliminations only when both β-positions of the olefin are occupied by aliphatic substituents, or when they are occupied by aromatic residues where rearrangement to acetylenes is impossible for steric reasons (as for example with 9-chloromethylenefluorene). With organolithium compounds a number of dehydrohalogenations, which are formally β-eliminations, actually proceed via deprotonation on the halogen-bearing carbon atom (α-metallation). α-Metallations are the rate-determining steps when ether is used as solvent, but proceed quickly in tetrahydrofuran even at low temperatures. Compounds of the type >C=C(Li)Cl may be prepared by this method and are recognized as intermediates in α-eliminations.

I. Introduction

Eliminations from olefins generally yield acetylenes, and constitute the most important method of synthesizing this class of substances. Reactions of this type have been known for over a hundred years and have since been the subject of many investigations. A number of reviews have been published fairly recently, in which some of the results from this field are collected, particularly from the viewpoint of the preparation and properties of acetylenes [1–4]. The aim of the present article is to survey the methods of carrying out elimination reactions of olefinic derivatives, for these have been greatly extended within recent years, and to describe present-day knowledge of the reaction mechanisms concerned with emphasis on base-initiated reactions.

[1] *T. L. Jacobs*, Org. Reactions 5, 1 (1949).
[2] *F. Bohlmann*, Angew. Chem. 69, 82 (1957).
[3] *W. Franke*, *W. Ziegenbein*, and *H. Meister*, Angew. Chem. 72, 391 (1960).
[4] *J. F. Arens* in: Advances in Organic Chemistry. Interscience Publishers, New York 1960, Vol. II, p. 121.

II. Classification of Elimination Reactions

The methods for eliminating substituents from olefinic hydrocarbons may be divided into two major groups: the first involves elimination using bases or metals, and includes dehydrobalogenation as its most important type. The second includes endothermic eliminations, *e.g.* retrodiene reactions. In this paper which naturally cannot review the entire literature, β-eliminations will be discussed first. In these reactions, residues X and Y are eliminated from different carbon atoms, in accordance with Equation (a). α-Eliminations are initi-

$$X-\overset{|}{C}=\underset{|}{C}-Y \rightarrow -C\equiv C- + X + Y \qquad (a)$$

ated by the same methods, X and Y being situated on the same carbon atom; such eliminations are dealt with in Section IIIc.

In the whole of this review, the prefixes "α" and "β" are used to designate olefinic carbon atoms in accordance with normal usage in the literature. This usage is different when applied to designate reaction mechanisms than when applied to characterize compounds. Thus, the α-carbon atom in styrenes is the one bearing the phenyl group, while in acrylic acids (including cinnamic acids!) it is the one adjacent to the carboxyl group. From the point of view of reaction mechanisms, the α-carbon atom is the one from which a cation (especially a proton) is liberated; the anion which is simultaneously released can then be removed from the adjacent (*i.e.* "β"-) carbon atom ("β-elimination") or from the same (*i.e.* "α"-) carbon atom ("α-elimination").

A. Elimination of Hydrogen and a Group Containing a Hetero-Atom

Many reactions involve removal of a proton [Equation (a), Y = H] and either a hetero-atom (*e.g.* halogen) or a group containing a hetero-atom from an olefin by the action of a base. Since the nature of the base is of vital importance, this section will be divided according to the bases used.

1. Elimination by Oxygen Bases

The reaction of halogenated olefins with oxygen bases such as alkali metal hydroxides or alkoxides provides a general method of preparing acetylenes. The first substituted acetylene, *viz.* methylacetylene, was prepared by this method from bromopropene [5]. Dihalogenoalkanes are more readily available and hence are more frequently used in preparative work, but here halogenoethylenes occur as intermediates. Following further investigations [6,7], *Glaser* applied the method to halogenostyrenes and cinnamic acids [8]. Ethanolic KOH was found to be particularly suitable for the elimination of hydrogen halide [see Equation (b)] and led *inter alia*, to the smooth conversion of β-chlorostyrene or β-bromostyrene into phenylacetylene [8,9] and of *cis*- or *trans*-chlorostilbenes [10,11] and bromostilbenes [12] into diphenylacetylene (tolane). Vinyl bromide [13] and its alkyl homologues [14] react with sodium ethoxide on a boiling water bath to give the

$$H_5C_6-CH=C(R)X \xrightarrow[120-140\,^\circ C]{KOH/C_2H_5OH} H_5C_6-C\equiv C-R \qquad (b)$$
$$R = H,\ C_6H_5$$

corresponding alkynes; the yields decrease with increasing chain length. Monohalogenoacetylenes can also be prepared in this way, *e.g.* bromo- or chlorophenylacetylenes from α,β- or β,β-dibromo- or dichlorostyrene [9] and chloroacetylene from 1,2-dichloroethylene; in the latter reaction, the *cis*-isomer reacts about 20 times faster than the *trans*-form [15].

The interesting dihalogenoacetylenes cannot be prepared with alkalis in this manner. When heated with alcoholic potassium hydroxide trichloroethylene does not yield the expected dichloroacetylene; apart from dichlorovinyl ethyl ether, the only product obtained is monochloroacetylene [16]. Tribromoethylene reacts similarly.

The "wet" process is further limited by the fact that monosubstituted acetylenes isomerize in the presence of base, with migration of the triple bond along the chain to yield disubstituted acetylenes, which are thermodynamically more stable [1,17]. One example of this is the complete rearrangement of the labile compound mycomycin *(1)* to its stable isomer *(2)* with a terminal methyl group on treatment of *(1)* with 0.1 N potassium hydroxide at room temperature [18].

$$HC\equiv C-C\equiv C-CH=C=CH-(CH=CH)_2-CH_2-COOH \rightarrow$$
(1)

$$H_3C-C\equiv C-C\equiv C-C\equiv C-(CH=CH)_2-CH_2-COOH$$
(2)

Competing substitutions and secondary reactions can also occur; they arise from the ease with which the initially formed acetylenes undergo nucleophilic additions. Thus, β-chlorostyrene reacts to give not only phenylacetylene according to Equation (b), but also β-styryl ethyl ether [9] and even, under more vigorous conditions, phenylacetaldehyde [19]. The principal products of the reaction of vinyl chloride with alkali metal alkoxides and the corresponding alcohols in an autoclave at 80–100 °C are vinyl ethers. The observation that acetylene was formed, but that the amount of it

[5] *V. Sawitsch*, C.R. hebd. Séances Acad. Sci. *52*, 399 (1861).

[6] *O. Overbeck*, Liebigs Ann. Chem. *140*, 39 (1866).

[7] Cf. the references given by *M. Kutscherov*, Ber. dtsch. chem. Ges. *14*, 1532 (1881).

[8] *C. Glaser*, Liebigs Ann. Chem. *154*, 137 (1870).

[9] *J. V. Nef*, Liebigs Ann. Chem. *308*, 264 (1899).

[10] *N. Zinin*, Liebigs Ann. Chem. *149*, 374 (1869).

[11] *J. J. Sudborough*, J. chem. Soc. (London) *71*, 218 (1897).

[12] *J. Wislicenus* and *F. Seeler*, Ber. dtsch. chem. Ges. *28*, 2693 (1895).

[13] *M. Miasnikoff*, Liebigs Ann. Chem. *118*, 330 (1861).

[14] *J. Loevenich, J. Losen*, and *A. Dierichs*, Ber. dtsch. chem. Ges. *60*, 950 (1927).

[15] *G. Chavanne*, Bull. Soc. chim. Belgique *28*, 234 (1914); Chem. Zbl. *1914*, II. 1144.

[16] *K. A. Hofmann* and *H. Kirmreuther*, Ber. dtsch. chem. Ges. *41*, 314 (1908).

[17] *A. E. Favorsky*, J. russ. physik.-chem. Ges. *19*, 414 (1887); Chem. Zbl. C *1887*, 1539.

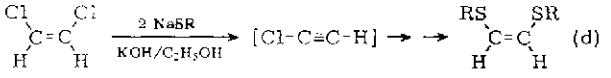
[18] *W. D. Celmer* and *I. A. Solomons*, J. Amer. chem. Soc. *74*, 1870 (1952).

[19] *C. Forrer*, Ber. dtsch. chem. Ges. *17*, 982 (1884).

decreased with time, while no products other than the vinyl ethers were formed, suggested that acetylene was an intermediate, and led to the discovery of base-catalysed vinylation of alcohols [20]; see Equation (c).

$$CH_2{=}CHCl \xrightarrow[-ROH,\ -NaCl]{NaOR} HC{\equiv}CH \xrightarrow[ROH]{NaOR} CH_2{=}CH{-}OR \qquad (c)$$

Substitution of many halogeno-olefins with aryl or alkyl sulfides also proceeds only in the presence of catalytic quantities of alkali metal hydroxide or alkoxide. A formal double substitution of *cis*-dichloroethylene leads, in accordance with Equation (d), to excellent yields of *cis*-1,2-di(arylthio)ethylenes [21–23].



(d)

Since the presence of alkali is essential, since chloroacetylene reacts with thiolates to give the same product, and since the reaction rate depends on the concentration of alkali, but not on that of the thiolate [24], this reaction is a multistage elimination-addition process, whose rate-determining first step is dehydrohalogenation of the substrate to form chloroacetylene. It is significant that *trans*-dichloroethylene does not satisfy the steric conditions for the energetically favored *trans*-elimination of HCl and is inert under these conditions.

The elimination of hydrogen halide is thus of both practical and theoretical interest as first step in the elimination-addition mechanism – one of at least three mechanisms known at present for nucleophilic substitutions of olefins.

Addition of nucleophiles onto the acetylenes initially formed can often be avoided if the gaseous halogeno-olefin is allowed to pass over heated solid potassium hydroxide. Use of this method with chlorostyrene yields only phenylacetylene [9]; similarly, *(3)* gives 3,3,3-trifluoropropyne [25].

$$CF_3{-}CH{=}CHX \rightarrow CF_3{-}C{\equiv}C{-}H$$
(3)

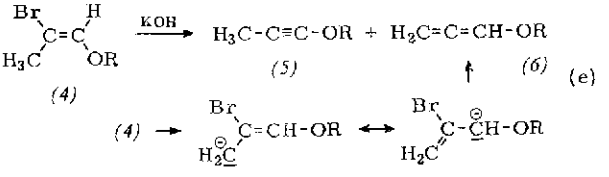
Dichloroacetylene was first prepared from trichloroethylene by this method [26].

$$Cl_2C{=}CHCl \xrightarrow[130°C]{KOH} Cl{-}C{\equiv}C{-}Cl$$

The "dry" process was found to be the first practicable method for the preparation of alkynyl ethers (which react extremely readily with nucleophilic reagents) from β-halogenovinyl ethers [4,27], although the yields are moderate [28].

$$R{-}CCl{=}CH{-}OR' \xrightarrow{KOH} R{-}C{\equiv}C{-}OR'$$

Preparative variants include distillation of the halogenoethylene with KOH under reduced pressure, or dropping the halide onto molten alkali at 200 °C [29]. A fundamental disadvantage of all oxygen bases still remains: the eliminations generally proceed smoothly only when the hydrogen and halogen can be removed from mutual *trans*-positions. Thus, *(4)* reacts with potassium hydroxide much less smoothly than the geometrical isomer, and its reaction yields a mixture of the allene *(6)* and the alkynyl ether *(5)* [30]. It is possible that this reaction, which is formally represented as a β-elimination from the olefin, actually proceeds by deprotonation in the allyl position to the ether oxygen atom [see Equation (e)].



(e)

On the other hand, *cis*-elimination of hydrogen chloride from *trans*-chlorostilbene at high temperatures on oxide surfaces proceeds more readily than *trans*-elimination from the *cis*-isomer, evidently for steric reasons [31]. It is not yet known whether these are free-radical or ionic reactions.

2. Elimination by Alkali Metal Amides

The use of the more reactive alkali metal amides in place of alkoxides has been known for a long time, at least in principle. Thus, various arylated or alkylated chloro- and bromo-olefins are converted into the corresponding acetylenes by sodamide in purified mineral oil between 110 and 180 °C [32]. Although it is theoretically possible for sodamide to add onto the alkyne initially formed [33] – a property which is exploited in the vinylation of amines [20] – the use of this reagent

[20] *W. Reppe* et al., Liebigs Ann. Chem. *601*, 81 (1956).

[21] *E. Fromm, H. Benzinger*, and *F. Schäfer*, Liebigs Ann. Chem. *394*, 325 (1912); *E. Fromm* and *E. Siebert*, Ber. dtsch. chem. Ges. *55*, 1014 (1922).

[22] *W. E. Truce* and *R. J. McManimie*, J. Amer. chem. Soc. *76*, 5745 (1954); *W. E. Parham* and *J. Heberling*, ibid. *77*, 1175 (1955).

[23] *H. J. Backer* and *J. Strating*, Recueil Trav. chim. Pays-Bas *73*, 565 (1954).

[24] *W. E. Truce, M. M. Boudakian, R. F. Heine*, and *R. J. McManimie*, J. Amer. chem. Soc. *78*, 2743 (1956); *J. Flynn, V. V. Badiger*, and *W. E. Truce*, J. org. Chemistry *28*, 2298 (1963).

[25] *H. R. N. Haszeldine*, J. chem. Soc. (London) *1951*, 2495.

[26] *E. Ott, W. Ottemeyer*, and *K. Packendorff*, Ber. dtsch. chem. Ges. *63*, 1941 (1930); *E. Ott* u. *K. Packendorff*, ibid. *64*, 1324 (1931); *E. Ott*, ibid. *75*, 1517 (1942).

[27] *M. Slimmer*, Ber. dtsch. chem. Ges. *36*, 289 (1903).

[28] *T. L. Jacobs* and *W. R. Scott*, J. Amer. chem. Soc. *75*, 5497 (1953).

[29] *F. Krafft* and *L. Reuter*, Ber. dtsch. chem. Ges. *25*, 2243 (1892).

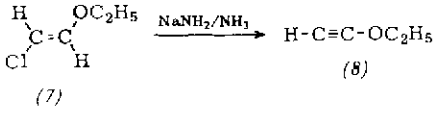
[30] *J. F. Arens*, Recueil Trav. chim. Pays-Bas *74*, 271 (1955); *J. R. Nooi* and *J. F. Arens*, ibid. *78*, 284 (1959).

[31] *P. Andréu, E. Schmitz*, and *H. Noller*, Angew. Chem. *76*, 184 (1964); Angew. Chem. internat. Edit. *3*, 135 (1964).

[32] *M. Bourguel*, Ann. Chemie (10) *3*, 191, 325 (1925); C. R. hebd. Séances Acad. Sci. *176*, 751 (1923); *L. Meunier* and *E. Desparmet*, Bull. Soc. chim. France (4) *1*, 342 (1907); *A. Willemart*, ibid. (4) *45*, 644 (1929).

[33] *E. Ott* and *G. Dittus*, Ber. dtsch. chem. Ges. *76*, 80 (1943); *H. G. Viehe*, Angew. Chem. *75*, 638 (1963); Angew. Chem. internat. Edit. *2*, 447 (1963).

in liquid ammonia has enjoyed increasing preparative importance, mainly because it eliminates hydrogen halide readily even from *cis*-positions of ethylene derivatives. Thus, not only *cis*-β-chlorovinyl ethyl ether, but also its *trans*-isomer *(7)* is converted into ethynyl ethyl ether *(8)* [33]. The same compound is also formed



(7) *(8)*

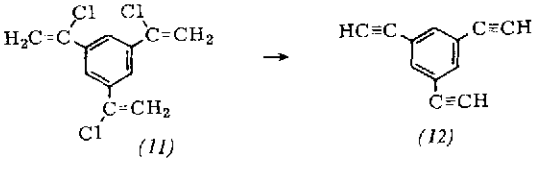
$ClCH_2-CH(OC_2H_5)_2$ *(9)*

from *(9)*, the chlorovinyl ether *(7)* occurring as an intermediate; *(8)* is therefore readily obtainable [34]. Liquid ammonia is a much better solvent for *cis*-elimination than aprotic solvents. Thus HBr is eliminated from the *trans*-form of *(10)* by treatment with sodamide in liquid ammonia, but not in dioxane at 77 °C. The *cis*-isomer reacts in both solvents [35].

$$Br-CH=CH-CH_2NH-C_4H_9 \rightarrow H-C\equiv C-CH_2NH-C_4H_9$$

(10)

Both halogen atoms of *trans*-dichloroethylene can be exchanged for mercapto groups in liquid ammonia [36], since the preceding elimination of HCl to form chloroacetylene occurs readily [37]. The method can be used for the preparation of various ethynylthiophenes under mild conditions [38]. Similarly, phenylacetylene is produced from α-chlorostyrene [39], and 1,3,5-triethynylbenzene *(12)* can be obtained in 60 % yield from *(11)*, which does not react with boiling methanolic potassium hydroxide [40].



(11) *(12)*

3. Elimination by Organo-Alkali Metal Compounds

Organometallic compounds, especially those of alkali metals, are most versatile in elimination reactions of the type under consideration. These are very strong bases and permit the elimination of HX from substrates which react only unsatisfactorily or not at all with weaker bases. At the same time, their nucleophilic character is comparatively weak; consequently, although subsequent addition onto the alkyne formed can be forced to occur in certain cases [41], it is generally possible only with halogenoacetylenes. Finally, besides debydrohalogenation, organolithium compounds can also effect dehalogenation according to Equation (f) under very mild conditions, owing to their ability to undergo halogen-metal exchange reactions [42].

$$Br-\underset{|}{\overset{|}{C}}=\underset{|}{\overset{|}{C}}-X \xrightarrow[-RBr]{R-Li} Li-\underset{|}{\overset{|}{C}}=\underset{|}{\overset{|}{C}}-X \xrightarrow{-LiX} -C\equiv C- \qquad (f)$$

β-Chlorostyrene reacts with two moles of either phenyllithium [43] or n-butyl-lithium [44] in ether at room temperature; the reaction is strongly exothermic. Hydrolysis of the resulting lithium salt *(13)* leads to an almost quantitative yield of phenylacetylene [43].

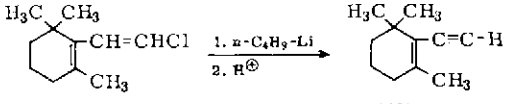
$$H_5C_6-CH=CHCl + 2\ H_5C_6-Li \xrightarrow[-C_6H_6]{-LiCl} H_5C_6-C\equiv C-Li \quad (13)$$

$$\xrightarrow{H^{\oplus}} H_5C_6-C\equiv C-H$$

Acetylene is obtained from vinyl bromide or vinyl chloride in a similar manner. Vinyl chloride is formed as an intermediate in the reaction of 1,2-dichloroethane with phenyl-lithium [45]; see Equation (g).

$$ClCH_2-CH_2Cl \xrightarrow[-HCl]{H_5C_6-Li} CH_2=CHCl \xrightarrow[2.\ H^{\oplus}]{1.\ H_5C_6-Li} HC\equiv CH \qquad (g)$$

On the other hand, in order to achieve smooth dehydrochlorination of 1,3,3-trimethyl-2-(β-chlorovinyl)cyclohexene *(14)*, n-butyl-lithium, which is more reactive, must be used; the resulting product is 2-ethynyl-1,3,3-trimethylcyclohexene *(15)* which polymerizes readily [46].



(14) *(15)*

With regard to the mechanism of the reaction it is significant that, in contrast to β-chlorostyrene, β-chloro-β-methylstyrene does not react completely with phenyl-lithium, even when the reaction is continued for some days, and resinous by-products are formed [47] (cf. Section III.B).

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[34] *G. Eglinton, E. R. H. Jones, B. L. Shaw,* and *M. C. Whiting,* J. chem. Soc. (London) *1954*, 1860; *E. R. H. Jones, G. Eglinton, M. C. Whiting,* and *B. L. Shaw,* Org. Syntheses *34*, 46 (1954).

[35] *A. T. Bottini, B. J. King,* and *J. M. Lucas,* J. org. Chemistry *27*, 3688 (1962).

[36] *H. J. Boonstra* and *J. F. Arens,* Recueil Trav. chim. Pays-Bas *79*, 866 (1960).

[37] *H.-G. Viehe,* Chem. Ber. *92*, 1270 (1959).

[38] *A. Vaitiekunas* and *F. F. Nord,* J. Amer. chem. Soc. *75*, 1764 (1953); J. org. Chemistry *19*, 902 (1954).

[39] *T. H. Vaughn, R. R. Vogt,* and *J. A. Nieuwland,* J. Amer. chem. Soc. *56*, 2120 (1934).

[40] *W. Hübel* and *R. Merényi,* Angew. Chem. *74*, 781 (1962); Angew. Chem. internat. Edit. *2*, 42 (1963); cf. *M. S. Svarcberg I. L. Kotljarevskii,* and *A. A. Verescagina,* Dokl. Akad. Nauk USSR, Otdel khim. Nauk *1963*, 1836.

[41] *K. Ziegler* and *H. Dislich,* Chem. Ber. *90*, 1107 (1957); *J. E. Mulvaney, Z. G. Gardlund,* and *S. L. Gardlund,* J. Amer. chem. Soc. *85*, 3897 (1963).

[42] *G. Wittig,* Naturwissenschaften *30*, 696 (1942); *R. G. Jones* and *H. Gilman,* Org. Reactions 6, 339 (1951).

[43] *G. Wittig* and *H. Witt,* Ber. dtsch. chem. Ges. *74*, 1474 (1941).

[44] *H. Gilman, W. Langham,* and *F. W. Moore,* J. Amer. chem. Soc. *62*, 2327 (1940); *H. Gilman* and *A. H. Haubein,* ibid. *67*, 1420 (1945).

[45] *G. Wittig* and *G. Harborth,* Ber. dtsch. chem. Ges. *77*, 306 (1944); *G. Wittig, W. Böll,* and *K.-H. Krück,* Ber. dtsch. chem. Ges. *95*, 2514 (1962).

[46] *G. Köbrich,* Angew. Chem. *74*, 33 (1962); Angew. Chem. internat. Edit. *1*, 51 (1962).

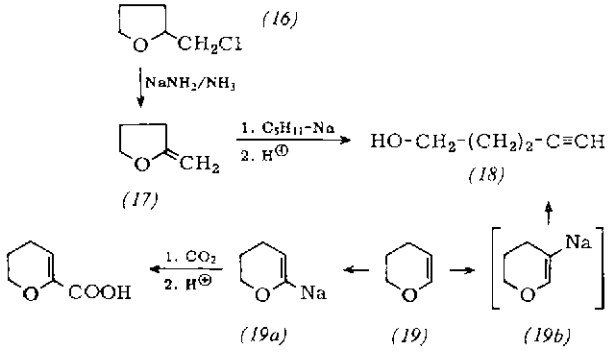
[47] *G. Wittig* and *G. Harborth,* Ber. dtsch. chem. Ges. *77*, 315 (1944).

Vinyl ethers can also be cleaved at room temperature with phenyl-lithium [45]. These eliminations yield acetylenes and lithium alkoxide but proceed more slowly than dehydrohalogenation. Vinyl phenyl ether reacts completely in accordance with Equation (h) within a few hours, but with more basic vinyl isobutyl ether, the reaction is complete only after several days.

$$CH_2{=}CH{-}OR \xrightarrow[2.\ H^{\oplus}]{1.\ H_5C_6{-}Li} H{-}C{\equiv}C{-}H + H{-}OR \qquad (h)$$

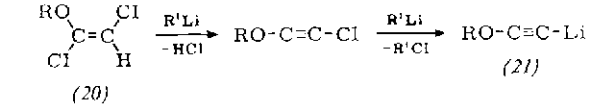
R = C_6H_5, i-C_4H_9

In the same way, the ring of α-methylenetetrahydrofuran is opened by amylsodium to yield 1-pentyn-5-ol *(18)* [48]. Amylsodium can also be used to metallate either of the olefinic hydrogens in dihydropyran *(19)*. The α-sodio compound *(19a)* is stable under the reaction conditions and can be detected, for example, by the formation of a carboxylation product with CO_2, whereas the β-sodio compound *(19b)* forms the open-chain compound *(18)*; *(18)* is also obtained from 3-bromodihydropyran by halogen-metal exchange with n-butyl-lithium [48].



2-Methylenetetrahydrofuran *(17)* results from treatment of *(16)* with sodamide in liquid ammonia, and is also converted into *(18)* under these conditions [49].

Where competition occurs between halogen and ether functions, as expected, halogen is eliminated preferentially even when the elimination of the alkoxide can occur via the energetically favorable *trans*-β-elimination. Thus, 1,2-dichlorovinyl ethers *(20)* are converted by organolithium compounds into chloroethynyl ethers, which then undergo halogen-metal exchange to form lithium acetylides *(21)* [50].



R = C_6H_5, C_2H_5

1-Ethoxy-2-thioethoxyethylene *(22)* is broken down by two moles of n-butyl-lithium into lithium ethoxide and the thioether *(23)* [51].

$$H_5C_2O{-}CH{=}CH{-}SC_2H_5 \xrightarrow{2\ n\text{-}C_4H_9\text{-}Li} C_2H_5OLi + Li{-}C{\equiv}C{-}SC_2H_5$$

(22) *(23)*

Elimination of lithium ethyl sulfide could conceivably compete with the above reaction but is not in fact observed; diethoxyethylene does not react under these conditions. The mobility of the hydrogen atom on the carbon atom bearing the thioether group is greater than that of the other hydrogen atom, since the carbanion *(23a)* is stabilized by resonance with the d-orbital of the sulfur atom. Since the

$$[H_5C_2O{-}CH{=}\bar{C}{-}SC_2H_5 \longleftrightarrow H_5C_2O{-}CH{=}C{=}\bar{S}C_2H_5]^{\ominus}$$

(23a)

deprotonation is the slowest step in the reaction in ether (cf. Section III.B), elimination of the ethoxyl group can be satisfactorily interpreted as a β-elimination. α-Elimination, which is also feasible, would lead to elimination of thiolate and consequently does not occur [51].

Nevertheless, vinyl thioethers can also be cleaved with organolithium compounds. Thus, thiophenol is eliminated as its lithium salt from *(24)* on reaction with n-butyl-lithium in ether, even at 0 °C [51, 52]. Since the fragments are obtained as lithium salts, the reverse

$$H_5C_6S{-}CH{=}CH{-}SC_6H_5 \xrightarrow[0°C;\ in\ H_5C_2{-}O{-}C_2H_5]{n\text{-}C_4H_9\text{-}Li} H_5C_6S{-}C{\equiv}C{-}Li + H_5C_6S{-}Li$$

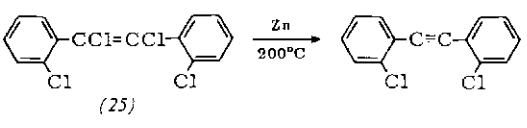
(24)

reaction is suppressed; lithium phenyl sulfide is insoluble, and so the acetylide, carrying a strong negative charge owing to anion formation, undergoes nucleophilic attack only with difficulty. To prevent recombination during work-up, the insoluble material must be filtered off or alkylated [52].

B. Elimination by Metals

1. Elimination of Halogen

The elimination of two halogen atoms attached to olefinic carbon atoms by metals in the absence of solvent is a classical route to acetylenes, but one which is seldom of practical value. However, α,β-dibromostyrene gives phenylacetylene in approximately 50 % yield on heating with zinc dust [9]; similarly, *(25)* is converted at 200 °C into bis-*o*-chlorophenylacetylene [53], whereas



diphenyldichlorostilbene is reported to be unaffected by sodium in the absence of solvent, even at 190 °C [54]. Dehalogenations, especially those effected by electropositive metals, occur readily in suitable solvents.

[48] *R. Paul* and *S. Tschelitchev*, Bull. Soc. chim. France *1952*, 808; cf. the review by *M. Schlosser*, Angew. Chem. *76*, 124 (1964); Angew. Chem. internat. Edit. *3*, 287 (1964).

[49] *G. Eglinton*, *E. R. H. Jones*, and *M. C. Whiting*, J. chem. Soc. (London) *1952*, 2873.

[50] *J. Normant*, Bull. Soc. chim. France *1963*, 1876.

[51] *W. E. Parham*, *R. F. Motter*, and *G. L. O. Mayo*, J. Amer. chem. Soc. *81*, 3386 (1959).

[52] *W. E. Parham* and *P. L. Stright*, J. Amer. chem. Soc. *78*, 4783 (1956).

[53] *F. Fox*, Ber. dtsch. chem. Ges. *26*, 653 (1893).

[54] *A. H. Gill*, Ber. dtsch. chem. Ges. *26*, 649 (1893).

Tolane dibromide *(26)* and the vinyl compound *(27)* are smoothly debrominated by zinc dust in acetone [55].

$C_6H_5-CBr=CBr-C_6H_5$ *(26)* $C_6H_5-CBr=CBr-CBr=CBr-C_6H_5$ *(27)*

Acetylenedicarboxylic esters are formed in good yield from dibromofumarates, as well as from the more slowly reacting dibromomaleates, by heating them with zinc in moist ether at 60–70 °C [56]. Zinc dust is particularly effective in alcohol; for example, *(28)* is converted into perfluoro-2-butyne in 90 % yield [57, 58].

$CF_3-CBr=CBr-CF_3 \rightarrow CF_3-C\equiv C-CF_3$ *(28)*

The use of zinc dust in ethanol always leads to reductive dehalogenation when the expected product is a halogenated acetylene. Tetrabromoethylene gives a mixture of acetylene and bromoacetylene instead of the expected dibromoacetylene [9]. Thus diacetylene and

$$Cl_2C[=CCl-CCl]_n=CCl_2 \xrightarrow{Zn/C_2H_5OH} H-C[\equiv C-C]_n\equiv C-H \quad (i)$$
$$n = 1;\ 2$$

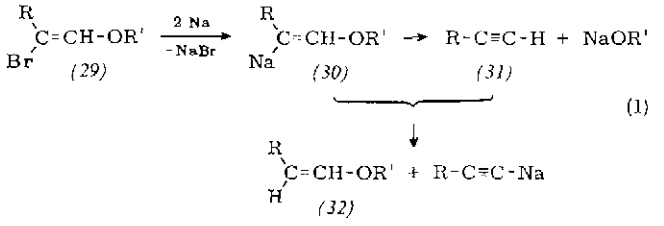
triacetylene can be obtained from perchlorobutadiene [59] and perchlorohexatriene [60], respectively, provided that the products are distilled off continuously to prevent reduction to an olefin [see Reaction (i)].

Dehalogenations with sodium in ether proceed very smoothly: for example, various α,β-dichlorostyrenes containing nuclear substituents are converted into the corresponding arylacetylenes [61]. Formation of the Grignard compound prior to the elimination step using the less reactive magnesium can be conveniently carried out in tetrahydrofuran [62]. In this way, 1-fluoro-1,2-dibromoethylene gives an 80 % yield of monofluoroacetylene [63], as shown in Equation (k).

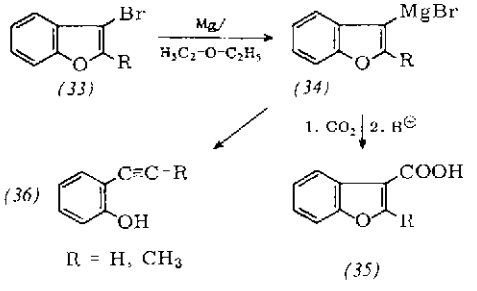
$$FCBr=CHBr \xrightarrow[65°C]{Mg/THF} F-C\equiv C-H \quad (k)$$

2. Cleavage of Ethers

β-Halogenated vinyl ethers follow the same reaction scheme as that shown in Equation (k). Thus, reaction of β-substituted β-bromovinyl ethers *(29)* with sodium powder in aprotic solvents, followed by hydrolysis, yields the expected acetylene *(31)* as shown in Equation (l); however, production of *(31)* is accompanied by formation of the dehalogenated ether *(32)*, since the intermediate *(30)* is evidently capable of converting part of the acetylene *(31)* formed into the sodium acetylide [64].

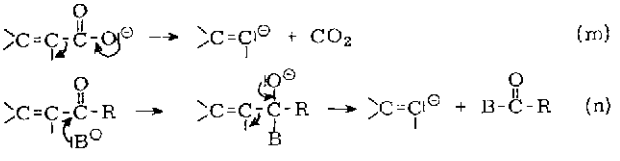


3-Bromobenzofuran [65] and its 2-methyl derivative [66] react even with magnesium in ether; after carboxylation, only traces of the carboxylic acid *(35)* to be expected from the Grignard compound *(34)* are present, the principal products being *o*-alkynylphenols *(36)*.



C. Fragmentation Reactions

Carbanions are known to occur not only in deprotonation and halogen-metal exchange reactions, but also as intermediates during decarboxylations in alkaline media [Equation (m)] and in the base-catalysed cleavage of esters and ketones [67] [Equation (n)].



Elimination occurs if the adjacent carbon atom carries a leaving group; the reaction is then referred to as a fragmentation.

1. Fragmentation Reactions of Acrylic Acid Derivatives

Examples of the fragmentation of olefinic carboxylic acids are mentioned in the earlier literature. Thus, when the potassium salt of β-chloro-*cis*-cinnamic acid *(37)* is heated at 120 °C for 5 h in concentrated aqueous solu-

[55] *F. Straus*, Liebigs Ann. Chem. *342*, 190 (1905).

[56] *A. Michael*, J. prakt. Chem. (2) *46*, 209 (1892); *52*, 344 (1895).

[57] *A. L. Henne* and *W. G. Finnegan*, J. Amer. chem. Soc. *71*, 298 (1949).

[58] *R. N. Haszeldine*, J. chem. Soc. (London) *1952*, 2504.

[59] *A. Roedig* and *A. Kling*, Liebigs Ann. Chem. *580*, 20 (1953).

[60] *A. Roedig*, *G. Voss*, and *E. Kuchinke*, Liebigs Ann. Chem. *580*, 24 (1953).

[61] *F. Kunckell* and *K. Eras*, Ber. dtsch. chem. Ges. *36*, 915 (1903).

[62] Cf. *H. Normant* in: Advances in Organic Chemistry. Interscience, New York 1960, Vol. II, p. 1 ff.

[63] *H. G. Viehe* and *E. Franchimont*, Chem. Ber. *95*, 319 (1962).

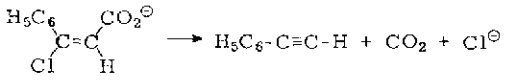
[64] *J. Ficini* and *H. Normant*, C. R. hebd. Séances Acad. Sci. *237*, 731 (1953).

[65] *R. Reichstein* and *J. Baud*, Helv. chim. Acta *20*, 892 (1937).

[66] *A. Gabert* and *H. Normant*, C. R. hebd. Séances Acad. Sci. *235*, 1407 (1952); *J. C. Montaigne* and *H. Normant*, ibid. *235*, 1656 (1952).

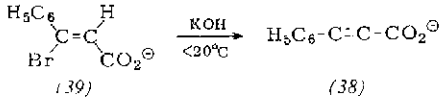
[67] Reviewed by *G. Köbrich*, Angew. Chem. *74*, 453 (1962); Angew. Chem. internat. Edit. *1*, 382 (1962); *D. J. Cram*, Chem. Engng. News *41*, No. 33, 92 (1963).

tion, it is completely converted into phenylacetylene [68]; the latter is also formed when the free acid is steam-distilled from weakly alkaline solution [69].



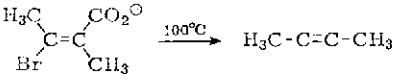
(37)

This reaction of β-chloro-*trans*-cinnamic acid in alkaline media cannot be *a priori* assumed to be a fragmentation. An alternative mechanism could involve elimination of hydrogen halide to yield phenylpropiolic acid *(38)*, which decarboxylates extremely readily [9]. Dehydrobromination of β-bromo-*trans*-cinnamic acid *(39)* by aqueous alkali does in fact occur even below 20 °C [70].

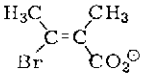


(39) (38)

Thus, there is no ambiguity only in the absence of hydrogen atoms on the α-carbon atom, or when the reaction occurs in neutral media. These prerequisites are met by the two geometric isomers of 2-bromo-3-carboxy-2-butene. Of these, the salt of angelic acid *(40)* reacts on merely heating at 100 °C in water; that of tiglic acid *(41)* does not react under these conditions[71].

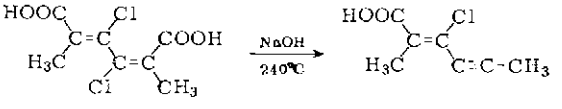


(40)



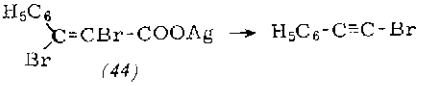
(41)

The preference for *trans*-elimination is obvious here, as well as in the reaction of the isomeric β-bromocinnamic acids. β-Bromo-*cis*-cinnamic acid undergoes fragmentation about 100 times more rapidly than its stereoisomer *(39)*, and hence presumably by a different mechanism (cf. Section III.A.1) [72]. The configuration of *(42)* was assigned on the grounds that, on heating at 240 °C with sodium hydroxide, it is converted into the acetylene derivative *(43)* [73].



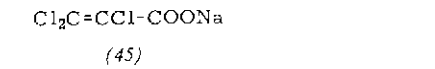
(42) (43)

Silver α,β-dibromocinnamate *(44)* yields 1-bromo-2-phenylacetylene on heating at 120–140 °C [9].

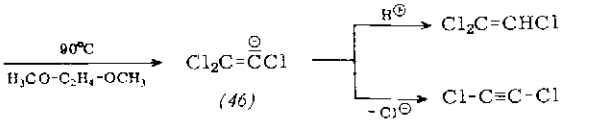


(44)

Similarly, sodium perchloroacrylate *(45)* is decarboxylated on prolonged heating at 90 °C in glycol dimethyl ether; reaction products are dichloroacetylene and trichloroethylene, since the intermediate carbanion *(46)* can be stabilized either by capture of a proton or by elimination of chloride [74].



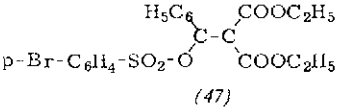
(45)



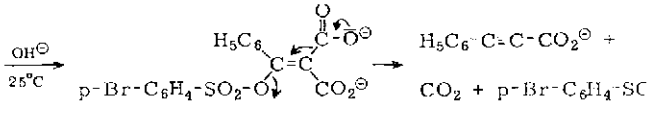
(46)

The carbanion *(46)* can be chlorinated with perchloropropene or isolated as its acetyl derivative by treatment with acetic anhydride [74].

Good leaving groups are particularly effective in promoting fragmentation. Thus, compound *(47)*, which can be prepared from diethyl benzoylmalonate and *p*-bromobenzenesulfonyl chloride, is broken down to propiolic acid, *p*-bromobenzenesulfonic acid, and carbon dioxide on standing for 12 h at room temperature with 0.2 N NaOH in aqueous dioxane [75]. This fragmentation is of



(47)



interest as a model reaction for the postulated mechanism of the biosynthesis of acetylene derivatives [76], a process which has not yet been clarified. The cleavage proceeds *in vitro* only when the enolic double bond is conjugated with another unsaturated group, but acetylene syntheses *in vivo* are subject to no such limitation.

2. Other Fragmentation Reactions

Only a few examples of fragmentations of olefins initiated by base in accordance with Equation (n) are so far known. 3-Chloro-3,4-dimethoxycinnamaldehyde *(48)* reacts with alkali to give 3,4-dimethoxyphenylacetylene *(49)* in approximately 80 % yield. The 4-mono-

[68] *Mulliken*, Ph.D. Thesis, Universität Leipzig, 1890 (cf. Beilsteins Handb. org. Chem., Vol. IX, p. 595).

[69] *Stockmeier*, Ph.D. Thesis, Universität Erlangen, 1893 (cf. Beilsteins Handb. org. Chem., Vol. IX, p. 598).

[70] *A. Michael*, Ber. dtsch. chem. Ges. *34*, 4215 (1901).

[71] *J. Wislicenus* and *M. Henze*, Liebigs Ann. Chem. *313*, 243 (1900).

[72] *C. A. Grob*, Bull. Soc. chim. France *1960*, 1360; Angew. Chem. *73*, 758 (1961); Gazz. chim. ital. *92*, 902 (1962).

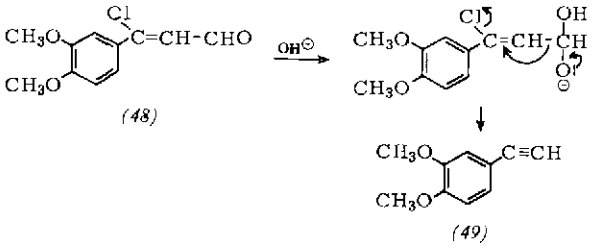
[73] *G. O. Schenck*, *W. Hartmann*, and *R. Steinmetz*, Chem. Ber. *96*, 498 (1963).

[74] *W. M. Wagner*, *L. Vriesman*, *H. Klosterziel*, and *A. F. Bickel*, Recueil Trav. chim. Pays-Bas *82*, 517 (1963).

[75] *J. Fleming* and *J. Harley-Mason*, Proc. chem. Soc. (London) *1961*, 245; J. chem. Soc. (London) *1963*, 4771; *J. C. Craig* and *M. Moyle*, ibid. *1963*, 5356.

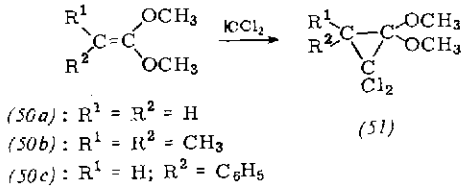
[76] *E. R. H. Jones*, Chem. Engng. News *39*, No. 12, 46 (1961); *F. Bohlmann*, Fortschr. Chem. org. Naturstoffe *14*, 1 (1957).

methoxy derivative and the compound with no nuclear substituent react in a similar manner [77].



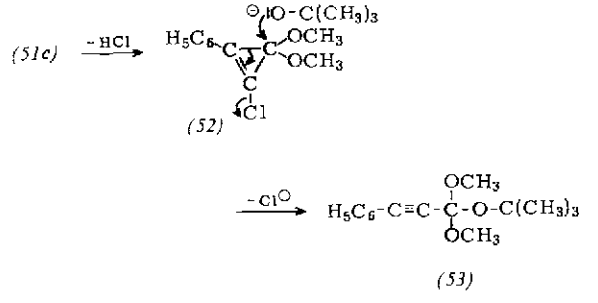
(48) (49)

Another interesting reaction belonging to this group is the "cyclopropanization" of ketene acetals with dichlorocarbene produced *in situ* from chloroform and potassium t-butoxide [78]. Whereas *(50a)* and *(50b)* give the expected cyclopropanone acetals *(51a)* and *(51b)* in good yield, the reaction of *(50c)* under the same conditions gives about 20% of the mixed orthoester *(53)*, among other products. The initially formed three-membered ring compound *(51c)* contains an acidic hydrogen atom on the carbon atom bearing the phenyl group, and reacts with excess butoxide with elimination of HCl to yield the cyclopropene derivative *(52)*. This highly strained system reacts further with base by elimination of chloride to form the product *(53)*.



(50a): $R^1 = R^2 = H$
(50b): $R^1 = R^2 = CH_3$
(50c): $R^1 = H$; $R^2 = C_6H_5$

(51)



(52) *(53)*

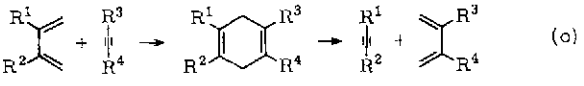
Evidence for the validity of this mechanism comes from the fact that an acetylene derivative analogous to *(53)* is also formed from *(51a)*, but not from *(51b)*, which cannot form a cyclopropene derivative without undergoing rearrangement [78].

D. Thermolytic and Photolytic Reactions

Endothermic cleavages are observed mainly with cyclic olefins, and have frequently been found to be of practical value. The driving force behind these eliminations is generally ring strain (*e.g.* in bicyclic compounds), the possibility of formation of an aromatic system, or the formation of gases of low free energy (*e.g.* nitrogen or carbon dioxide).

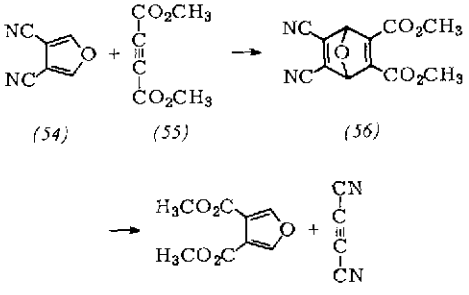
1. Retrodiene Reactions

Apart from the trivial case involving reformation of the starting materials, reversal of the diene synthesis can lead to decomposition involving cleavage of C–C bonds within the moiety that was originally the diene component of the adduct [79]. If the dienophile is an acetylene derivative, its substituents are exchanged in the final product for those in the 2- and 3-positions of the diene [Equation (o)].



(o)

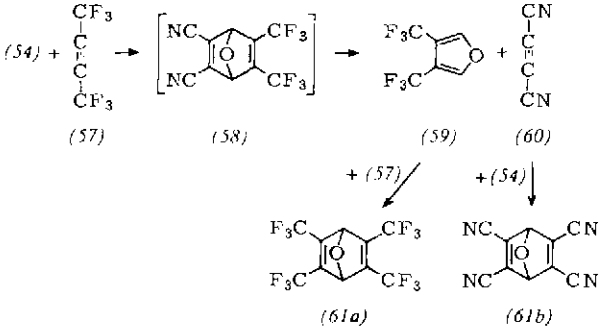
Thus, when compound *(56)*, which can be obtained from 3,4-dicyanofuran *(54)* and dimethyl acetylenedicarboxylate *(55)*, is heated at 175–180 °C, it gives exclusively dimethyl furan-3,4-dicarboxylate and dicyanoethyne. The reaction proceeds even more readily



(54) *(55)* *(56)*

without isolation of the intermediate adduct *(56)* [80] if *(54)* and *(55)* are boiled in xylene or mesitylene.

The Diels-Alder reaction of *(54)* and perfluoro-2-butyne *(57)* follows a more complex course [81]. The reaction proceeds only at 160 °C and yields only the symmetrical products *(61a)* and *(61b)* in yields of 30 and 35%, respectively. The primary adduct *(58)* is apparently unstable under the conditions of its formation, and undergoes a retrodiene reaction to form the compounds *(59)* and *(60)* with "transposed" substituents; these in turn react selectively with the starting materials to yield the energetically favored symmetrical products.



(57) *(58)* *(59)* *(60)* *(61a)* *(61b)*

[77] *K. Bodendorf* and *P. Kloss*, Angew. Chem. *75*, 139 (1963); Angew. Chem. internat. Edit. *2*, 98 (1963).

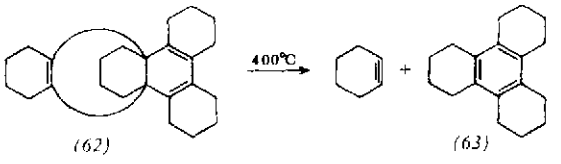
[78] *S. M. McElvain* and *P. L. Weyna*, J. Amer. chem. Soc. *81*, 2579 (1959).

[79] *O. Diels* and *K. Alder*, Ber. dtsch. chem. Ges. *62*, 2337 (1929).

[80] *C. D. Weis*, J. org. Chemistry *27*, 3520 (1962).

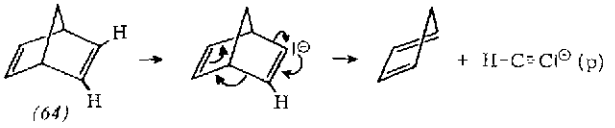
[81] *C. D. Weis*, J. org. Chemistry *27*, 3693 (1962).

If an aromatic compound can be formed, even a highly strained and hence energy-rich cycloalkyne can be eliminated under vigorous conditions. Thus, according to *Wittig*, the cyclobutene ring of the polycyclic compound *(62)* is opened at 400 °C to form cyclohexyne and dodecahydrotriphenylene *(63)* in 29 % yield [82].



(62) *(63)*

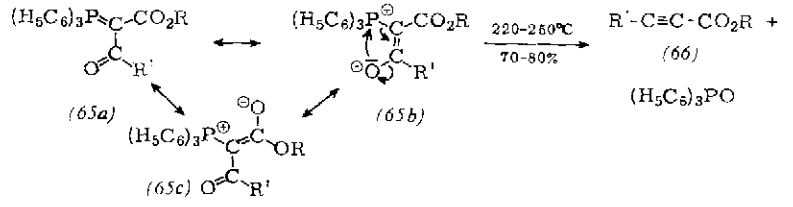
The reaction of amylsodium and bicyclo[2,2,1]heptadiene *(64)* [83] followed by carboxylation yields acetylene and (dimeric) cyclopentadienoic acid; these can also be formally regarded as resulting from a retrodiene reaction. Since metallation with n-butyl-lithium results in substitution of only vinyl hydrogen [84], it may be assumed that the reaction with amylsodium also leads first to introduction of metal on a vinyl carbon atom, followed by the cleavage, as indicated in Equation (p).



(64) (p)

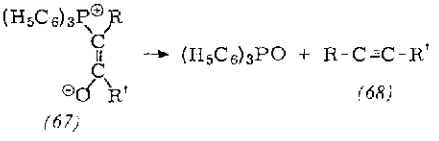
2. Cleavage of Acylated Methylenephosphoranes

The acylalkoxycarbonylmethylenetriphenylphosphoranes *(65a)–(65c)*, which can be obtained by acylation of alkoxycarbonylmethylenephosphoranes are stabilized by resonance but decompose at 220–250 °C to give good yields of triphenylphosphine oxide and the corresponding propiolic esters *(66)* [85].



(65a) *(65b)* *(65c)* *(66)*

On the basis of resonance formulae *(65a)* and *(65b)*, the reaction can be regarded as an intramolecular *Wittig* synthesis. Like the latter, it is generally applicable, since all betaines *(67)* in which neither R nor R′ is hydrogen but in which one or both are phenyl or some other electron-attracting group evidently give good to very good yields of disubstituted acetylenes *(68)* [86].

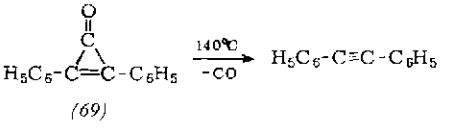


(67) *(68)*

Diacetylenes can also be obtained by this method when R = $-C\equiv C-R''$ [87].

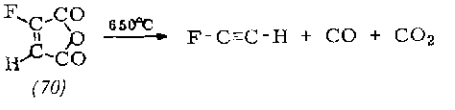
3. Elimination of CO, CO_2, and N_2 from Unsaturated Cyclic Compounds

It is known that CO is readily eliminated from bicyclic compounds with a carbonyl bridge; analogously carbon monoxide can be eliminated from the highly strained diphenylcyclopropenone *(69)* at 140 °C to give moderate yields of diphenylacetylene [88].



(69)

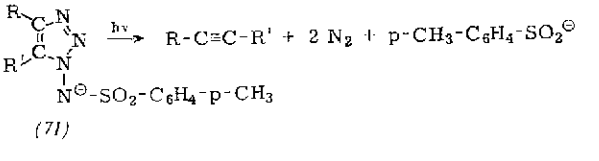
Pyrolysis *in vacuo* (5–7 mm) of fluoromaleic anhydride *(70)* gives excellent yields of fluoroacetylene which readily undergoes trimerization; the compound was in fact first prepared by this method [89].



(70)

Alkali metal salts of *N*-(*p*-toluenesulfonamido)triazoles *(71)* undergo photolytic elimination of sulfinate and nitrogen to yield acetylenes (when R = R′ = C_6H_5, yield = 85 %) [90].

This method is especially interesting for the preparation of cycloalkynes with small rings under mild conditions.



(71)

[82] *G. Wittig* and *U. Mayer*, Chem. Ber. *96*, 342 (1963); *G. Wittig* and *J. Weinlich*, unpublished results; *G. Wittig*, Pure appl. Chem. *7*, 173 (1963).

[83] *R. A. Finnegan* and *R. S. McNees*, Tetrahedron Letters *1962*, 755.

[84] *G. Wittig* and *E. Hahn*, Angew. Chem. *72*, 781 (1960); *G. Wittig* and *J. Otten*, Tetrahedron Letters *1963*, 601; *A. Streitwieser* and *R. A. Caldwell*, J. org. Chemistry *27*, 3360 (1962).

[85] *G. Märkl*, Chem. Ber. *94*, 3005 (1961).

[86] *S. T. D. Gough* and *S. Trippett*, J. chem. Soc. (London) *1962*, 2333; *S. Trippett* and *D. M. Walker*, ibid. *1959*, 3874.

[87] *S. T. D. Gough* and *S. Trippett*, J. chem. Soc. (London) *1964*, 543.

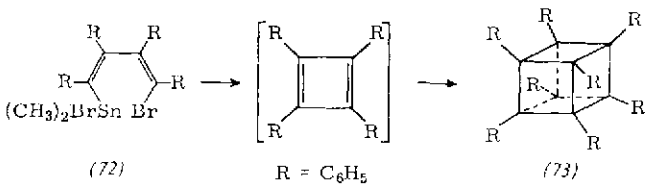
[88] *R. Breslow*, *R. Haynie*, and *J. Mirra*, J. Amer. chem. Soc. *81*, 247 (1959).

[89] *W. J. Middleton* and *W. H. Sharkey*, J. Amer. chem. Soc. *81*, 803 (1959).

[90] *F. G. Willey*, Angew. Chem. *76*, 144 (1964); Angew. Chem. internat. Edit. *3*, 138 (1964).

4. Ring Closure *via* 1,4-Elimination

An interesting 1,4-elimination is observed with the *cis*-diene *(72)*. On thermolysis, this compound loses dimethyltin dibromide to form octaphenylcubane *(73)* [91] (presumably *via* tetraphenylcyclobutadiene). The



(72) R = C_6H_5 *(73)*

formation of tricyclo-octadiene derivatives, which is observed in dimerization reactions of cyclobutadienes [82,92], is believed to be suppressed in this reaction in favor of the formation of *(73)*, owing to the size of the phenyl groups. – Meanwhile it has been shown [91a], that octaphenylcyclooctatetraene instead of *(73)* is formed from *(72)*.

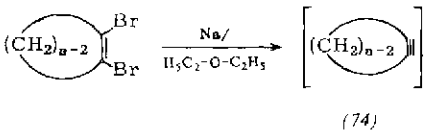
5. Cleavage of Cyclooctatetraene

Cyclooctatetraene can be cleaved to acetylene and benzene by normal or mercury-sensitized photolysis [92a]. The 1,2,4,6-tetraphenyl derivative is converted under the same conditions into diphenylacetylene and *p*-terphenyl, using heptane as solvent; an intermediate of unknown constitution is involved [92b].

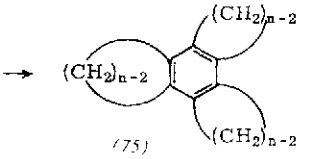
E. Reactions of Strained Cycloalkynes

Owing to substituent effects, the acetylenes obtained by β-eliminations from olefins often possess enhanced reactivity leading to subsequent addition reactions (cf. Section II.A). This is particularly true when the alkyne is part of a small-ring system. Examination of atomic models shows that the smallest ring system in which the four carbon atoms involved in sp hybridized bonds are free of strain is cyclononyne; the smaller rings have a higher energy content due to bond deformation. and are consequently more reactive [93].

Apart from the oxidation of dihydrazones of cycloalkanediones, the principal methods of preparing cycloalkynes are the elimination reactions discussed in Sections II.A and II.B applied to the corresponding cycloalkenes. Efforts in this direction started as early as the turn of this century but were at first unsuccessful [94]. *Favorsky* et al. [95] concluded from the cyclic trimers *(75)*, obtained by treatment of dihalogenocycloalkenes with sodium in ether, that the monomeric compounds *(74)* (n = 5, 6, or 7) were formed as intermediates; however, these could not be isolated.



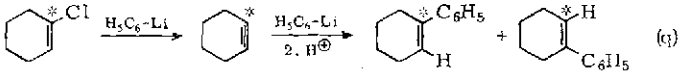
(74)



(75)

Thus it was not until 1933 that the first cycloalkynes – with 15 and 17 carbon atoms in the ring – were synthesized by dehydrobromination of the corresponding bromo-olefins with alcoholic potassium hydroxide at 180 °C; their chemical behavior was found to be similar to that of the open-chain acetylenes [96]. Cyclononyne can be obtained either by heating 1-chlorocyclononene with KOH [97] or by oxidizing cyclononadione dihydrazone [98]; cyclooctyne can also be prepared by the latter method [99] or by the action of alkali metal amides on 1-chlorocyclooctene in liquid ammonia [100].

1-Phenylcyclohexene, which is obtained by the reaction of 1-chlorocyclohexene with phenyl-lithium in ether [45], and 1-phenylcyclopentene, which is prepared in the same way from 1-chlorocyclopentene [101], are both formed *via* symmetrical intermediates – presumably cyclohexyne and cyclopentyne, respectively – since, when one of the two olefinic carbon atoms in the starting material is labelled with ^{14}C, the phenyl substituent is found on both olefinic carbons to almost equal extents in the product [102]; see Equation (q).



(q)

Other methods of preparing cyclohexyne are the reaction of 1-fluorocyclohexene with n-butyl-lithium and the formation of a Grignard compound from

[91] *H. H. Freedman*, J. Amer. chem. Soc. *83*, 2195 (1961).

[91a] *H. P. Throndsen, P. J. Wheatley*, and *H. Zeiss*, Proc. chem. Soc. (London) *1964*, 357; *G. S. Pawley, W. N. Lipscomb*, and *H. H. Freedman*, J. Amer. chem. Soc. *86*, 4725 (1964).

[92] Reviewed by *R. Criegee*, Angew. Chem. *74*, 703 (1962); Angew. Chem. internat. Edit. *1*, 519 (1962).

[92a] *I. Tanaka* and *M. Akuda*, J. chem. Physics *22*, 1780 (1954); *H. Yamazaki* and *S. Shida*, ibid. *24*, 1278 (1956).

[92b] *R. L. Stern* and *E. H. White*, 141st Meeting Amer. chem. Soc. 1962, Abstracts of Papers; cf. *L. O. Chapman* in: Advances in Photochemistry. Interscience, New York 1962, Vol. 1, p. 394.

[93] Reviewed with further literature references by *G. Wittig*, Angew. Chem. *74*, 479 (1962); Angew. Chem. internat. Edit. *1*, 415 (1962); *G. Wittig* and *A. Krebs*, Chem. Ber. *94*, 3260 (1961).

[94] *W. Markovnikov*, J. prakt. Chem. (2) *49*, 430 (1894); Liebigs Ann. Chem. *327*, 67 (1903).

[95] *A. Favorsky* and *W. Boshovsky*, Liebigs Ann. Chem. *390*, 122 (1912); *A. Favorsky, M. F. Chestakovsky*, and *N. A. Domnine*, Bull. Soc. chim. France *1936*, 1727.

[96] *L. Ruzicka, M. Hürbin*, and *H. A. Boeckenoogen*, Helv. chim. Acta *16*, 498 (1933).

[97] *A. T. Blomquist, L. H. Liu*, and *J. C. Bohrer*, J. Amer. chem. Soc. *74*, 3643 (1952).

[98] *V. Prelog, K. Schenker*, and *W. Küng*, Helv. chim. Acta *36*, 471 (1953).

[99] *A. T. Blomquist* and *L. H. Liu*, J. Amer. chem. Soc. *75*, 2153 (1953).

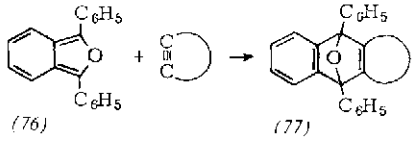
[100] *G. Wittig* and *R. Pohlke*, Chem. Ber. *94*, 3276 (1961).

[101] *J. D. Roberts* and *F. Scardiglia*, Tetrahedron *1*, 343 (1957).

[102] *L. K. Montgomery* and *J. D. Roberts*, J. Amer. chem. Soc. *82*, 4750 (1960).

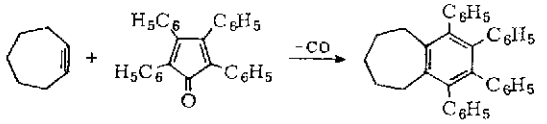
1,2-dibromocyclohexene [103]; these reactions can also be used to prepare seven- and five-membered rings [100, 103].

In an elegant method of detecting cycloalkyne intermediates these are trapped with 1,3-diphenylbenzo-[c]furan *(76)* to form *(77)* or with other dienes [82, 93, 100, 103]; at the same time, this reaction yields qualitative information regarding the life-time of



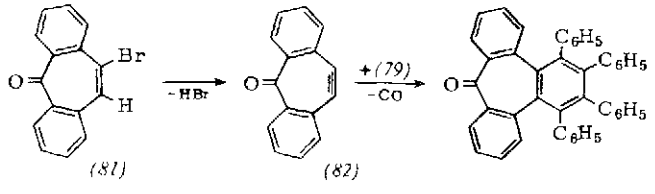
(76) *(77)*

such intermediates, which decreases with decreasing ring size, as is reflected in decreasing yields of adduct. It has recently been shown by capture with dienes that cycloheptyne *(78)* is stable for several minutes at room temperature. The compound was prepared from the triazole derivative *(71)*, R + R′ = – $(CH_2)_5$ – (see Section II.D.3), and converted into 2,3,4,5-tetraphenylbenzocycloheptene *(80)* in moderate yield by treatment with tetraphenylcyclopentadienone *(79)* even after completion of the photolysis [90].



(78) *(79)* *(80)*

Elimination of HBr from bromodibenzotropone by treatment with potassium t-butoxide in ether gives the cycloheptyne derivative *(82)* which can be trapped by furans or tetracyclone [104].



(81) *(82)*

The rate of elimination of hydrogen bromide is influenced strongly by cationic activation of the olefinic hydrogen atom by the carbonyl group. When *(81)* is compared to the corresponding dimethylacetal and the analogous sulfone [*(81)*, $C(OCH_3)_2$ or SO_2 instead of C-O], the rate constants are reduced by a factor of 150 in the case of the acetal, but increased by a factor of at least 1000 in the case of the sulfone.

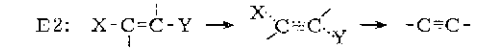
Here, as in similar eliminations from furan and thiophene derivatives, similarities can be observed with the chemistry of benzyne [105].

[103] *G. Wittig* and *U. Mayer*, Chem. Ber. *96*, 329 (1963).

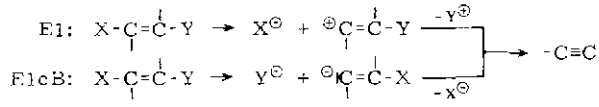
[104] *W. Tochtermann*, Angew. Chem. *74*, 432 (1962); Angew. Chem. internat. Edit. *1*, 403 (1962); *W. Tochtermann, K. Oppenländer*, and *U. Walter*, Chem. Ber. *97*, 1318 (1964); Angew. Chem. *76*, 612 (1964); *W. Tochtermann*, personal communication.

A. β-Eliminations

According to *Ingold* [106], β-eliminations can occur either in one step (E2) or in two (E1). The E2 mechanism is a synchronous process in which the elimination of substituents X and Y from two adjacent carbon atoms and the formation of the π-bond between the carbon atoms occur simultaneously; the four atoms involved lie in a single plane and, for reasons which have not yet been satisfactorily explained [106a], X and Y are always in *trans*-relationship to each other.



Two-stage eliminations are characterized by primary loss of the anion $X^{\ominus}$ to form a carbonium ion (E1 mechanism) or by primary removal of a cation $Y^{\oplus}$ to form a carbanion (E1cB mechanism).



The three mechanisms E2, E1, and E1cB represent extremes of a continuous range of possible courses; the factors determining which course is adopted have recently been discussed in detail [107] for saturated compounds, for here plentiful experimental data are available.

Mechanistic studies of β-eliminations from olefins are relatively rare. Owing to the greater electronegativity of sp^2-hybridized carbon compared to sp^3-hybridized carbon [108], it may be expected, in principle, that olefinic carbon atoms can accept a negative charge more readily than saturated carbon atoms, but can much less readily accept a positive charge. Hence, although E1 reactions, as well as S_N1 reactions, involving carbonium ion intermediates frequently occur with saturated compounds, they are less likely to occur with olefins. Conversely, base-initiated eliminations, which for saturated compounds proceed by an E2 mechanism, and only in exceptional cases by an E1cB-type mechanism [109], evidently proceed more readily *via* carbanions in the case of olefins, even when the steric conditions for the E2 mechanism are satisfied.

[105] Reviewed by *G. Wittig*, [93]; Angew. Chem. *69*, 245 (1957); *R. Huisgen* and *J. Sauer*, ibid. *72*, 91 (1960); *R. Huisgen* in *H. Zeiss:* Organometallic Chemistry. Reinhold Publ. Corp., New York 1960, p. 36; *H. Heaney*, Chem. Reviews *62*, 81 (1962).

[106] *C. K. Ingold:* Structure and Mechanism in Organic Chemistry. G. Bell and Sons Ltd., London 1953, p. 420.

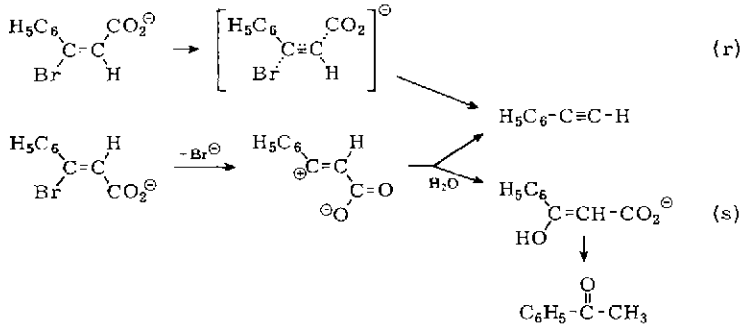
[106a] However, cf. *J. Csapilla*, Chimia *18*, 37 (1964).

[107] *J. F. Bunnett*, Angew. Chem. *74*, 731 (1962); Angew. Chem. internat. Edit. *1*, 225 (1962).

[108] *C. A. Coulson:* Valence. Clarendon Press, Oxford 1958, p. 206.

[109] *E. S. Gould:* Mechanism and Structure in Organic Chemistry. Henry Holt, New York 1959, p. 472; *J. Hine:* Physical Organic Chemistry. 2nd Edit., McGraw-Hill, NewYork 1962, Chapter 8.

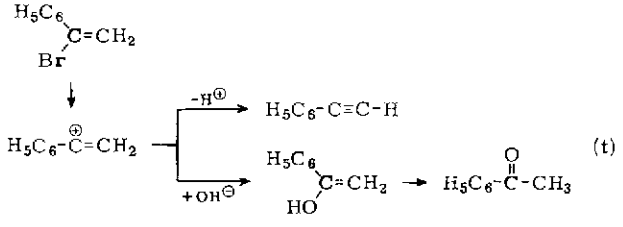
The ease of fragmentation of halogenated acrylates in which the halogen is *trans* to the carboxylate group (Section II.C.1) suggests that the cleavage follows an E2 mechanism, as indicated in Equation (r). β-Bromo-*trans*-cinnamic acid is more difficult to decarboxylate, and in this reaction acetophenone is found as a by-product [72]. This is compatible with the assumption of an initial unimolecular reaction involving formation of a carbonium ion which undergoes a rapid secondary reaction to form the products isolated [72], see Equation (s).



(r)

(s)

This mechanism is probably followed owing to the good solvating power of the medium, as well as to the negative charge of the carboxylate group which helps to stabilize the carbonium ion. The latter effect is not decisive, however, as can be seen from the fact that α-bromostyrene also undergoes solvolysis in ethanol/water at 100 °C [110]. Besides acetophenone, the products include about 20 % phenylacetylene; a base-catalysed dehydrobromination can be excluded for formation of the latter. Here, too, the branching of the reaction course is therefore likely to occur starting from the initially formed carbonium ion, as shown in Equation (t). As expected, formation of the carbonium ion is facilitated by



(t)

electron-donating groups in *para*-position to the phenyl group (stabilization of the positive charge); a *p*-amino group causes acceleration of the reaction by a factor of 10^8 compared to the rate for the parent compound. Conversely, the solvolysis is suppressed by the electron-attracting nitro group [110].

[110] *C. A. Grob* and *G. Cseh*, Helv. chim. Acta *47*, 194 (1964).

In order to become acquainted with the controlling factors in these eliminations, dehydrohalogenation of olefins by base, being the simplest and most important type of reaction, may be considered. Both mechanisms involve bimolecular reactions of first order with respect to both substrate and base. The following statements can be made:

1. When an oxygen base is used, *trans*-eliminations always proceed much more rapidly than *cis*-eliminations. In addition to the examples given earlier (Section II.A.1), it should be mentioned that dehydrochlorination of *trans*-chlorostilbene with NaOH in ethanol is about 400 times faster than that of the *cis*-isomer [111].

The preference for *trans*-elimination agrees with the fact that additions onto acetylenes, especially those catalysed by bases, are always *trans*-additions [112], as *Michael* [113] pointed out.

2. If cleavage of the carbon-halogen bond is involved in the rate-determining step, the rate of elimination under a given set of conditions is expected to decrease in the order I > Br > Cl > F corresponding to increasing bond energy. Thus, *trans*-elimination of hydrogen halide from *cis*-1,2-diiodoethylene with sodium methoxide at 60 °C is 10^2 and 10^5 times faster than that from the dibromo and dichloro compounds, respectively (cf. Table 1) [114].

Table 1. Rate constants k_2 and activation parameters (activation energy E_a and entropy $\Delta S^{\neq}$) for the dehydrohalogenation of dihalogenoethylenes with sodium methoxide in methanol [114].

	cis-Isomer			*trans*-Isomer		
	k_2 [l/mole/sec]	E_a [kcal/mole]	$\Delta S^{\neq}$ [e. u.]	k_2 [l/mole/sec]	E_a [kcal/mole]	$\Delta S^{\neq}$ [e. u.]
$C_2H_2Cl_2$	1.4×10^{-5}	35.1	+ 22	4.2×10^{-9}	29.0	− 12
$C_2H_2Br_2$	1.8×10^{-2}	28.1	+ 16	3.3×10^{-8}	33.4	+ 5
$C_2H_2I_2$	1.6	24.7	+ 14	1.2×10^{-5}	35.8	+ 24

[111] *S. J. Cristol* and *R. S. Bly*, J. Amer. chem. Soc. *83*, 4027 (1961).

[112] *S. I. Miller*, J. Amer. chem. Soc. *78*, 6091 (1956); *W. E. Truce*, *M. M. Boudakian*, *R. F. Heine*, and *R. J. McManimie*, *ibid.* *78*, 2742 (1956), and subsequent papers.

[113] *A. Michael*, J. prakt. Chem. (2) *52*, 344 (1895).

[114] *S. I. Miller* and *W. P. Noyes*, J. Amer. chem. Soc. *74*, 629 (1952).

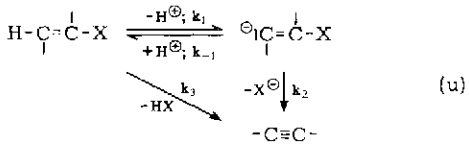
3. The more strongly a proton is acidified by electron-attracting substituents on the olefin, the more readily will it be detached by base; this substituent effect is greatest for a substituent on the same carbon atom as the leaving hydrogen atom. Thus, dehydrobromination of *cis*-β-bromostyrene with NaOH/isopropanol at 43 °C proceeds more slowly than that of the corresponding *p*-nitro-*cis*-β-bromostyrene [115] by a factor of 1200 [116].

4. If the carbon atom bearing the leaving group X also carries an electron-attracting substituent, the elimination is retarded, since this substituent renders the carbon atom, to which it is attached, more positive and so opposes release of the bonding doublet.

The question is, therefore, when is the E2 reaction realized, and when does an E1cB mechanism prevail? In view of the apparently favored position of the synchronous process in general, there is a tendency to classify all bimolecular eliminations *a priori* as E2 reactions, whenever a carbanion cannot be detected as an intermediate. Strictly speaking, a carbanion can be detected only if the corresponding organometallic compound can be isolated and its rate of decomposition measured.

In principle, as the parameters 1. to 4. are varied, an E1cB mechanism should be favored when halogen is firmly bonded to the carbon atom and the α- and β-carbon atoms carry electron-attracting substituents. These conditions are ideally satisfied in trifluoroethylene whose lithium derivative (as a potential carbanion) can be prepared in solution [117] and is reasonably stable in ether at −70 °C [118] (for further examples, see Section III.B). If the intermediate carbanion cannot be isolated, it must be detected indirectly by introduction of reagents which can compete with the elimination step for the carhanion. The simplest case, the reversibility of the deprotonation, is tested by carrying out the reaction in the presence of a deuterium donor; elimination is then interrupted prematurely and the substrate is examined for incorporation of deuterium. An equivalent method is the use of a deuterated substrate in the presence of a proton donor.

Detection of a carbanion intermediate makes an E1cB mechanism likely, but does not prove it conclusively; it is conceivable that the elimination still occurs as a synchronous process, and that the acid-base equilibrium ($k_1 \rightleftarrows k_{-1}$) indicated by Equation (u) represents a reversible side-reaction.



(u)

[115] *A. T. Dann, A. Howard,* and *W. Davies,* J. chem. Soc. (London) *1928*, 605.

[116] *S. J. Cristol* and *W. P. Norris,* J. Amer. chem. Soc. *76*, 3005 (1954).

[117] *D. Seyferth, D. E. Welch,* and *G. Raab,* J. Amer. chem. Soc. *84*, 4266 (1962).

[118] *P. Tarrant, P. Johncock,* and *J. Savory,* J. org. Chemistry *28*, 839 (1963).

The possibility has recently been discussed that the energy of the transition state of the E2 elimination may be less in such cases than that of the elimination step from the carbanion ($k_3 > k_2$) [119].

An additional criterion for the two-stage process is provided by kinetic measurements: the deuterated, compound should undergo elimination in deuterium-active media at approximately the same rate as the non-deuterated substrate in the corresponding protonic solvent, since an isotope effect can manifest itself in only a slight displacement of the initial equilibrium $k_1 \rightleftarrows k_{-1}$, with a resultant slight change in the steady-state concentration of the carbanion, but it cannot affect the rate-determining elimination step to any great extent.

Competition experiments also yield information on the configurative stability of the intermediate carbanion, since, if inversion of configuration occurs, the starting material which is recovered is a mixture of *cis*- and *trans*-isomers if one of the two olefinic carbon atoms carries different substituents [120] [*].

Apparently all olefins with hydrogen and halogen substituents on the same unsaturated carbon atom can undergo base-catalysed H–D exchange, as indicated by experiments on bromostyrene, 1,2-dihalogenoethylenes [121], and 1,1-diphenyl-2-chloroethylene [122]. The rates at which *cis*-dichloroethylene and *cis*-dibromoethylene undergo exchange with sodium methoxide in D_2O are roughly equal, but the rates of deuteration of the *trans*-compounds decrease in the order of decreasing acidity of their hydrogen atoms, *i.e.*

CHCl=CHCl > CHBr=CHBr > CHI=CHI.

Isomerization of the bromo-olefins, but not of the chloro-olefins, occurs in the course of this reaction. The isotope effect k_h/k_d found for the *cis*-dibromo compound at 35.4 °C is 1.03, a very low value indeed [121]. Thus it seems that this *trans*-elimination proceeds by an E1cB mechanism. This mechanism can also be assumed to apply to the elimination of HCl from trichloroethylene; this compound is deuterated in alkaline media [123]. The intermediate trichlorovinyl anion can be isolated as its Hg salt by alkaline mercuric cyanide [16]. The same method can be applied to *trans*-dichloroethylene, but not to the *cis*-isomer [124]. The trichlorovinyl anion is also obtained as an intermediate on decarboxylation of salts of perchloroacrylic acid [74] (see Section II.C.1).

[119] *R. Breslow,* Tetrahedron Letters *1964*, 399.

[120] The configurational stability of alkenyl anions is remarkably high compared to that of alkyl anions, cf. *D. Y. Curtin* and *W. J. Koehl,* J. Amer. chem. Soc. *84*, 1967 (1962), where references to earlier publications are given; *R. L. Letsinger,* Angew. Chem. *70*, 151 (1958); also reviewed by *D. Seyferth,* Progr. inorg. Chem. *3*, 129 (1962), and by *H. D. Kaesz* and *F. G. A. Stone* in H. Zeiss: Organometallic Chemistry. Reinhold Publ. Corp., New York 1960, p. 88.

[*] This method is not of great value if $k_2 \gg k_{-1}$ in Equation (u) for the inverted carbanion; this possibility and its consequences have been discussed by *Miller* and *Noyes* [114].

[121] *S. I. Miller* and *W. G. Lee,* J. Amer. chem. Soc. *81*, 6313 (1959).

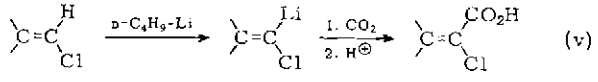
[122] *J. G. Pritchard* and *A. A. Bothner-By,* J. physic. Chem. *64*, 1271 (1960).

[123] *T. J. Houser, R. B. Bernstein, R. G. Miekka,* and *J. C. Angus,* J. Amer. chem. Soc. *77*, 6201 (1955).

[124] *M. FitzGibbon,* J. chem. Soc. (London) *1938*, 1218.

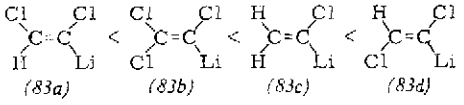
B. Metallated Halogeno-Olefins as Intermediates

Some of the chloroethylene carbanions which have so far been formulated only as intermediates can be prepared in solution as their lithium derivatives by metallation of the chloroethylenes with n-butyl-lithium in tetrahydrofuran at sufficiently low temperatures. Subsequent carboxylation and acidification [see Equation (v)] yield the chloroacrylic acids expected from *(83b)* to *(83d)*, in yields of 80–100 % [125].



(v)

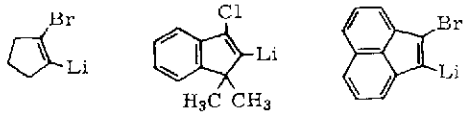
The stabilities of the carbanions increase as follows:



(83a) *(83b)* *(83c)* *(83d)*

It can be seen that the more unstable compounds have the metal atom in the *trans*-position with respect to a halogen atom. *trans*-β-Elimination evidently takes place with greater ease than the equally feasible *cis*-β- or α-eliminations [125].

A few five-membered cyclic olefins, *e.g. (84)*, *(85)*, and *(86)*, with adjacent lithium and halogen substituents are



(84) *(85)* *(86)*

stable for some time even at room temperature, since elimination of lithium halide is opposed by the extremely high ring strain in the cyclopentyne derivative expected as elimination product (cf. Section II.E) [125a]. Proof that vinyl chloride, for example, is deprotonated on the halogen-substituted carbon atom by means of n-butyl-lithium in tetrahydrofuran, raises the possibility that this reaction, as well as other dehydrohalogenations caused by strong bases in ethereal solvents and formally appearing as β-eliminations proceed *via* α-metallation. On the basis of his work on β-bromostyrene *Cristol* put forward this suggestion together with the observation that several dehydrohalogenations by organolithium compounds or alkali metal amides described in the literature proceed very readily when the halogen-substituted carbon atom is also bonded to a hydrogen atom [126]. This phenomenon is illustrated [47] by the fact that β-methyl-β-chlorostyrene reacts only incompletely with phenyl-lithium in ether, even after several days, whereas β-chlorostyrene reacts instantaneously under these conditions (cf. Section II.A.3).

1,1-Diphenylchloroethylene also reacts more rapidly with phenyl-lithium than either of the two isomeric chlorostilbenes [111], obviously because the hydrogen atom is more acidic. The α-metal compounds cannot be detected in ether which is only slightly polar, because here the deprotonation is the slow step, and therefore the rate-determining one, being followed by the elimination which proceeds rapidly. On the other hand, in the more strongly polar tetrahydrofuran, the rate of irreversible removal of protons can be increased by means of the organometallic base, so that it occurs more quickly than the elimination (see below).

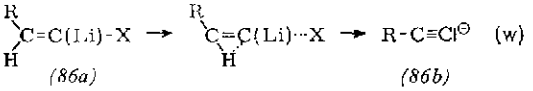
A number of examples have been reported in which *trans*-elimination of hydrogen halide by strong bases was not more favored than *cis*-elimination, and sometimes proceeded even more slowly than the latter. These examples are listed in Table 2 (cf. Section II.A.3). Isomerization prior to elimination might make it appear as if the rates were approximately equal, but

Table 2. Relative rates of dehydrohalogenation of stereoisomeric olefins with strong bases.

Substrate	Base/Solvent	k_{cis}/k_{trans} [*]	Ref.
$C_6H_5-CH=CBr-C_6H_5$	Lithium piperidide/ Diethyl ether	1.7	[129]
$C_6H_5-CH=CCl-C_6H_5$	Phenyl-lithium/ Diethyl ether	23	[111]
$C_6H_5-CH=CHBr$	Phenyl-lithium/ Di-n-butyl ether	6	[126]
	Phenyl-lithium/ Diethyl ether	2	[126]
	α-Piperidyl-lithium/ Diethyl ether	1.3	[129]
$C_6H_5-CH=CHCl$	Phenyl-lithium/ Diethyl ether	9.9	[127]
$ClCH=CHCl$	Methyl-lithium/ Diethyl ether	0.8	[130]

[*] Here *cis* and *trans* denote the relative positions of hydrogen and halogen atoms in the substrate.

this is not the case [120]. Owing to the stability within the series *(83a)* to *(83d)* there is no reason to suppose that in these cases the validity of the rule is broken, according to which removal from the *trans*-arrangement of the two substituents at neighboring carbon atoms is preferred. Thus the reaction rates must depend on differences in the acidity of the olefinic hydrogen atoms and on steric factors and solvent effects.



(86a) *(86b)*

(w)

It is an interesting question, though not yet fully solved, how α-metalled substrates *(86a)*, bearing a hydrogen atom on the β-carbon atom, are converted into the end product of the elimination, *viz.* an anionized acetylene

[125] *G. Köbrich* and *K. Flory*, Tetrahedron Letters *1964*, 1137.

[125a] *G. Wittig* u. *H. Heyn*, Chem. Ber. *97*, 1609 (1964); *J. Weinlich*, Ph.D. Thesis, Universität Heidelberg, 1964; *K. Rasheed*, Ph.D. Thesis, Universität Heidelberg, 1964.

[126] *S. J. Cristol* and *R. F. Helmreich*, J. Amer. chem. Soc. *77*, 5034 (1955).

[127] *M. Schlosser* and *V. Ladenberger*, Tetrahedron Letters, *1964*, 1945.

[128] *D. Y. Curtin*, *E. W. Flynn*, and *R. F. Nystrom*, J. Amer. chem. Soc. *80*, 4599 (1958).

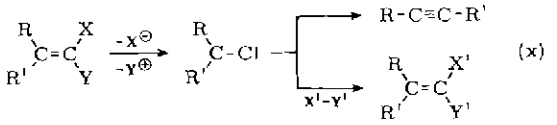
[129] *W. Mack* and *K. Herbig*, unpublished results cited by *R. Huisgen* und *J. Sauer*, Angew. Chem. *72*, 91 (1960), p. 102.

[130] *H.-G. Viehe*, Chem. Ber. *92*, 1950 (1959).

derivative *(86b)*. A carbene is not formed as a product of α-elimination [Equation (x)] in the case of vinyl chloride [125] and β-chlorostyrene [127]. A competitive experiment [127] shows that phenylacetylene is excluded as an intermediate arising from dehydrochlorination of β-chlorostyrene using phenyllithium in ether. Accordingly, the β-hydrogen atom is abstracted by the base [either *(86a)* or excess reagent] while it is yet bound to the β-carbon atom. This process may occur on an intermediate where – by analogy with the Fritsch-Buttenberg-Wiechell rearrangement (see following section) – the hydrogen atom is situated between both olefinic carbon atoms [Equation (w)] thus assisting removal of halogen [125]; or the base can attack the metallated substrate *(86a)* directly [127]. In *(86a)* the metal atom promotes negative polarization of the olefin. This makes deprotonation of the β-carbon atom more difficult, but facilitates removal of halogen from the α-carbon atom. Is it probable that protons become sufficiently mobile only when partial removel of the halogen atom, involving (relative) positive polarization of the rest of the molecule, occurs. The mechanism of dehydrohalogenation of substrates of type R–CH–CHX with organolithium compounds is then a limiting case of α-elimination and "E1-type" β-elimination.

C. α-Eliminations

α-Eliminations are characterized by the fact that both leaving groups X and Y are situated on the same carbon atom. The methods of cleavage are the same as those discussed for β-eliminations. In contrast with the latter, however, α-eliminations do not lead directly to stable products, but instead an organic residue with an



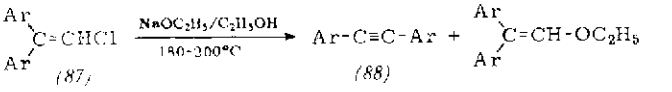
(x)

electron sextet can be considered to be formed, as indicated in Equation (x), which is then stabilized by secondary reactions, such as addition of suitable reagents or rearrangement to acetylenes.

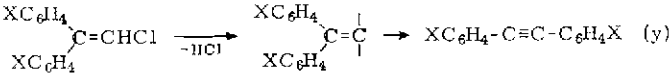
1. Fritsch-Buttenberg-Wiechell Rearrangement

a) *Scope and Limitation*

In 1894, while investigating 1,1-diaryl-2-chloroethylenes *(87)* [131, 132], *Fritsch*, *Buttenberg*, and *Wiechell* found that the parent compound and its various *p*-substituted derivatives were converted into diphenylacetylenes on reaction with sodium ethoxide/ethanol at 180–200 °C. Vinyl ethers were also formed in this reaction by substitution, in amounts depending upon the aromatic residues involved. Thus, only 9 % of the acetylene *(88)* is obtained from *(87)* with Ar = C_6H_5, but the yield of *(88)* is 85 % when Ar = *p*-CH_3–C_6H_4. The positions of the substituents in the aromatic residue remain unchanged during the rearrangement, *i.e.* the bonds which are broken and the new bonds which are formed are on the same aromatic carbon atom.



The rearrangement was formulated as a sextet rearrangement, according to Equation (y) [131]. The reaction between molten KOH and 1,1-diphenyl-2-bromoethylene also gives high yields of diphenylacetylene

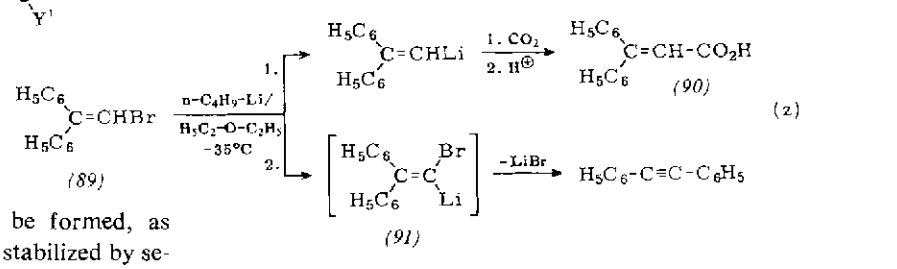


(y)

[133]; α-methyl-β-bromostyrene is converted in a similar manner into phenylmethylacetylene, 1-phenylcyclopropene being postulated as an intermediate [134]. Diphenylacetylenes can be obtained from the appropriate chloro- [135] or bromo-olefins [136] under very much milder conditions with alkali metal amides in liquid ammonia, often in 90–95 % yields.

1,1-Diphenyl-2,2-dichloroethylene also gives diphenylacetylene on reaction with sodium powder/benzene [137] or phenyl-lithium/ether [138]; its reaction with sodamide or benzhydrylpotassium in liquid ammonia, on the other hand, leads predominantly to substitution products [138].

α-Eliminations from diarylhalogenoethylenes initiated by organolithium compounds were first investigated by *Curtin*. 1,1-Diphenyl-2-bromoethylene *(89)* is rapidly attacked by n-butyl-lithium in ether at –35 °C; sub-



(z)

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[131] *P. Fritsch*, Liebigs Ann. Chem. *279*, 319 (1894); *W. P. Buttenberg*, ibid. *279*, 324 (1894); *H. Wiechell*, ibid. *279*, 337 (1894).

[132] A short review of results published up to 1958 is given by *V. Franzen*, Chemiker-Ztg. *82*, 220 (1958).

[133] *P. Lipp*, Ber. dtsch. chem. Ges. *56*, 567 (1923).

[134] *M. Tiffeneau*, C. R. hebd. Séances Acad. Sci. *135*, 1346 (1902).

[135] *G. H. Coleman* and *R. D. Maxwell*, J. Amer. chem. Soc. *56*, 132 (1934).

[136] *G. H. Coleman*, *W. H. Holst*, and *R. D. Maxwell*, J. Amer. chem. Soc. *58*, 2310 (1936).

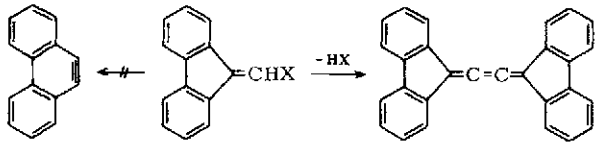
[137] *E. E. Harris* and *G. B. Frankforter*, J. Amer. chem. Soc. *48*, 3144 (1926).

[138] *F. B. Kirby*, *W. G. Konfron*, and *C. R. Hauser*, J. org. Chemistry *28*, 2176 (1963).

sequent carboxylation yields roughly equal amounts of diphenylacetylene and β-phenylcinnamic acid *(90)*, owing to competition between deprotonation and halogen-metal exchange [Equation (z)]. The halogen-free lithium compound is stable, and can therefore be converted into a derivative, while the metal compound *(91)* postulated as a primary product of metallation, rearranges instantaneously to diphenylacetylene, with elimination of LiBr [139].

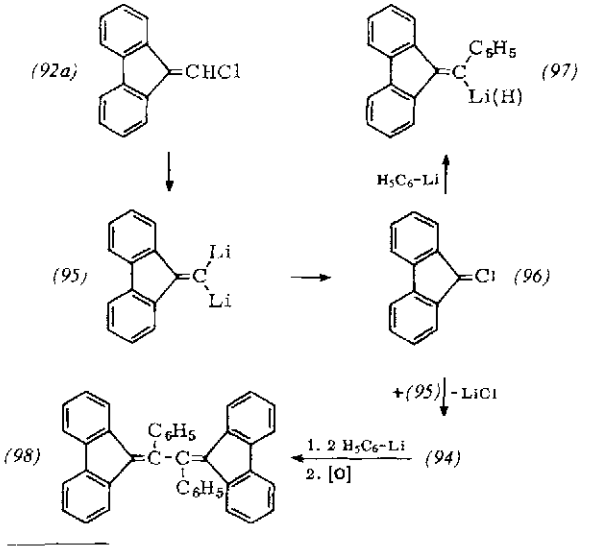
In accordance with the rule formulated by *Wittig*, replacement of bromine by chlorine in *(89)* leads predominantly to metallation (Route 2); with iodine instead of bromine in *(89)*, halogen-metal exchange (Route 1) predominates. The extent to which the reaction follows each of the two paths also depends on the organolithium compound, salt effects, and effects of the substituents on the aryl residue [139, 140]. The reaction of 1,1-diphenyl-2,2-dibromoethylene with phenyl-lithium can only proceed by Route 2, *via* halogen-metal exchange [140].

The interesting question of the extent to which linkage of the two aryl residues suppresses the Fritsch-Buttenberg-Wiechell rearrangement has been examined independently by two groups of workers [140, 141]. Rearrangement of 9-halogenomethylenefluorene *(92)* should lead to the highly strained compound 9,10-dehydrophenanthrene *(93)*; however, the reaction of *(92)*, X = Br, with potassamide in liquid ammonia leads to a 95 % yield of the cumulene compound *(94)*,



(93) *(92)* *(94)*

which was already known [142] and which is also the principal product of the reaction of *(92)* with phenyl-lithium in ether at −35 °C [140]. The reaction of 9-chloromethylenefluorene *(92a)* with phenyl-lithium



[139] *D. Y. Curtin* and *E. W. Flynn*, J. Amer. chem. Soc. *81*, 4714 (1959).

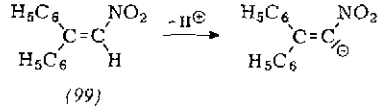
[140] *D. Y. Curtin* and *W. H. Richardson*, J. Amer. chem. Soc. *81*, 4719 (1959).

[141] *C. R. Hauser* and *D. Lednicer*, J. org. Chemistry *22*, 1248 (1957).

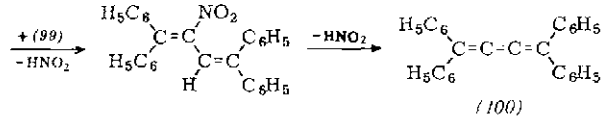
[142] *R. Kuhn* and *G. Platzer*, Ber. dtsch. chem. Ges. *73*, 1410 (1940).

yields only 18 % of 1,4-bis-*o,o'*-biphenylylbutatriene *(94)*, together with an approximately equal amount of 9-benzylidenefluorene *(97)* and a hydrocarbon of the supposed structure *(98)*; *(98)* may result from additon of two moles of phenyl-lithium onto *(94)*, followed by oxidation. The formation of the cumulene derivative *(94)* and of benzylidenefluorene *(97)*, is thought to be due to the carbene compound *(96)* [140, 141], which can add on phenyl-lithium or the metal compound *(95)* postulated as an intermediate.

1,4-Bis-*o,o'*-biphenylylbutatriene *(94)* could also be formed by an alternate route, such as that discussed for the formation of tetraphenylbutatriene *(100)* from 1,1-diphenyl-2-nitroethylene *(99)* with potassium t-butoxide. This route is easily understood from Equation (α) without further comment [143].

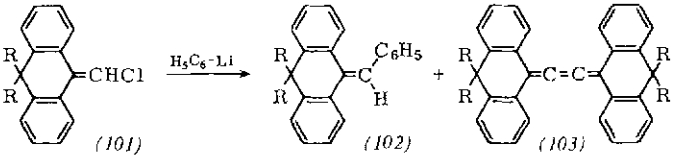


(99) (α)



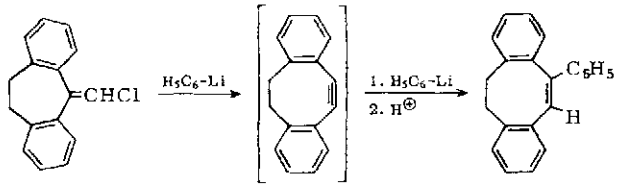
(100)

Phenyl-lithium reacts with 10,10-dialkyl-9-chloromethylene-9,10-dihydroanthracene *(101)* to form the hydrocarbons *(102)* and *(103)* which seem to have been formed in the same way as *(94)* and *(97)* from *(92a)* [140].



(101) *(102)* *(103)*

On the other hand, the seven-membered ring compound *(104)* does not give a cumulene derivative, but gives instead 3-phenyldibenzo[*a,e*]cycloocta-1,3,5-triene *(106)* the only product identified, in 23 % yield.



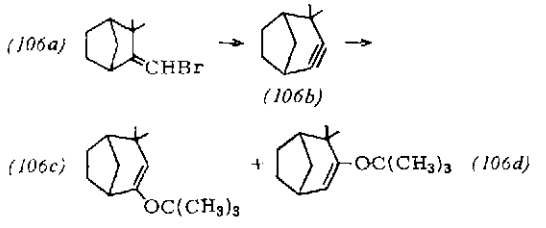
(104) *(105)* *(106)*

It appears that this system is already flexible enough to permit a Fritsch-Buttenberg-Wiechell rearrangement to occur. Dibenzo[*a,e*]cycloocta-1,5-dien-3-yne *(105)* formed in the first step is so reactive, because of ring strain (Section II.E) that it adds on phenyl-lithium across the triple bond [140].

β-Dialkylated halogeno-olefins are not known to undergo the Fritsch-Buttenberg-Wiechell rearrange-

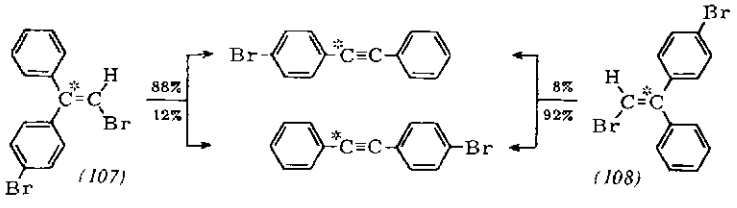
[143] *W. M. Jones* and *C. D. Broaddus*, J. org. Chemistry *26*, 2316 (1961).

ment. An exception is the bicyclic ω-bromocamphene *(106a)* which, using potassium t-butoxide in toluene, gives in high yield a mixture of the isomeric ethers *(106c)* and *(106d)*; the reaction involves ring enlargement, the strained compound *(106b)* probably being formed as an intermediate [143a].



b) *Mechanism*

In view of the experimental findings discussed above, it might appear that α-elimination proceeds *via* a carbene, which either undergoes the Fritsch-Buttenberg-Wiechell rearrangement as shown in Equation (x) or is stabilized by addition reactions. However, it appears from a number of observations that formation of carbenes does not occur during reactions where the rearrangement takes place. Thus, typical carbene reactions, such as their addition onto multiple bonds (*e.g.* in diphenylacetylene already formed by the reaction or in added olefins) or insertion reactions, are unknown [144]. It has also been shown that the rearrangement is stereospecific. Thus, the principal product obtained when *trans*-[2-^{14}C]-2-(*p* bromophenyl)-2-phenylvinyl bromide *(107)* is heated for 36 h with potassium t-butoxide in t-butanol is *p*-bromodiphenylacetylene in which the labelled carbon atom carries the bromophenyl residue, whereas the *cis*-isomer *(108)*, gives the same product with the phenyl residue attached to the radioactive carbon atom [145].

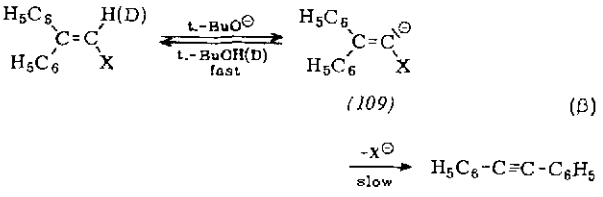


Essentially similar behavior is shown by the analogous chloro compounds on rearrangement with n-butyllithium in ether [128]. Thus, since the reaction is stereospecific, it cannot be due to a carbene which is symmetrical with respect to the olefinic axis.

The same isotope technique was used to show that, during α-elimination from 1-phenyl-1-(*p*-anisyl)-2-bromoethylene with sodium glycoxide, the anisyl group always migrates preferentially [146]. The greater tendency of the anisyl group to migrate has been confirmed by other experiments.

However, this experiment is not conclusive, since it has evidently not yet been checked whether partial isomerization of the substrate (which is quite possible at high temperatures) prior to elimination might not simply be simulating a uniform migration.

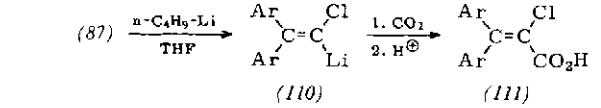
Eliminations in alkoxide/alcohol systems differ characteristically in their mechanism from those with lithium alkyls in ether. Kinetic measurements with potassium t-butoxide in t-butanol revealed an isotope exchange between the olefinic hydrogen of diphenylhalogenoethylenes and *O*-deuterated solvents, which is rapid in comparison with the rearrangement [122]. It can therefore be assumed (with the limitation discussed above, cf. Section III.A.2) that the rearrangement is preceded by rapid establishment of an acid-base equilibrium as indicated in Equation (β), and that the rearrangement is in fact that of the carbanion *(109)* [122].



The effect of the halogen atom on the rate of rearrangement at 95 °C decreases in the order Br > I ⋙ Cl; the opposing effects of bond strength and acidification of the vinyl hydrogen cause optimum reaction to occur with the bromo compound [122].

In the reaction of diarylhalogenoethylenes with butyllithium in ether, on the other hand, the rate-determining step is deprotonation [139], as evidenced by the lower rate of reaction of the deuterated ethylenes and by the fact that vinyl-lithium intermediates cannot be isolated. Consequently, it cannot be said with certainty whether the anion *(109)* postulated in Equation (β) (or the corresponding lithium compound) is in fact formed in this solvent, or whether the reaction is a multicenter concerted process with simultaneous deprotonation, elimination of halogen, and migration of the aryl residue [111].

As with the halogenoethylenes discussed above, the metallation is greatly accelerated by using n-butyllithium in the more strongly polar solvent, tetrahydrofuran and becomes the faster reaction step. The halogenovinyl-lithium compounds *(110)* can therefore be prepared and characterized as the carboxylation products *(111)* [147].



[143a] *J. Wolinsky*, J. org. Chemistry *26*, 704 (1961), and references given there.

[144] *W. Kirmse*, Angew. Chem. *73*, 161 (1961); Progress in Organic Chemistry. Butterworth, London 1964, Vol. 6, p. 164; *P. Miginiac*, Bull. Soc. chim. France *1962*, 2000; *E. Chinoporos*, Chem. Reviews *63*, 235 (1963).

[145] *A. A. Bothner-By*, J. Amer. chem. Soc. *77*, 3293 (1955).

[146] *W. Tadros, A. B. Sakla, M. S. Ishak*, and *E. R. Armanious*, J. chem. Soc. (London) *1963*, 4218.

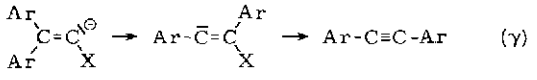
[147] *G. Köbrich* and *H. Trapp*, Z. Naturforsch. *18b*, 1125 (1963).

Lithium chloride is eliminated on heating, yielding the corresponding diarylacetylenes; this supplies conclusive proof that the rearrangement occurs in the (potential) carbanion [147].

To summarize: the Fritsch-Buttenberg-Wiechel rearrangement takes place in the vinyl anion; it does not proceed *via* a carbene intermediate, but is largely stereospecific, the group in the *trans*-position relative to the halogen migrating to the neighboring carbon atom; the rearrangement is intramolecular, since no symmetrical acetylenes are isolated when the starting materials contain dissimilar aryl substituents; the nature of the halogen atom has a decisive influence on the rate of the rearrangement.

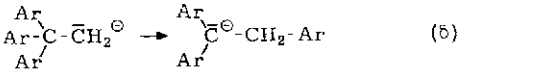
On the basis of these facts, two mechanisms are possible:

1. The migrating aryl group is transferred to the anionic vinyl carbon atom carrying the halogen atom by an intramolecular nucleophilic aromatic substitution; this results in displacement of the negative charge to the adjacent carbon atom. Halide is then eliminated in a secondary reaction [cf. Equation (γ)].



(γ)

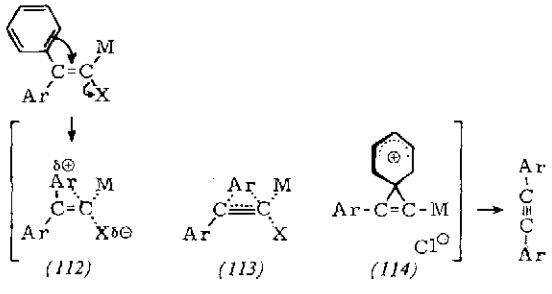
A parallel to this is the rearrangement of 1,1,1-triarylethyl anions [Grovenstein-Zimmerman rearrangement, see Equation (δ)] [148], although the driving force for



(δ)

this isomerization – namely greater stabilization of the resulting carbanion – can scarcely be effective in Reaction (γ) [*]. Moreover, on the basis of the observed effect of the halogeno substituent, it is necessary to make the improbable assumption that the elimination of halogen from the rearranged anion is rate-determining.

2. The halogen is eliminated from the anion with simultaneous migration of the aryl residue, possibly *via* transition or intermediate states such as *(112)–(114)*



(112) *(113)* *(114)*

[148] *H. E. Zimmerman* and *A. Zweig*, J. Amer. chem. Soc. *83*, 1196 (1961); *E. Grovenstein* and *L. P. Williams*, ibid. *83*, 412, 3537 (1961). The rearrangement does not always proceed intramolecularly, cf. *E. Grovenstein* and *G. Wentworth*, J. Amer. chem. Soc. *85*, 3305 (1963).

[*] It can be shown by deuterium exchange that a phenyl substituent does not appreciably acidify the hydrogen atom on an olefinic carbon atom to which it is attached. This can be explained by the fact that benzenoid and olefinic carbon atoms have the same hybridization [121].

[M = metal] which differ only in the extent to which the breaking and formation of bonds and the build-up of the electron doublet has advanced.

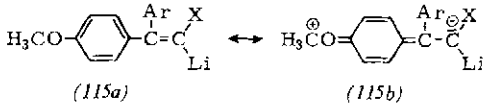
A mechanism of this type was postulated by *Bothner-By* in 1955 [145]. It requires that the aryl residue assumes a partial positive charge in the transition state, whereas it is negatively charged in Mechanism 1.

The question as to which mechanism is correct can be settled conclusively by introduction of substituents into the aryl residue: rearrangement by Mechanism 2 should be accelerated by electron-releasing substituents in the *o*- and/or *p*-positions, whereas that by Mechanism 1 should be retarded. It is found in confirmation of Mechanism 2, for instance, that the lithium compound *(110)*, Ar = C_6H_5, is still at least 83 % undecomposed after 1 h at −72 °C, whereas at least 91 % of its *p*-methoxy derivative *(110)*, Ar = *p*-CH_3O-C_6H_4, is rearranged. Furthermore, 88 % of *(110)* with Ar = *p*-Cl-C_6H_4 remains intact at −45 °C under conditions under which the unsubstituted derivative (Ar = C_6H_5) is completely decomposed [147, 149].

Mechanism 2 is also supported by kinetic measurements on various nuclear-substituted diarylhalogenoethylenes in the system t-butoxide/t-butanol [150] and ethoxide/ethanol [151] at elevated temperatures. However, here allowance must be made for the possible occurrence of side reactions and for the fact that nuclear substituents have a strong effect on the acidity of the vinyl protons [139, 147, 149] and hence, *via* the initial acid-base equilibrium [Equation (β)], on the steady-state concentration of vinyl anions.

All the experimental results obtained so far indicate that the aryl residue migrates with its bonding electron pair to the adjacent carbanion. The negative charge on the olefinic carbon atom evidently satisfies the condition for easy elimination of halogen.

The extent to which the migrating aryl residue favors the elimination in the sense of anchimeric assistance is not yet known. The great retendency of the *p*-methoxyphenyl compound *(110)* to undergo rearrangement compared to the unsubstituted compound can be explained, not only by a stronger neighboring-group effect of this substituent relative to phenyl, which is really quite plausible, but also because it imparts additional negative charge to the α-carbon atom as a result of resonance *(115a)* ↔ *(115b)* which is demonstrated



(115a) *(115b)*

by the greater difficulty of metallation of this compound compared to the simple phenyl derivative [147, 149]. The fact that the lithium derivative of *(116)* rearranges more slowly [149] and that in the ethoxide/ethanol system *(117)* rearranges more rapidly [152] than their respective stereoisomers may

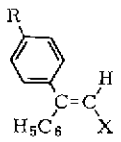
[149] *G. Köbrich*, *H. Trapp*, and *I. Hornke*, Tetrahedron Letters *1964*, 1131.

[150] *W. M. Jones* and *R. Damico*, J. Amer. chem. Soc. *85*, 2273 (1963).

[151] *P. Beltrame* and *S. Carra*, Gazz. chim. ital. *91*, 889 (1961); *P. Beltrame* and *G. Favini*, ibid. *93*, 757 (1963).

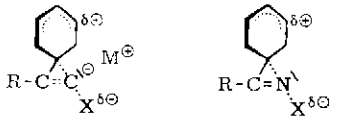
[152] *M. Simonetta* and *S. Carra*, Tetrahedron *19*, Suppl. 2, 467 (1963).

be due to active participation of the migrating aryl residue in the expulsion of halogen.



(116): R = X = Cl
(117): R = OCH_3; X = Br

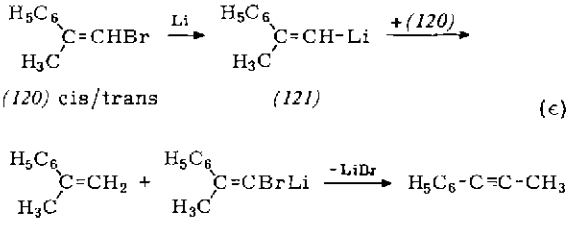
If an electromeric effect such as the mesomerism *(115a)* ↔ *(115b)* were the decisive factor, the opposite result would be expected. The neighboring-group effect should be weaker than in the formally comparable [145] first step of the Beckmann or Chapman rearrangement where a phenonium ion occurs as an intermediate [153], since the group $X^{\ominus}$ is probably more easily expelled from the carbanion *(118)* than from the uncharged nitrogen atom in *(119)*.



(118) *(119)*

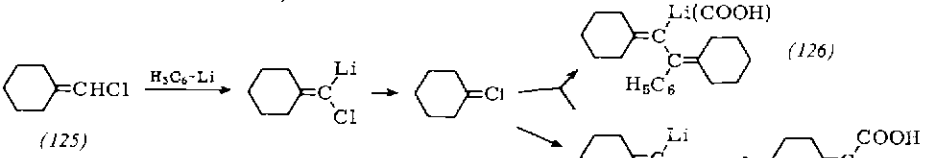
c) *Variants*

The production of disubstituted acetylenes *via* a rearrangement is also observed occasionally in the reaction of halogenated ethylenes with alkali metals, when an α-hydrogen atom is present. For example, *(120)* reacts with lithium in ether to yield equimolar quantities of methylphenylacetylene and α-methylstyrene [154]. It may be assumed that, owing to the difference in acidity between the halogenated and the non-halogenated olefin, the lithium compound *(121)* initially formed undergoes metal transfer with unreacted substrate *(120)* which then undergoes the Fritsch-Buttenberg-Wiechell rearrangement [Scheme (ε)].



(120) cis/trans *(121)* (ε)

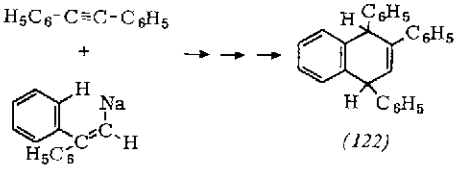
The olefins and acetylenes occurring as by-products in the reaction of β-halogenostyrenes [134] or 1-halogenopropenes with metals are probably formed in a similar manner,



(125)

although no definite conclusion can be reached at present owing to the presence of the β-hydrogen atom, and another mechanism has been proposed for the decomposition of the Grignard compound [155].

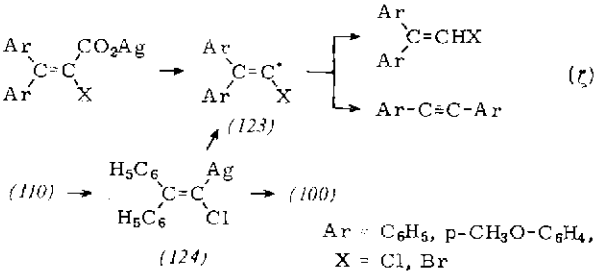
1,2,4-Triphenyl-1,4-dihydronaphthalene *(122)* is obtained on treatment of 1,1-diphenyl-2-bromoethylene with sodium in ether [156]. It is assumed that here the ring closure is due to addition of the metal compound onto diphenylacetylene formed analogously to the methylphenylacetylene in Equation (ε).



(122)

Attention is called in this connection to the formation of 1,2,3-triphenylnaphthalene by the action of lithium on diphenylacetylene; this reaction is related to the above with regard to the cyclization [157].

Rearrangement of the carbon skeleton is also observed on thermolysis of the potassium and silver salts of α-halogeno-β-arylcinnamic acids [158]. The thermolysis of the potassium salts proceeds *via* carbanions [cf. *(109)*], that of the silver salts possibly *via* free radicals *(123)* [Equation (ζ)] which are partly converted into ethylene by uptake of hydrogen, but which mainly undergo elimination of halogen to yield acetylenes.



(ζ)

(123)

(110) → *(124)* → *(100)*

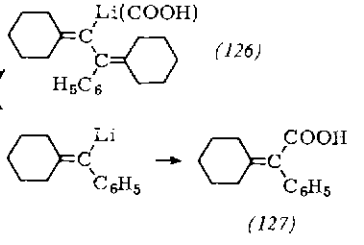
Ar = C_6H_5, p-CH_3O-C_6H_4,
X = Cl, Br

The same products are obtained by decomposition of the silver compound *(124)*, which in turn is formed by metathesis of the lithium alkenyl *(110)* with AgCl at low temperatures; furthermore, up to 40% tetraphenylbutatriene *(100)* can also be isolated [159].

2. α-Elimination *via* Carbenes

With the exception mentioned in Section III.C.1.a, no rearrangement of β,β-dialkylhalogenoethylenes to dialkylacetylenes has so far been observed. As in the case of substrates with interlinked aryl residues, reactions

(125)



(126) *(127)*

[153] Reviewed by *P. A. S. Smith* in P. de Mayo: Molecular Rearrangements. Interscience Publishers, New York-London 1963, Vol. I, p. 483.

[154] *D. Y. Curtin* and *J. W. Crump*, J. Amer. chem. Soc. *80*, 1922 (1958).

[155] *H. Normant*, [62], p. 7.

[156] *O. Blum*, Ber. dtsch. chem. Ges. *62* 881 (1929).

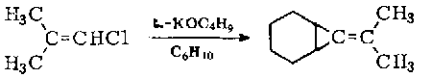
[157] *F. C. Leavitt*, *T. A. Manuel*, *F. Johnson*, *L. U. Matternas*, and *D. S. Lehmann*, J. Amer. chem. Soc. *82*, 5099 (1960); *E. H. Braye*, *W. Hübel*, and *I. Caplier*, J. Amer. chem. Soc. *83*, 4406 (1961).

[158] *G. Köbrich* and *H. Fröhlich*, Angew. Chem. *76*, 495 (1964); Angew. Chem. internat. Edit. *3*, 455 (1964).

[159] *G. Köbrich*, *H. Fröhlich*, and *W. Drischel*, unpublished results.

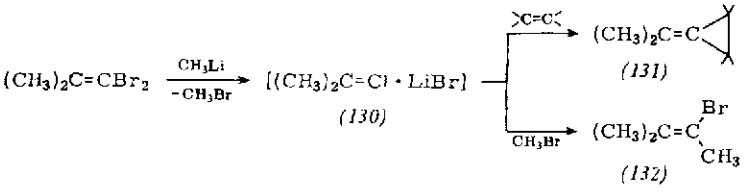
occur here which are compatible with the intermediate formation of carbenes. Treatment of chloromethylenecyclohexane *(125)* with phenyl-lithium in ether, followed by carboxylation, yields the acids *(126)* and *(127)* [160].

Compound *(129)* can be obtained in 8 % yield from 1-chloroisobutylene *(128)* and potassium t-butoxide in refluxing tetrahydrofuran in the presence of cyclohexane [161].



(128) *(129)*

One variant of the reaction *(128)* → *(129)* makes use of halogen-metal exchange between 1,1-dimethyl-2,2-dibromoethylene and methyl-lithium; with olefins, particularly vinyl ethers, the cyclopropane derivatives *(131)* are obtained, sometimes in good yield; these are always accompanied by bromotrimethylethylene *(132)* in a quantity inverse to the yield of cyclopropane.

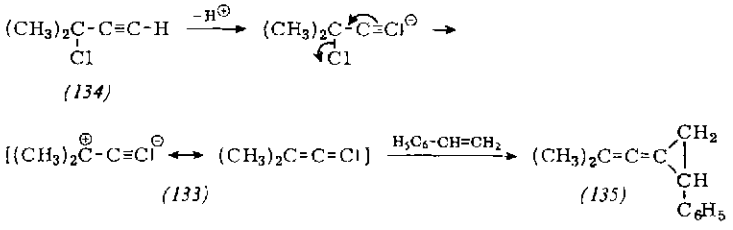


(130) *(131)* *(132)*

Whether, as has been suggested [162], both products are formed from the same intermediate *(130)*, which must then possess both electrophilic and nucleophilic properties, has not yet been settled, since other mechanisms are conceivable for the formation of *(132)*.

Apart from the fundamental objections which can be brought against the occurrence of carbenes in organometallic reactions [163], carbene reactions such as additions onto double bonds occur during α-elimina-

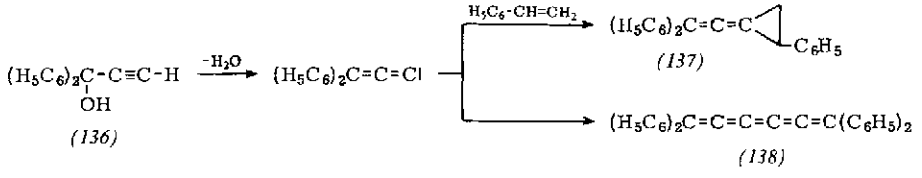
tions from olefins, as far as is known at present, only when isomerization by migration of a β-substituent (H or an aryl group) is not possible. 1,2-Shifts also predominate for aliphatic [164] and, in particular, for cyclopropyl compounds [165] and can be often more readily explained as reactions of the organometallic intermediate. The formation of carbene is facilitated here, as with haloforms, by hetero-substituents which permit resonance stabilization of the electron sextet ($X-\dot{\underset{|}{C}} \leftrightarrow {}^{\oplus}X = \dot{\underset{|}{C}}^{\ominus}$) [166]. Among the olefins, a similar stabilization is possible with the allenecarbenes. This is probably the reason for the ease of formation of *(133)* by γ-elimination on treatment of 3-chloro-3-methylbut-1-yne *(134)* with bases [166a]; *(133)* can be isolated in 48 % yield by trapping it with styrene as the cyclopropane derivative *(135)*.



(134) *(133)* *(135)*

The same product was obtained from 1,1-dimethyl-3-chloroallene — which is isomeric with *(134)* — by reaction of potassium t-butoxide in the presence of styrene [168].

Similarly, the adduct *(137)* is obtained on treating *(136)* with acetic anhydride and potassium hydroxide in absolute ether in the presence of styrene [167]; in the absence of styrene a dimer, tetraphenylhexapentaene *(138)*, is formed [169].



(136) *(137)* *(138)*

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Translated by Express Translation Service, London

[160] *H. Günther* and *A. A. Bothner-By*, Chem. Ber. *96*, 3112 (1963).

[161] *M. Tanabe* and *R. A. Walsh*, J. Amer. chem. Soc. *85*, 3522 (1963).

[162] *H. D. Hartzler*, J. Amer. chem. Soc. *86*, 526 (1964).

[163] *G. L. Closs* and *L. E. Closs*, J. Amer. chem. Soc. *85*, 99 (1963); *H. Hoberg*, Liebigs Ann. Chem. *656*, 1 (1962).

[164] *W. Kirmse* and *B.-G. v. Bülow*, Chem. Ber. *96*, 3323 (1963); *W. Kirmse* and *B. Graf v. Wedel*, Angew. Chem. *75*, 672 (1963); Angew. Chem. internat. Edit. *2*, 481 (1963).

[165] *W. v. E. Doering* and *P. M. LaFlamme*, Tetrahedron *2*, 75 (1958); *W. R. Moore*, *H. R. Ward*, and *R. F. Merritt*, J. Amer. chem. Soc. *83*, 2019 (1963); *W. R. Moore* and *H. R. Ward*, J. org. Chemistry *27*, 4179 (1962); *25*, 2073 (1960); *W. M. Jones*, *M. H. Grasley*, and *W. S. Brey*, J. Amer. chem. Soc. *85*, 2754 (1963); *W. M. Jones*, ibid. *82*, 6200 (1960); *L. Skatteböl*, Chem. and Ind. *1962*, 2146; Tetrahedron Letters *1961*, 167; *T. J. Logan*, ibid. *1961*, 173.

[166] *J. Hine* and *S. J. Ehrenson*, J. Amer. chem. Soc. *80*, 824 (1958).

[166a] *G. F. Hennion* and *D. E. Maloney*, J. Amer. chem. Soc. *73*, 4735 (1951); *G. F. Hennion* and *K. W. Nelson*, ibid. *79*, 2142 (1957).

[167] *H. D. Hartzler*, J. Amer. chem. Soc. *81*, 2024 (1959); *83*, 4990, 4997 (1961); *V. J. Shiner* and *J. W. Wilson*, ibid. *84*, 2402 (1962); cf. *F. Serratosa*, Tetrahedron Letters *1964*, 895.

[168] *H. D. Hartzler*, J. org. Chemistry *29*, 1311 (1964).

[169] *P. Cadiot*, Ann. Chimie (13) *1*, 214 (1956).

Pyrolysis of Alkyl Azidoformates in the Gas Phase [1]

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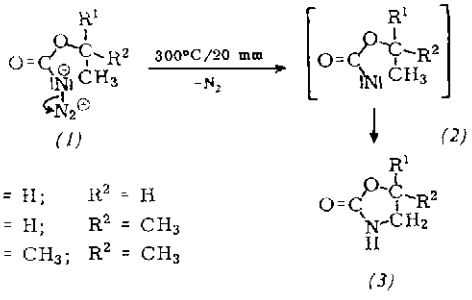
Institut für Organische Chemie der Technischen Hochschule Darmstadt (Germany)

Photolysis or thermolysis of alkyl azidoformates *(1)* causes elimination of nitrogen leading to alkoxycarbonylazenes *(2)*, which insert themselves into C–H bonds or dehydrogenate the solvent to form the corresponding alkylurethanes [2]. In order to avoid these secondary reactions, we investigated the pyrolysis of alkyl azidoformates in the gas phase in the presence of nitrogen as inert diluent. At 300 °C/20 mm, the ethyl, isopropyl, and t-butyl esters *(1a)*–*(1c)* release nitrogen to form oxazolidones *(3)* in yields of 45–75 %.



(1) *(2)* *(3)*

(a), R^1 = H; R^2 = H
(b), R^1 = H; R^2 = CH_3
(c), R^1 = CH_3; R^2 = CH_3

When ethyl azidoformate was thermolysed in carbon tetrachloride or 1,1,2-trichlorotrifluoroethane, it is not the oxazolidone *(3a)* that is formed [2a]; instead, two molecules of the azido ester interact with loss of nitrogen to form diethyl azodicarboxylate [2a, 3]. This compound could not so far be detected during pyrolysis in the gas phase. We assume that the concentration of *(1)* and *(2)* in the gas phase is so small as a result of the dilution with nitrogen that the dimerization observed in solution cannot occur [4].

In contrast, t-butyl azidoformate *(1c)* reacts exclusively intramolecularly to form the oxazolidone *(3c)* in solution as well. It seems that the t-butyl group shields the azene nitrogen and that the close proximity of the methyl group promotes the cyclization [2a, 2b].

According to *Smolinsky* and *Feuer* [5], thermal decomposition of (*S*)-2-methylbutyl azidoformate in the gas phase yields 4-ethyl-4-methyl-2-oxazolidone. The configuration of the asymmetric carbon atom remains unchanged during this reaction.

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[1] Pyrolysis of Organic Azides, Part 2. – Part 1: *R. Kreher* and *D. Kühling*, Angew. Chem. *76*, 272 (1964); Angew. Chem. internat. Edit. *3*, 309 (1964).

[2a] *R. Puttner* and *K. Hafner*, Tetrahedron Letters *1964*, 3119.

[2b] *R. Kreher* and *G. H. Bockhorn*, Angew. Chem. *76*, 681 (1964); Angew. Chem. internat. Edit. *3*, 589 (1964).

[2c] *D. S. Breslow* et al., Tetrahedron Letters *1964*, 2483, 2945.

[2d] *J. Hora*, Collect. czechoslov. chem. Commun. *29*, 1079 (1964).

[3] Cf. the investigations by *W. Lwowski*, *T. W. Mattingly*, and *T. J. Maricich* (Tetrahedron Letters *1964*, 1591) on the formation of diethyl azodicarboxylate from *(1a)* and *(2a)*.

[4] It remains an open question whether and to what extent the difference in behavior of *(1)* in the gas phase and in solution is determined by the reaction temperature and by solvation.

[5] *G. Smolinsky* and *B. I. Feuer*, J. Amer. chem. Soc. *86*, 3085 (1964).

Pentaleno[2,1,6-def]heptalene – a Non-benzenoid Isomer of Pyrene

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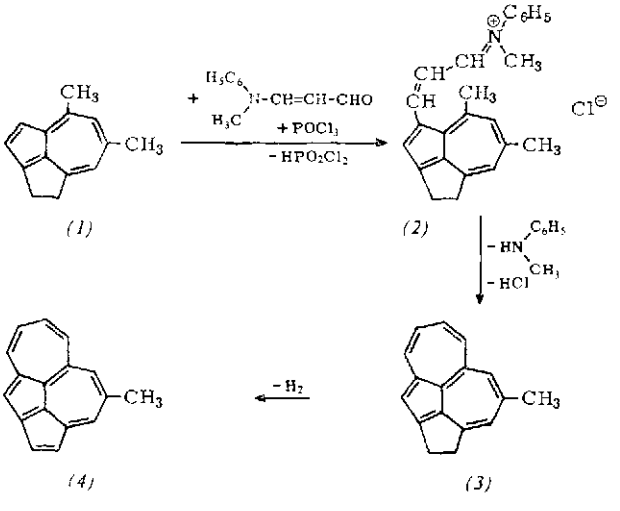
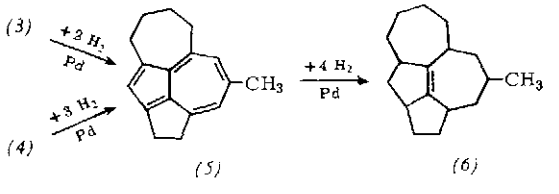
Polycyclic conjugated non-benzenoid hydrocarbons are of great theoretical interest in connection with the question of the relationships between structure and aromaticity [1].

Starting from 4,6-dimethyl-1,8-cyclopentenoazulene *(1)* [2], we have prepared a non-benzenoid isomer of methylpyrene, *viz.* the tetracyclic hydrocarbon *(4)*, which can formally be viewed as consisting either of a pentalene and a heptalene system or of two azulene systems. Moreover the structural elements of sesquifulvalene and heptafulvene are recognizable. Hydrocarbon *(1)* reacts with *N*-methylanilinoacrolein in the presence of phosphorus oxide chloride at 20 °C to form the immonium salt *(2)* in 90 % yield; the perchlorate of *(2)* forms dark violet crystals which decompose above 260 °C. When *(2)* is heated with sodium methoxide in boiling methanol, it loses a molecule of *N*-methylaniline and undergoes intramolecular condensation to give *(3)*, m.p. 62–63 °C, in 35 % yield; the trinitrobenzene π-complex of *(3)* melts at 196 °C. Dehydrogenation of *(3)* with chloranil in benzene at 20 °C produces a 65 % yield of *(4)* as thermostable black needles, m.p. 109 °C, which



(1) *(2)* *(3)* *(4)*

dissolve in organic solvents to give wine-red solutions which exhibit a green fluorescence. The electronic spectrum of *(4)* in n-hexane has maxima at 255 (log ε = 4.55), 262 (4.57), 284 (4.75), 291 (4.83), 317 (4.24), 367 (3.55), 382 (3.61), 396 (3.38), 405 (3.35), 421 (3.58), 449 (3.76), 504 (2.74), 539 (3.00), 582 (3.11), 710 (2.08), and 813 mμ (1.70). Its NMR spectrum contains a multiplet for the 9 ring protons at 1.5–3.3 τ in addition to a singlet for the methyl protons at 7.25 τ. Compound *(4)* forms a π-complex with trinitrobenzene of m.p. 209 °C. When hydrogenated at normal pressure it absorbs 3 moles of hydrogen to form the azulene derivative *(5)* as



(3) *(4)* *(5)* *(6)*

blue-green needles, m.p. 64 °C; the trinitrobenzene derivative of *(5)* melts at 139 °C. Reduction of *(3)* also gives rise to *(5)*. Further catalytic hydrogenation of *(5)* at normal pressure leads to an uptake of 4 moles of hydrogen, presumably to yield the hydrocarbon *(6)*, whose double bond can be detected with bromine or tetranitromethane. Although *(4)* is a cyclic conjugated system with $4n$ π-electrons ($n = 4$), it is surprisingly inert toward electrophilic reagents. It dissolves in 70 % perchloric acid and can be recovered unchanged from the solution by dilution at 0 °C.

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[1] *K. Hafner*, Angew. Chem. *75*, 1041 (1963); Angew. Chem. internat. Edit. *3*, 165 (1964).

[2] *K. Hafner* and *J. Schneider*, Liebigs Ann. Chem. *624*, 37 (1959).

Synthesis of Olefins from Sulfenes and Diazoalkanes via Episulfones

By Priv.-Doz. Dr. G. Opitz and Dipl.-Chem. Klaus Fischer

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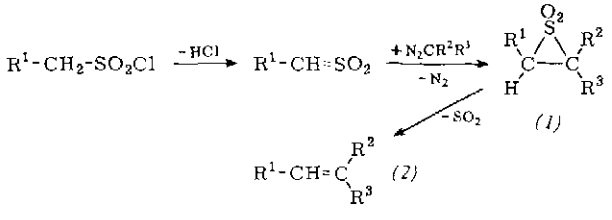
Diazomethane and sulfur dioxide react to form ethylene sulfone [1], which yields ethylene by elimination of SO_2. The reaction of higher diazoalkanes and sulfur dioxide leads via the corresponding episulfones to symmetrically substituted olefins [2].

We have now found that sulfenes $R^1-CH=SO_2$ [3], which are produced by dehydrochlorination of primary alkanesulfonyl chlorides with triethylamine, react readily *in situ* with diazoalkanes at 0 °C to form isolable episulfones *(1)*. Thermal elimination of SO_2 from the latter produces unsymmetrically substituted olefins *(2)* in good yields.



	R^1	R^2	R^3	Yield [%]	M.p. [°C] (B.p. [°C/mm])
(1a)	H	H	H	64	19
(1b)	C_2H_5	H	H	95	(80/0.2; decomp.)
(1c)	C_6H_5	H	H	35	39 (decomp.)
(2c)	C_6H_5	H	H	67	
(1d)	$C_6H_5CH_2$	H	H	99	49—51
(2d)	$C_6H_5CH_2$	H	H	97	(44/10)
(2e)	$C_6H_5CH_2$	H	CH_3	91	(62/10)
(1f)	$C_6H_5CH_2$	CH_3	C_2H_5	76	77—78
(1g)	7,7-Dimethyl-2-oxobicyclo-[2,2,1]hept-1-yl	H	H	94	83—85
(2g)		H	H	74	63 - 64
(1h)		H	CH_3	36	77—79
(2h)		H	CH_3	64	(62/0.02)
(2i)		CH_3	C_2H_5	71	(67/0.02)

When phenylethanesulfonyl chloride is added slowly to a solution of diazomethane and triethylamine cooled in ice, triethylamine hydrochloride is precipitated with simultaneous evolution of nitrogen, and allylbenzene episulfone *(1d)* is formed. The solution is filtered at room temperature and the ether evaporated from the filtrate leaving 99 % *(1d)* as colorless crystals, m.p. 49—51 from petroleum ether, which release SO_2 slowly at room temperature and rapidly on heating to 80 °C to afford a 97 % yield (based on the original sulfonyl chloride) of allylbenzene *(2d)*. The episulfones *(1a)*, *(1b)*, *(1c)*, *(1d)*, *(1f)*, *(1g)*, and *(1h)* have bands in the infrared at 3080 cm^{-1} due to the C—H vibration from the three-membered ring and intense sulfone bands at 1160 and 1305 cm^{-1}.

The olefin forms without isomerization, even when — as in the examples *(2d)—(2f)* — isomerization would lead to an increase in conjugation and hence in resonance energy. The synthesis of olefins by this method may be of preparative use. This is shown by the reaction of the readily available D-camphor-10-sulfonyl chloride to give the 10-alkylidene derivatives *(2g)—(2i)* of camphor whose synthesis by other methods is probably extremely difficult.

Received, November 4th, 1964 [Z 855/681 IE]
German version: Angew. Chem. 77, 41 (1965)

[1] *G. Hesse*, *E. Reichold*, and *S. Majmudar*, Chem. Ber. *90*, 2106 (1957). *G. Hesse* and *S. Majmudar*, ibid. *93*, 1129 (1960).

[2] *H. Staudinger* and *F. Pfenninger*, Ber. dtsch. chem. Ges. *49*, 1941 (1916); *L. von Vargha* and *E. Kovács*, ibid. *75*, 794 (1942); *N. P. Neurieter* and *F. G. Bordwell*, J. Amer. chem. Soc. *85*, 1209 (1963).

[3] *G. Opitz* and *K. Fischer*, Z. Naturforschg. *18b*, 775 (1963).

Preparation of 1-Vinylcyclohexa-1,3-diene from 5,6-Diacetoxycyclooctene

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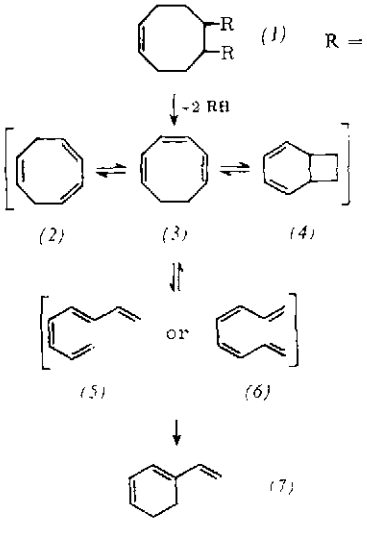
Following pyrolysis of 5,6-diacetoxycyclooctene *(1)*, b.p. 103—105 °C/1.5 mm, $n_D^{20} = 1.4731$, at 500 °C/20 mm under nitrogen, refinement of the products by distillation affords a hydrocarbon fraction, b.p. 47 °C/20 mm, $n_D^{20} = 1.5400$, in about 50 % yield which consists mainly of an olefin of the composition C_8H_{10} and a little styrene. The olefin can be isolated in about 40 % yield based on *(1)* by chromatography with n-pentane on a cloumn (2 m long) of Al_2O_3. This hydrocarbon ($n_D^{20} = 1.5377$) is colorless, is polyunsaturated, and polymerizes readily when pure; it is not 1,3,6-cyclooctatriene *(2)*, 1,3,5-cyclooctatriene *(3)*, bicyclo[4,2,0]-octa-2,4-diene *(4)* [1], *trans,trans*-1,3,5,7-octatetraene [2], nor *cis,trans*-1,3,5,7-octatetraene *(5)* [3]. Its elemental composition, its ultraviolet, infrared, NMR, and mass spectra, its oxidative degradation, and its hydrogenation to ethylcyclohexane identify the compound as the hitherto unknown 1-vinylcyclohexa-1,3-diene *(7)*, $\lambda_{max} = 288$ ($\varepsilon = 8340$), 298 (8420), and 310 mμ (4980) in isooctane.

The results of the pyrolysis of the diacetate *(1)* can be explained by intermediate formation of the valence-bond isomers *(2)* or *(3)* or of *(4)*, which is in equilibrium with these two, and of *cis,trans*- *(5)* or *cis,cis*-1,3,5,7-octatetraene *(6)* [4].



The formation of styrene can be explained by dehydrogenation of *(7)*, probably *via* ethylbenzene as isomerization product.

Compound *(7)* is also produced in 15% yield alongside a 1,2-trimethylenecyclopentadiene on pyrolysis of 2,3-diacetoxybicyclo[3,3,0]octane, b.p. 96–96.5 °C/1 mm, $n_D^{20} = 1.4647$.

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[*] The author wishes to thank Dr. *Therese Böhm-Gössl*, Dr. *L. Rohrschneider*, and Ing. *G. Peitscher* for the physico-chemical studies and measurements and their interpretation.

[1] *W. Sanne* and *O. Schlichting*, Angew. Chem. *75*, 156 (1963); *A. C. Cope, A. C. Haven, F. L. Ramp*, and *E. R. Trumbull*, J. Amer. chem. Soc. *74*, 4867 (1952); *E. Vogel, O. Roos*, and *K.-H. Disch*, Liebigs Ann. Chem. *653*, 55 (1962).

[2] *G. F. Woods* and *L. H. Schwartzmann*, J. Amer. chem. Soc. *71*, 1396 (1949); *E. R. Lippincott, W. R. Feairheller*, and *C. E. White*, J. Amer. chem. Soc. *81*, 1316 (1959); U.S.-Patent 2707196 (Sept. 28th, 1949/April 26th, 1955), inventor: *G. F. Woods*; Chem. Abstr. *50*, 2649 (1956); *D. E. Evans*, J. chem. Soc. (London) *1961*, 2566.

[3] *W. Ziegenbein*, unpublished synthesis; λ_{max} 302 (ε = 50880), 288.5 (57240), 276.5 (38050), and 266 mμ (19928) in isooctane.

[4] Cf. *W. v. E. Doering* and *W. R. Roth*, Angew. Chem. *75*, 27 (1963); Angew. Chem. internat. Edit. *2*, 115 (1963); Tetrahedron *19*, 715 (1963).

Synthesis and Elucidation of the Structures of 7-Alkylamino-7-phenyl-8-thioxo-1,2,3,4,5,6-hexathiocanes

By Prof. Dr.-Ing. F. Asinger, Dr. W. Schäfer, and Dipl.-Chem. H.-W. Becker

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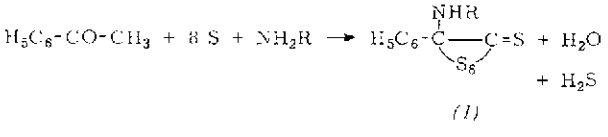
der Technischen Hochschule Aachen (Germany)

Elemental sulfur and primary amines react with acetophenone in methanol [1] at room temperature to yield 7-alkylamino-7-phenyl-8-thioxo-1,2,3,4,5,6-hexathiocanes *(1)* [see Table 1]. All the hexathiocanes are stable, intensely



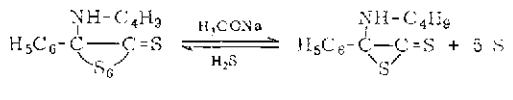
(1)

Table 1. 7-Alkylamino-7-phenyl-8-thioxo-1,2,3,4,5,6-hexathiocanes *(1)*.

Compound	R	M.p. [°C]	Yield [%]
(1a)	CH_3	145–146	22
(1b)	C_2H_5	139	18
(1c)	n-C_3H_7	139	11
(1d)	i-C_3H_7	140	10
(1e)	n-C_4H_9	109–110	20

yellow, crystalline compounds; they are also formed from acetophenone imines, sulfur and amines.

The constitution of the hexathiocanes has been proved unequivocally by degradation experiments with *(1e)* and by nuclear magnetic resonance studies of *(1a)* [2]. The NMR spectrum of *(1a)* [3] contains three proton signals: the signal from the monosubstituted benzene ring at $\delta = -0.1$ ppm, the peak for the secondary amino group at $\delta = 1.1$ ppm, and the signal for the methyl protons at $\delta = 4.5$ ppm, which is split into a doublet, indicating that the methyl group is directly adjacent to the hydrogen atom of the secondary amino group. Since desulfurizing hydrogenation of *(1e)* with Raney nickel



(1e) *(2)*

at room temperature affords n-butyl-1-phenylethylamine [4], the position of the nitrogen atom in the molecule is assured. Reduction of *(1e)* with hydrogen sulfide in the presence of amines [5] yields bis-(2-phenylethyl) polysulfide, and treatment of *(1e)* with sodium methoxide in methanol causes elimination of elemental sulfur produce 2-n-butylamino-2-phenyl-3-thioxothiirane *(2)*, which can be "resulfurized" with hydrogen sulfide and sulfur to reform *(1e)*.

Received, November 5th, 1964 [Z 857/683 IE]
German version: Angew. Chem. 77, 41 (1965)

[1] *F. Asinger, W. Schäfer, K. Halcour, H. Saus*, and *H. Triem*, Angew. Chem. *75*, 1050 (1963); Angew. Chem. internat. Edit. *3*, 19 (1964).

[2] The tentative formulation of *(1e)* as *N*-n-butyl-1-phenyl-2,3,4,5,6,7-hexathiacycloheptan-1-thiocarboxamide (cf. [1] p. 1056/p. 25) owing to its solubility in bases and its absorption at 1530 cm^{-1} must therefore be amended.

[3] We express our gratitude to Dr. *Frenzel* and Ing. *Peitscher*, Chemische Werke Hüls AG., Marl/Westfalen (Germany), and to Dr. *Kosfeld*, Institut für Physikalische Chemie der Technischen Hochschule Aachen, for measuring and interpreting the nuclear magnetic resonance spectra.

[4] *F. Asinger* and *K. Halcour*, Mh. Chem. *94*, 1029 (1963).

[5] Cf. [1], p. 1056/p. 25.

Gas-Chromatographic Separation and Estimation of Aliphatic Monocarboxylic Acids with 1—5 Carbon Atoms

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Institut für Lebensmittelhygiene
der Freien Universität Berlin (Germany)

Quantitative separation and estimation of formic acid and acetic acid mixed with aliphatic monocarboxylic acids containing 3–5 carbon atoms involve considerable difficulties.

We have now succeeded in separating and estimating these acids by gas chromatography in the form of their amyl esters. About 100 mg of the free acids are weighed into a 10 ml measuring flask with a standard ground-glass joint, and 3 ml of diethyl ether, 0.1 ml of boron trifluoride, and an equimolar (based on the free acids) amount of 1-pentanol are added; the flask is attached to a Dimroth condenser 50 cm long and heated in an air-bath until the first white vapors of BF_3 appear. The solution, which contains a quantitative yield of the amyl esters [2] is cooled to room temperature and filled up to the mark with ether. The solution is dried over anhydrous sodium sulfate plus sodium hydrogen carbonate and is then ready for chromatographic analysis.

The analysis was conducted with a 50 m capillary band column filled with Apiezon L grease in a Perkin-Elmer F 6/4 HF Fraktometer. The working temperature was 100 °C and the rate of gas flow was 1 ml of helium per minute. One microliter samples were injected at a separating factor of 1:100.

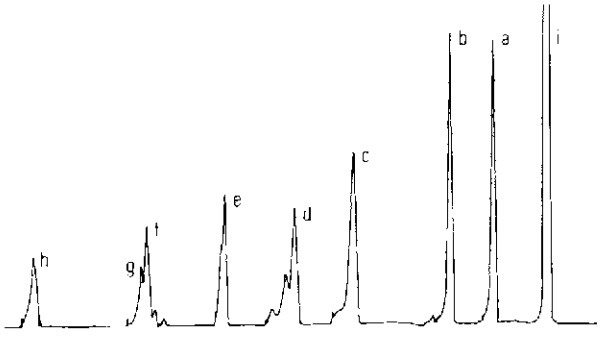

Fig. 1. Gas chromatogram of the amyl esters of: a = formic acid, b = acetic acid, c = propionic acid, d = isobutyric acid, e = n-butyric acid, f = isovaleric acid, g = 2,2,2-trimethylacetic acid, and h = n-valeric acid; i = diethyl ether (solvent).

A flame ionization detector was used on account of the extremely minute amounts of material to be expected from biological materials; the detector sensitivity was X:4 and R:1. The temperature of the injection block, the detector leads, and the standard gas outlet was 300 °C.

The recorder was a Siemens Elektronenkompensograph with a speed of 1 cm/min. By utilizing the complete sensitivity of the apparatus, quantities of acid down to 0.1 ng (10^{-10} g) can be detected; by concentrating the ether solutions (the esters boil at 110 °C and higher) and by decreasing the separating factor to 1:5–1:10 amounts down to 10^{-12} g can be measured. Figure 1 shows a typical gas chromatogram.

A mean error of ± 2.5 % was observed in six acetic acid analyses with samples weighing 100.5–207.9 mg; for ten injections of 207.0 mg of acetic acid, 207.16 ± 0.1 mg was recovered.

Received, November 9th, 1964 [Z 861/687 IE]
German version: Angew. Chem. 77, 95 (1965)

[1] We are indebted to *E. Malek*, Berlin, for carrying out the analyses.

[2] Excess amyl alcohol is used for the esterification of biological material. Amyl alcohol recurs as an unsymmetrical band between acetic acid and propionic acid and does not interfere.

A Stable Triradical [*]

By Prof. Dr. Richard Kuhn, Dr. F. A. Neugebauer, and H. Trischmann

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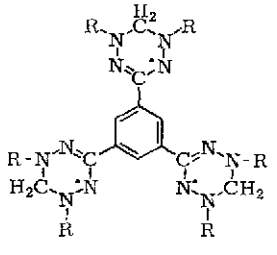
für Medizinische Forschung, Heidelberg (Germany)

The ease of formation and stability of the verdazyls [1] has made it possible to secure a compound with three unpaired electrons per molecule. 1,3,5-Triformylbenzene was converted *via* its trisphenylhydrazone with crystalline benzenediazonium chloride in pyridine into its extremely insoluble red trisformazan, which decomposes explosively at 272 to 273 °C.

A suspension of this derivative in dimethylformamide (DMF) reacted with BaO plus $Ba(OH)_2$ and methyl iodide [1] to form the deep green triradical 1,3,5-tris-(1,5-diphenylverdazyl-3-yl)benzene *(1)*, which contains ten six-membered rings (7 benzene rings and 3 heterocycles) in conjugation, and which crystallizes from DMF/methanol as almost black prisms which decompose at 242–243 °C.



(1), R = C_6H_5

On catalytic hydrogenation over $Pd/BaSO_4$ in DMF, *(1)* rapidly absorbs 1.48–1.50 moles of hydrogen (calc. 1.50 moles). Its molar extinction in DMF (ε = 12500 at λ_{max} = 721 mμ) is almost three times as large as that of 1,3,5-triphenylverdazyl (ε = 4400 at λ_{max} = 720 mμ).

The paramagnetic susceptibility μ_{eff}/μ_B of *(1)* – calculated for three non-coupled unpaired electrons it should be $\sqrt{9} = 3$ – was measured with the magnetic balance and was found to be 2.96 ± 0.06 at 298 °K, 2.97 at 195 °K, and 3.02 at 77 °K. Its ESR spectrum – like that of 1,3,5-triphenylverdazyl – extends over 50 gauss [2]. The fact that the hyperfine structure of *(1)* is not resolved – in contrast to that of 1,3,5-triphenylverdazyl with 9 lines at 6-gauss intervals in intensity ratios of 1:4:10:16:19:16:10:4:1 – is considered to be due to interaction between the spins of the free electrons.

The measurements revealed that the three unpaired electrons in the π-electron system of the triradical are practically free from coupling (↑ ↑ ↑) in the magnetic field of over 3000 gauss used.

In contrast to the biradicals porphyrindin [3] and nitrosoindigo [4] whose paramagnetism decreases with decreasing temperature, the electrons in the triradical *(1)* remain unpaired down to 77 °K, although mesomeric forms of a zwitterionic monoradical can be written in which the spin concentration of the substance would be reduced to one-third (↑ ↓ ↑).

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German version: Angew. Chem. 77, 43 (1965)

[*] Communication No. 5 on Verdazyls; – Communication No. 4: Angew. Chem. *76*, 691 (1964); Angew. Chem. internat. Edit. *3*, 762 (1964); – Communication No. 3: Angew. Chem. *76*, 230 (1964); Angew. Chem. internat. Edit. *3*, 232 (1964).

[1] *R. Kuhn* and *H. Trischmann*, Angew. Chem. *75*, 294 (1963); Angew. Chem. internat. Edit. *2*, 155 (1963); Mh. Chem. *95*, 457 (1964).

[2] We express our thanks to Prof. Dr. *K. H. Hausser* for carrying out and interpreting the electron spin resonance measurements.

[3] *R. Kuhn* and *H. Katz*, Angew. Chem. *46*, 478 (1933); *E. Müller* and *I. Müller-Rodloff*, Liebigs Ann. Chem. *521*, 81 (1936).

[4] *R. Kuhn* and *W. Blau*, Liebigs Ann. Chem. *615*, 99 (1958).

The Crystal Structure of Nitrogen Selenide

By Dr. H. Bärnighausen, Dipl.-Chem. T. von Volkmann, and Prof. Dr. J. Jander [1]

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der Technischen Hochschule München (Germany)

In continuation of our studies on the crystal structure of nitrogen selenide [2], we have now succeeded in interpreting its three-dimensional Patterson synthesis. The resultant structural model – which is presently being refined – gave a reliability index of 13 % for the 536 X-ray diffraction lines observed and therefore seems sufficiently well established.

Nitrogen selenide consists of discrete N_4Se_4 molecules. Although nitrogen sulfide N_4S_4 [3] and N_4Se_4 are not isotypic, there is great similarity between the molecular geometries of the two compounds. Thus, for example, as in N_4S_4, the nitrogen and selenium atoms in N_4Se_4 are in an alternating sequence and assume the boat form of a strongly puckered eight-membered ring, whose symmetry can be described in good approximation by the symbol $\bar{4}2m$. The four nitrogen atoms in the eight-membered ring almost form a square with N–N distances of 2.82 Å, and the four selenium atoms are situated at the corners of a slightly deformed tetrahedron. The distances between selenium atoms separated by a nitrogen atom are 2.97 Å on the average, while those situated diagonally opposed in the eight-membered ring are only 2.76 Å apart. This distance is very much shorter than the effective diameter of selenium atoms held together by van der Waals forces. It follows that the molecule must be subject to a strong geometric strain, which may afford an explanation for the tendency of nitrogen selenide to explode. The average value for the length of the Se–N bonds is 1.80 Å and thus corresponds roughly to the sum of the respective covalent radii [r(Se) + r(N) = 1.14 + 0.7 = 1.84 Å]. The N–Se–N bond angle is 103 ° and the Se–N–Se bond angle is 111 °.

The arrangement of the N_4Se_4 molecules in the crystal lattice is approximately that of a hexagonal closest packing. The hexagonal pseudo-cell has the lattice constants a ≈ 10 Å and c ≈ 5.9 Å and is oriented in such a way relative to the monoclinic unit cell that the c axis coincides with the direction [$\bar{1}$12], and the hexagonal basis lies approximately in the ($\bar{1}$11) plane, which is the main limiting surface of the platelet single crystals. The c/a ratio of 1.7 agrees well with the theoretical value of 1.633 for hexagonal closest packing. However, the base of the pseudo-cell has a considerable deformation, which is most probably due to relatively strong intermolecular

interactions, since the distances between the Se and N atoms in neighboring molecules is shorter by 0.2 Å on the average than the sum of the corresponding van der Waals radii.

Received, November 19th, 1964 [Z 863/688 IE]
German version: Angew. Chem. 77, 96 (1965)

[1] We are indebted to *A. von Plehwe* for composing several computing programs for a Siemens 2002 Digital Computer.

[2] *H. Bärnighausen, T. von Volkmann,* and *J. Jander,* Acta crystallogr. *15,* 615 (1962).

[3] *B. D. Sharma* and *J. Donohue,* Acta crystallogr. *16,* 891 (1963).

N-Bromohexamethyldisilazane [1]

By Dr. N. Wiberg and Dipl.-Chem. F. Raschig

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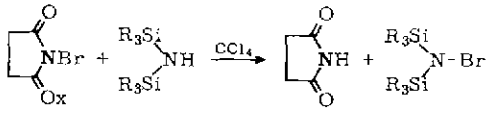
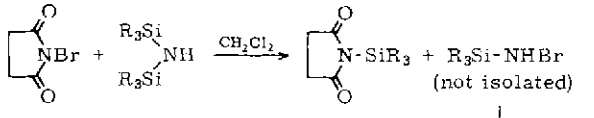
der Universität München (Germany)

N-Bromohexamethyldisilazane *(1)* is formed in about 60 % yield from *N*-bromosuccinimide at temperatures between 0 and 25 °C. Surprisingly, no *(1)* is formed in acetone or



R = CH_3 *(1)*

methylene chloride; instead, cleavage of the Si–N bonds occurs, and *N*-trimethylsilylsuccinimide *(2)* is produced in 50–70 % yield.



R = CH_3 *(2)*

N-Chlorosuccinimide and *N*-iodosuccinimide react with hexamethyldisilazane even in carbon tetrachloride to yield *(2)*. The *N*-chlorohexamethyldisilazane [2] to be expected is not formed; however, a little *N*-iodohexamethyldisilazane [3,4] could be detected in the reaction mixture together with nitrogen triiodide.

These results lead to the conclusion that *(2)* is probably formed by cationic exchange of the bromine for the trimethylsilyl group, whereas the formation of *(1)* – by analogy to allyl bromination by *N*-bromosuccinimide [5] – proceeds via a radical mechanism.

Compound *(1)* is a yellow-brown liquid, b.p. (extrapolated) 176 °C/760 mm, which smells rather like bromine; it has log p [mm] = −2326/T + 8.060, a Trouton constant of 23.7 cal/mole/°C, a heat of evaporation of 10.6 kcal/mole, $d^{21} = 1.13$, and $n_D^{21} = 1.4580$. It is thermally more stable than *N*-chlorohexamethyldisilazane [2], but both compounds have similar chemical properties.

Received, November 26th, 1964 [Z 865/692 IE]
German version: Angew. Chem. 77 (1965), in the press.

[1] The Production and Reactions of *N*-Halogenosilylamines, Part I.

[2] *N. Wiberg* and *A. Gieren,* Angew. Chem. *74,* 942 (1962); Angew. Chem. internat. Edit. *1,* 664 (1962); *N. Wiberg* and *F. Raschig,* Angew. Chem. *76,* 614 (1964).

[3] Cf. *U. Wannagat,* Angew. Chem. *75,* 173 (1963); Angew. Chem. internat. Edit. *2,* 161 (1963).

[4] For purposes of comparison, we prepared *N*-iodohexamethyldisilazane from *N*-sodiohexamethyldisilazane and iodine(I) chloride in pentane at −50 °C: brown-red liquid, b.p. 62 °C/5 mm, which is very readily hydrolysed (caution! it gives rise to nitrogen triiodide).

[5] Cf. *L. Horner,* Angew. Chem. *71,* 349 (1959).

Addition Reactions of Cyanic Esters

By Dr. D. Martin, Dipl.-Chem. H.-J. Herrmann, cand. chem. S. Rackow, and K. Nadolski

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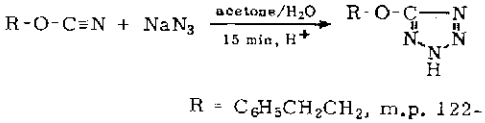
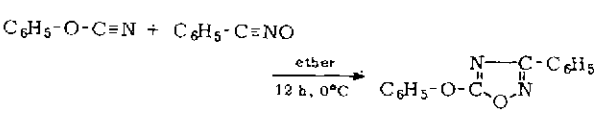
The cyanic esters recently described [1,2] are characterized by the high reactivity of their C≡N group. Reactions which occur with nitriles only under drastic conditions and on prolonged heating proceed very readily, sometimes even in the cold, with these esters, as can be seen from the following survey. On account of their strong dehydrating action, cyanic esters ought to be of interest as agents for eliminating water in acylation and phosphorylation reactions.

1. *Cycloadditions*

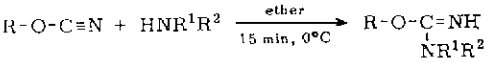


R = $C_6H_5CH_2CH_2$, m.p. 122–124 °C, 36%
R = C_6H_5, m.p. 37–138 °C, 93%



m.p. 52–54 °C, 30%

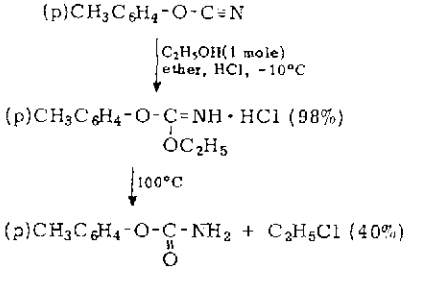
2. *Addition of amines*



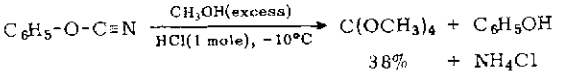
R	R^1	R^2	M.p. [°C]	Yield [%]
C_6H_5	C_6H_5	H	104–105	47
C_6H_5	$-(CH_2)_2-O-(CH_2)_2$	–	66–67	95
p-$CH_3C_6H_4$	NH–CO–NH_2	H	194–195	92

3. *Addition of alcohols*

a) Conversion of alcohols into alkyl halides

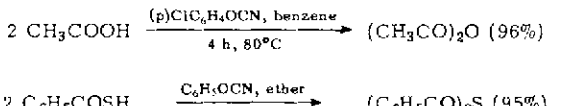


b) Synthesis of orthocarbonates



4. *Dehydrations*

a) Anhydride formation

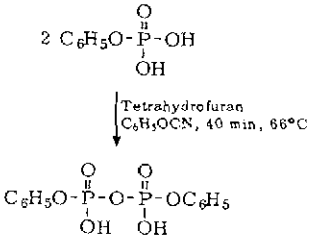


b) Esterification

$$ClCH_2\text{-}COOH + C_2H_5OH \xrightarrow[24\ h,\ 20°C]{C_6H_5OCN} ClCH_2\text{-}COOC_2H_5$$

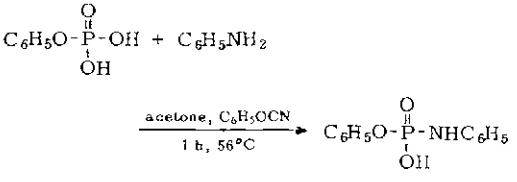
84 %

c) Pyrophosphate formation



Dicyclohexylammonium salt [3]:
m.p. 257–262°C, 100%

d) Phosphoramidic ester formation



Cyclohexylammonium salt [3]:
m.p. 201–203°C, 86%

Received, November 30th, 1964 [Z 869/690 IE]
German version: Angew. Chem. 77, 96 (1965)

[1] *D. Martin*, Chem. Ber. *97*, 2689 (1964); Tetrahedron Letters *1964*, 2829.

[2] *K. A. Jensen* and *A. Holm*, Acta chem. scand. *18*, 826 (1964).

[3] *F. Cramer* and *G. Weimann*, Chem. Ber. *94*, 996 (1961).

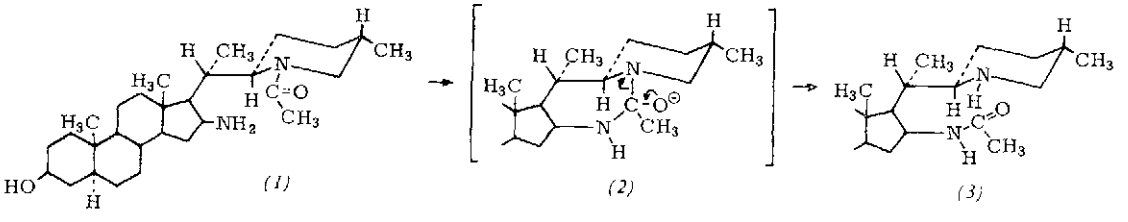
1,4-N → N′-Acyl Migration in a Diamino Steroid [1]

By Dr. G. Adam and Dr. habil. K. Schreiber

Institut für Kulturpflanzenforschung Gatersleben der Deutschen Akademie der Wissenschaften zu Berlin (Germany)

Up to the present, intramolecular $N \rightarrow N'$-acyl migrations have been observed only in simple ethylene diamine derivatives [2] and in 3,8-diazabicyclo[3,2,1]octanes [3]. These examples are all 1,2-diamino compounds.

We have now found that (22*R*,25*S*)-16β-amino-22,26-acetimino-5α-cholestan-3β-ol *(1)* [4] gives rise to a new amino steroid with $R_F = 0.11$ [4] when heated for 30 h at 110 °C with 6.7 N HCl in absolute ethanol in a sealed tube; the new product was separated from unchanged *(1)* by fractional crystallization of the hydrochlorides from methanol/acetone.



The new hydrochloride, m.p. 320–323 °C (decomp.), is less soluble and is obtained in 56 % yield; it has the same elemental composition $C_{29}H_{50}N_2O_2 \cdot HCl$ as the hydrochloride of *(1)*, m.p. 278–281 °C (decomp.). The free base has a double melting point (164–167 and 230–232 °C) and $[\alpha]_D^{19} = +26.8°$; its infrared spectrum contains bands at 1550 and 1651 (secondary amide), 3265 (secondary amine), 3305 (secondary amide), 3395 and 3450 cm^{-1} (hydroxyl). From this it follows that *(1)* is not hydrolysed to the diamine by the ethanolic hydrogen chloride; instead, the acetyl residue migrates from the secondary to the primary amino group to form *(3)*. This is confirmed by the molecular mass spectrum of the free amine *(3)*.

The reaction probably proceeds via a seven-membered cyclic transition state *(2)*. It appears that the peculiar steric arrangement in the region of the two nitrogen atoms brings the reaction centers involved into close proximity. At present it cannot be decided whether and to what extent differences in the basicity or nucleophilicity of the two nitrogen atoms are of importance. Measurements of the apparent acidity constants [5] of *(1)* and *(3)* gave $pK^*_{MCS} = 9.22$ and 9.06, respectively, *i.e.* there is a relatively small difference in basicity. Attempts to effect the reverse acyl migration *(3)* → *(1)* by means of alkali or thermal treatment were without success.

Received, November 16th, 1964 [Z 862/689 IE]
German version: Angew. Chem. 77, 94 (1965)

[1] *Solanum* Alkaloids, Part 57. – Part 56: *G. Adam* and *K. Schreiber*, Z. Chem., in the press.

[2] *C. J. M. Stirling*, J. chem. Soc. (London) *1958*, 4351.

[3] *G. Cignarella*, *E. Testa*, and *C. R. Pasqualucci*, Tetrahedron *19*, 143 (1963).

[4] *G. Adam* and *K. Schreiber*, Z. Chem., in the press. Compound *(1)* has m.p. 231–233 °C, $[\alpha]_D^{20} = -23.3°$ in $CHCl_3$, and $R_F = 0.17$ on thin-layer chromatograms on Silica Gel G [from E. Merck, Darmstadt (Germany)] developed with an 8:2 mixture of methylene chloride and methanol which had been shaken in a 1:1 ratio with 25 % ammonia. Iodine reagent was used for detecting the spots.

[5] We wish to thank Dr. *W. Simon*, Zürich (Switzerland), for carrying out these measurements.

Tetrabenzylbutatriene (1,6-Diphenyl-2,5-dibenzylhexa-2,3,4-triene) [1]

By Doz. Dr. G. Köbrich and W. Drischel [1a]

Organisch-Chemisches Institut
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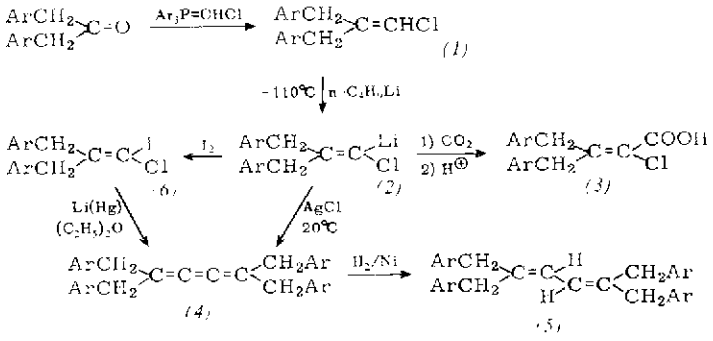
On account of their tendency to polymerize and of their sensitivity towards alkalies and acids, benzylcumulenes could not be obtained to date by any of the known cumulene syntheses [2]. We have now obtained tetrabenzylbutatriene *(4)* in the following way. Chloromethylenation [3] of dibenzyl ketone gives a 55 % yield of pure 1,1-dibenzyl-2-chloroethylene *(1)*, b.p. 135–137 °C/0.2 mm, $n_D^{20} = 1.5722$. Metallation of *(1)* with n-butyl-lithium at −110 °C [4] leads almost exclusively to 2,2-dibenzyl-1-chlorovinyl-lithium *(2)*, despite the presence of acidic benzyl/allyl hydrogens in the molecule, for carboxylation of the metallation product led to the acid *(3)*, m.p. 111 °C, which was isolated in 92 % yield; the structure of the acid *(3)* was proved by its NMR spectrum and other properties. When *(2)* was allowed to warm up to room temperature in the presence of an equimolar amount of silver chloride, a 69 % yield [based on *(1)*] of pure *(4)* was obtained. This compound is stable in the solid state and is

relatively insensitive to heat; it melts at 121–122 °C. However, it polymerizes rapidly in solution, *e.g.* on attempts to crystallize it from cyclohexane without exclusion of oxygen.



Ar = C_6H_5

The proof of the structure *(4)* is based on its molecular weight, ultraviolet spectrum (λ_{max} = 274.5 mμ, log ε = 4.40 in cyclohexane), and NMR spectrum which contains no signals for olefinic protons but only peaks for aromatic protons and for a single species of aliphatic protons at −3.2 ppm (tetramethylsilane as standard). The ratio of aromatic to aliphatic protons is 5:2.

Catalytic hydrogenation of *(4)* over Raney nickel afforded an oil plus tetrabenzylbutadiene *(5)* [m.p. 154–154.5 °C, main peak in the ultraviolet λ_{max} = 253 mμ, log ε = 4.51], whose NMR spectrum indicates olefinic protons by a sharp signal at −6.35 ppm; the ratio of aromatic:aliphatic:olefinic protons is 10:4:1.

Another synthesis of tetrabenzylbutatriene *(4)* proceeds by way of 1,1-dibenzyl-2-chloro-2-iodoethylene *(6)*, m.p. 54 °C, which is obtained in 97 % yield from *(2)* with iodine. When shaken with lithium amalgam in diethyl ether at room temperature, *(6)* dimerizes by α-elimination to form *(4)*.

Received, November 27th, 1964 [Z 866/693 IE]
German version: Angew. Chem. *77*, 95 (1965)

[1] On the Existence of Carbon Atoms with Halogen and Alkali-Metal Substituents, Part VI. – Part V: *G. Köbrich, K. Flory*, and *W. Drischel*, Angew. Chem. *76*, 536 (1964); Angew. Chem. internat. Edit. *3*, 513 (1964).

[1a] We wish to thank the Deutsche Forschungsgemeinschaft, the Wirtschaftsministerium des Landes Baden-Württemberg, and the Fonds der Chemischen Industrie for financial assistance.

[2] Reviewed by: *P. Cadiot, W. Chodkiewicz*, and *J. Rauss-Godineau*, Bull. Soc. chim. France *1961*, 2176.

[3] *G. Wittig* and *M. Schlosser*, Chem. Ber. *94*, 1373 (1961).

[4] *G. Köbrich* and *H. Trapp*, Z. Naturforsch. *18b*, 1125 (1963); *G. Köbrich, H. Trapp*, and *I. Hornke*, Tetrahedron Letters *1964*, 1131; *G. Köbrich* and *K. Flory*, ibid. *1964*, 1137; *G. Köbrich, K. Flory*, and *W. Drischel* [1].

CONFERENCE REPORTS

VIth International Congress of Biochemistry

The Congress was held from July 26th to August 1st, 1964 in New York. The results presented in over 600 plenary and symposium lectures and research reports combined to form an impressive mosaic representing the current status of biochemistry. In particular, the advances made in the chemistry and biochemistry of nucleic acids and proteins and, in this connection, in genetics and in evolutionary research became most evident. In the following report, an attempt is made to summarize some of the most remarkable results.

Nucleic Acids

P. Berg (U.S.A.) reported on the concentration of specific species of t-RNA [1] from *Escherichia coli*. Gradient partition chromatography on columns (1–4 m long) of dextran gel using solvent systems containing aqueous potassium phosphate, ethoxyethanol, butoxyethanol, and triethylamine led to three- to sevenfold enrichment. At the same time, t-RNA species of the same specificity were separated. A second approach involved enzymatic loading of the desired t-RNA with an amino acid, oxidation of unloaded t-RNA chains with periodate, and separation of the products on a column of aminoethyldextran. Depending on the purity of the starting material, five- to sevenfold concentration of valine-specific t-RNA was achieved. Since the losses of t-RNA incurred are only small, both processes can be applied in series.

M. Staehelin (Switzerland) chromatographed the products of hydrolysis of crude yeast t-RNA with pancreas RNase and obtained di- and trinucleotides containing the following unusual nucleosides: 1-methylguanosine, 2-methylguanosine, 2,2-dimethylguanosine, inosine, 6-methyladenosine, 5-ribosyluridine, 5-methylcytidine, and thymine riboside. In order to identify these components, use was made, *inter alia*, of ribonuclease T_1, which has the following specificity: phosphodiester bonds on 2-methylguanosine are split with formation of a 3′-terminal phosphate group; phosphodiester bonds on 2,2-dimethylguanosine are also cleaved, but here cyclic phosphates are formed; phosphodiester bonds on 1-methylguanosine remain unaltered. Serine-specific t-RNA does not contain any thymine ribotide, but does contain the unusual doublet guanyl-5-hydroxymethylcytidine.

R. W. Holley et al. (U.S.A.) degraded purified alanine-, tyrosine-, and valine-specific t-RNA with takadiastase-RNase T_1 and found an unusual tetranucleotide with the sequence TpΨpCpGp, where Tp represents ribothymidylic acid and Ψp is pseudouridylic acid. Since this tetranucleotide was isolated from all three types of t-RNA, it is thought that it occurs quite generally in t-RNA and is in some way involved in the transferring activity. Ψp also occurs in alanine-specific t-RNA as a dinucleotide with 1-methylinosinic acid.

A t-RNA containing 8-azaguanine instead of guanine was examined by *D. H. Levin* and *M. Litt* (U.S.A.). They obtained this product by incubating *Bacillus cereus* with 8-azaguanine.

[1] The following abbreviations have been used in this report:
RNA = ribonucleic acid
t-RNA = transfer RNA
m-RNA = messenger RNA
RNase = ribonuclease
DNA = deoxyribonucleic acid
DPN = diphosphopyridine nucleotide (nicotine adenine dinucleotide)
DPNH = reduced DPN
CoA = coenzyme A
ATP = adenosine triphosphate
ADP = adenosine diphosphate
P = phosphate

Chromatography of the RNA on hydroxyapatite gave fractions with 8-azaguanine contents of between 26 and 62 %. Differences in the secondary structure of these fractions were detected from the course of their ultraviolet absorption on warming from 20 to 90 °C. As the content of 8-azaguanine rose, the melting temperature T_m and hyperchromicity decreased. Hence it follows that the hydrogen bonds in the pair 8-azaguanine-cytosine are weaker than those in the pair guanine-cytosine, with the result that the RNA containing the guanine analogue is more thermolabile.

U. Z. Littauer (Israel) investigated the significance of the methylated purine and pyrimidine bases which always occur in t-RNA in small amounts. t-RNA of low methyl content obtained from *E. coli* cells grown on a methionine-deficient medium takes up amino acids to about the same extent as normal t-RNA. However, the transfer activity of normal t-RNA in the synthesis of poly-Phe and poly-Leu is about 25 % higher than that of low-methyl t-RNA. In addition, low-methyl t-RNA is degraded by diesterase from *E. coli* about twice as fast as normal t-RNA. Methylation apparently therefore confers greater stability on the t-RNA in metabolic processes.

Eleven enzymes which transfer methyl groups from *S*-adenosylmethionine to nucleic acids were discovered in *E. coli* by *M. Gold* and *J. Hurwitz* (U.S.A). Six of these enzymes react only with t-RNA, and four others with t-RNA or ribosomal RNA. A further enzyme fraction is specific for DNA. The enzymes were separated and purified. They also differ in their specificities for the bases to which the methyl groups are transferred.

F. C. Wettstein (U.S.A.) described the structure of the active complex involved in the biosynthesis of proteins: there are always three molecules of t-RNA attached to the ribosome. One of these bears the activated amino acid, the second holds the growing polypeptide chain, and the third contains neither protein nor amino acid. This third molecule of RNA is released from the ribosome in a buffer containing a low concentration of Mg^{2+} ions; the two other RNA molecules are more securely attached.

In order to examine the site of attachment of ribosomes onto microsomal membranes, *D. Sabatini* (U.S.A.) dissociated microsomes from guinea-pig liver by adding increasing amounts of EDTA. No dissociation occurs at EDTA concentrations below 10 μmoles per amount of microsomes obtained from 0.5 g of liver. Small subunits (32 S) are split off between 10 and 20 μmoles of EDTA; larger subunits (47 S) and unattacked ribosomes remain attached to the microsomes. Above 20 μmoles of EDTA (up to 200 μmoles), further ribosomes are dissociated, and the 47 S, subunits are also released from the microsomes. The necessity for such high EDTA concentrations suggests that Mg^{2+} ions participate in the bonding between the ribosomes and the microsomes. Electron micrographs of negatively stained microsomes revealed that the groove between the 32 S and 47 S subunits in ribosomes runs parallel to the microsomal membrane surface. From this and the dissociation data it follows that ribosomes are attached to the microsomes only *via* their 47 S subunits.

Actinomycin forms a complex with DNA and thus inhibits RNA synthesis. Nucleohistones bind much less actinomycin than pure DNA does. The portions of the DNA occupied by histones are apparently unable to form complexes with actinomycin. These findings were used by *E. Harbers* and *H. Bujard* (Germany) to demonstrate that transplanted tumors of rats and mice have a higher histone:DNA ratio than normal tissue in these rodents. This observation may help to explain the tumor specificity of actinomycin.

H. Bielka (Germany) found a difference between ribosomal RNA from normal and from malignant cells. He isolated ribosomal RNA from normal rat liver and from hepatoma which had been induced by butter yellow or diethylnitrosamine. Both types of RNA had the same base composition, but the number of free amino groups in the RNA from healthy liver (about 45 % of the total amino groups) was higher than that in hepatoma RNA (about 25 %). The denaturation temperature (helix-coil transformation) is higher for hepatoma RNA (57.6 °C) than for healthy liver RNA (52.8 °C). In addition, hepatoma RNA is split more slowly by RNase than normal liver RNA.

According to *U. Bachrach* (Israel), oxidized spermine, *i.e.* the dialdehyde

$$OHC-(CH_2)_2-NH-(CH_2)_2-NH-(CH_2)_2-CHO,$$

forms a complex with the DNA from coliphages of the series T-uneven. The aldehyde is formed from spermine by the action of the enzyme serum amine oxidase. Phages incubated with the dialdehyde at 37 °C are still absorbed by *E. coli* cells and inject their DNA into the cells, but the DNA is no longer infectious and does not prevent subsequent infection with virulent T5 phages.

The mode of action of levophanol, a growth inhibitor for *E. coli* with a morpholine-like structure, was investigated by *E. J. Simon* (U.S.A.). This substance inhibits the incorporation of [^{14}C]uracil into ribosome RNA by up to 90 or 95 %, but influences the synthesis of other types of RNA to a much lesser extent. For example, the induction of β-galactosidase proceeds still at half of the original rate within two hours after addition of levophanol; this suggests a continuous synthesis of m-RNA. t-RNA isolated from cells containing levophanol by density gradient centrifugation contains 60–70 % less [^{14}C]uracil than t-RNA from a normal control culture. Levophanol inhibits the synthesis of RNA in 16-S and 23-S ribosome components to roughly equal extents.

Phosvitin, the most important phosphoprotein from hen's egg yolk, is biosynthesized by the laying hen only in the liver. *P. J. Heald* and *P. M. McLachlan* (England) found that neither other tissues of the mature hen nor the liver of chicks form phosvitin. If cockerels are injected with diethylstilbestrol, the same phosvitin concentration is present in their plasma proteins 48 h after administration of the hormone as in laying hens. *O. Greengard* and *G. Acs* (U.S.A.) found that the effect of diethylstilbestrol demands an intact RNA-synthesizing system in its initial stages, for if actinomycin is administered to the cockerels within 5 h after the application of the hormone in order to inhibit RNA synthesis, no phosvitin is formed.

Fractionation of hexa- and heptaribonucleotide fractions was accomplished by *B. P. Doctor* and *G. J. McCormick* (U.S.A.) using countercurrent distribution. They treated yeast t-RNA with RNase from pancreas and separated the hydrolysis products according to their chain lengths by chromatography on DEAE-cellulose using 7 M urea and an NaCl gradient. The hexa- and heptanucleotide fractions were then subjected to 600 transfers in a countercurrent distribution using a system prepared as follows: 30 g of ammonium sulfate plus 1 ml of acetic acid were made up to 100 ml with distilled water, and 4 ml of formamide and 40 ml of 2-ethoxyethanol were added to this solution. The separation gave five fractions containing hexanucleotides and four containing heptanucleotides. The guanylic acid content of these fractions decreased with rising partition coefficients, their content of adenylic acid increased in the same direction.

The interaction between nucleic acid bases was used by *H. Tuppy* and *E. Küchler* (Austria) to separate nucleosides by chromatography; guanosine was linked *via* its sugar residue onto a fine-grain resin. A chromatographic column filled with this exchanger retained deoxycytidine from an aqueous mixture of deoxycytidine and thymidine more strongly than the thymidine. On the other hand, a column of resin loaded with adenosine instead of guanosine retained the thymidine more strongly. These findings suggest some specificity in the interactions between the bases. It must be primarily hydrogen bonds which are responsible for the effect, for methylation at positions at which hydrogen bonds are normally formed reduces the separatory action of the resin; no separation at all is obtained with a 7 M solution of urea as a solvent.

D. Lipkin et al. (U.S.A.) reported on methods for iodinating nucleosides and nucleotides. The best reagents were iodine monochloride and *N*-iodosuccinimide in *N*-ethylacetamide or dimethylsulfoxide. Iodination of pyrimidine bases leads to 5-iodo derivatives, guanine and xanthine derivatives yield the 8-iodo compounds. Alkaline hydrolysis of 5-iodocytidine and 5-iododeoxycytidine leads *via* a rearrangement to 6-hydroxy derivatives, whereas 5-iodouridine after the same treatment gives rise to a new type of cyclonucleotide, *viz.* 6-hydroxy-*O*(6),5'-cyclouridine.

Proteins, Peptides, and Amino Acids

Three symposium lectures were devoted to the relations between the biological activities of peptides and their amino-acid compositions. *V. du Vigneaud* (U.S.A.) and *J. Rudinger* (Czechoslovakia) reported on their investigations of oxytocin. *Rudinger* expressed the opinion that every phase in the biological activity of a substance (transport, binding, action, excretion, inactivation) is probably dependent in different ways upon the nature of the molecule and that the effects produced by different structural changes are not directly comparable. *DuVigneaud* et al. found that the phenolic hydroxyl group in the tyrosyl residue in oxytocin makes a significant contribution to the avian-depressor and oxytocic effects produced by the protein, although both of these properties are still manifested in the absence of this hydroxyl group. It is remarkable that the reduction in the blood pressure brought about by the hormone is less when the hydroxyl group is methylated than when it is missing. If the free amino group in the cysteinyl residue 1 is removed, then a substance is obtained which in some respects is more active than the unchanged hormone. On the other hand, here too blockage of the amino group by acetylation or methylation leads to almost complete loss of activity or even to anti-hormonal activity. *Rudinger* et al. substituted the same amino group with amino-acid residues or short peptide chains which could be removed enzymatically and found that the products possessed protracted antidiuretic, uterotonic, and natriuretic activity, depending on the nature of the group attached.

K. Hofmann (U.S.A.) reported on functional relationships in ACTH, a straight-chain polypeptide containing 39 amino acids. In corticotropins from the pituitaries of pigs, sheep, beef, and humans, amino acids 1–24 are the same in all species, differences occuring only in the positions 25–32. The smallest synthetic polypeptide exhibiting ACTH-like activity, *i.e.* producing a decrease in the ascorbic acid content of the adrenals and stimulating steroid synthesis, contains the amino acids 1–13. If the peptide chain is extended corresponding to its natural structure, the full activity of the natural hormone (about 100 units/mg) is attained when the chain contains a total of 20 amino acids. It therefore appears that the "active site" of the hormone lies in the *N*-terminal tridecapeptide, and that the amino acids 14–20 (particularly 15–18) are responsible for attachment of the hormone onto the receptor. *N*-Acetylation or oxidative deamination of the *N*-terminal serine residue causes significant reduction in the activity of the hormone, but replacement of the serine by glycine has practically no effect. The hydroxymethyl side-chain therefore appears to have no significance for the biological activity. Glutamic acid in position 5 seems to be equivalent to glutamine as concerns biological activity, but the C-amino groups in lysine residues 11, 15, and 16 must not be blocked by formylation.

In the research reports, *K. Harada* and *S. W. Fox* (U.S.A.) described the formation of aspartic acid, threonine, serine, glutamic acid, proline, glycine, alanine, valine, alloisoleucine, isoleucine, leucine, tyrosine, phenylalanine, *etc.* from methane ammonia, and water vapor at 900–1100 °C on SiO_2 or Al_2O_3. Since all the components of this reaction are postulated to have occurred in a primitive terrestial atmosphere, it can be considered that a thermochemical synthesis of amino acids may have taken place under these conditions.

A general method for preparing *C*-substituted amino acids was described by *J. Kollonitsch* et al. (U.S.A.). When the amino acids are dissolved in strong acids (H_2SO_4, $ClSO_3H$, conc. HCl, or CF_3COOH), the functional amino and carboxylic groups are protonated and thus protected, but the carbon chain is still accessible to free-radical chlorination. This surprisingly selective reaction leads to chloro amino acids without racemization; the latter are suitable starting materials for further substitutions. For example, depending on the conditions, L-glutamic acid gives rise to γ- or β-chloroglutamic acid in yields of 70–80 %. Hydrolysis of the γ-chloroglutamic acid gives the γ-hydroxy derivative, and ammonolysis of the β-chloroglutamic acid yields β-amino-L-glutamic acid, a new diamino dicarboxylic acid. γ-Chloro-L-lysine is obtained similarly in 80 % yield, and its hydrolysis produces γ-hydroxy-L-lysine. Catalytic deuterolysis of many of the chloro amino acids gives rise to specifically labelled amino acids.

D. W. Nooner and *J. Oró* (U.S.A.) described non-enzymatic synthesis of polypeptides using polyphosphate esters according to the method of *Schramm* [2]. They heated amino acids with polyphosphate esters in a 1:3 ratio at 60 °C and obtained polymers of DL-leucine, DL-valine, DL-serine, and DL-phenylalanine in yields of up to 60 %. The degree of polymerization for the polyleucine was about 12, but shorter peptides were also detected, which are probably intermediates.

J. H. Pazur and *K. Kleppe* (U.S.A.) were able to show that the glucose oxidase from *Aspergillus niger* is a glycoprotein. The enzyme was purified by fractionation with ammonium sulfate and chromatography on DEAE-cellulose and contains about 15 % D-mannose, D-glucose, and D-glucosamine. The protein and carbohydrate remained inseparable on curtain electrophoresis and density gradient centrifugation. Hydrolysis of the enzyme with protease and separation of the products on Sephadex yielded a glycopeptide, which on hydrolysis with acid yielded D-mannose, D-glucosamine, glutamic acid, aspartic acid, serine, threonine, and ammonia.

A procedure for cleaving acyl-proline bonds specifically with $LiAlH_4$ was reported by *M. A. Ruttenberg* and *L. C. Craig* (U.S.A.). The peptide is dissolved or suspended in anhydrous tetrahydrofuran and treated with a ten- or one-hundredfold molar excess of $LiAlH_4$ for 1 h at room temperature or at 0 °C. Excess hydride is decomposed with 6 N HCl, the solution is evaporated to dryness *in vacuo*, and the residue is desalted by chromatography on a column of Sephadex G-25 equilibrated with 50 % acetic acid. The reaction affords an aldehyde and an *N*-terminal proline. The aldehyde group is reduced to a hydroxyl group with $NaBH_4$ or H_2/PtO_2. Peptides split in this way (yields in brackets) include: Gly-L-Pro (20 % at 25 °C), L-Leu-L-Pro-Gly (23 % at 0 °C, 98 % at 25 °C), *S*-benzyl-L-Cys-L-Pro-L-Leu-Gly (100 % at 25 °C), gramicidin S (42 % at 25 °C), and tyrocidin B (30 % at 0 °C). Side reactions encountered include reduction of the carboxamido groups of glutamine and asparagine, and reductive cleavage of other peptide bonds, where the reactivity decreases in the series tertiary amides ⩾ primary amides > secondary amides. The process has proved its value in helping to elucidate the structure of the cyclic decapeptide tyrocidin B. This peptide contains a proline residue and was cleaved there to give an open-chain peptide, whose amino-acid sequence was then determined using conventional methods.

Biochemical Genetics

The changes that have occured in the structure of cytochrome c in the course of evolution were investigated by *E. Margoliash* and *E. L. Smith* (U.S.A.). Depending on its source, this protein contains 104–108 amino acids plus a hem group,

[2] *G. Schramm, H. Grötsch,* and *W. Pollmann,* Angew. Chem. *74,* 53 (1962); Angew. Chem. internat. Edit. *1,* 1 (1962).

which is attached covalently to the peptide chain. Cytochrome c molecules from 13 species (yeasts, insects, vertrebates) showed over 50 % identity in the amino-acid sequence of their peptide chains. This suggests that all the cytochrome c types existing today have been derived from a common ancestral form. Moreover, the number of differences decreases the closer the species are related phylogenetically. Thus, for example, the cytochrome c molecules from the species of mammals investigated differ from those of birds in only 10–15 amino acids. The difference between the cytochrome c of mammals and birds on the one hand and that of fish on the other amounts to 18–21 amino acids; that of mammals, birds, and fish differs from that of baker's yeast by 43–49 amino acids. The cytochromes of humans and rhesus monkeys differ by only one amino acid, but those of humans and tuna by up to 21. Some of the constant amino-acid sequences are related to the function of the protein, but for others no such relationship is known and possibly does not exist. The greatest differences occur at positions 89 and 92 of the peptide chain: six different amino acids have been found in position 89 and five in position 92.

Similar conclusions were drawn by *V. Rudloff* (Germany) from his investigations of hemoglobins from various species of animals. There are significant differences in the amino-acid sequences in the hemoglobins of higher and lower vertebrates. The hemoglobin from lampreys (*Lampetra fluviatilis*) has a molecular weight of only 17000 – that of other vertebrates has a molecular weight of 64000 – and consists of only a single peptide chain, which resembles neither the α- nor the β-chain of human hemoglobin but which appears to be intermediate between these and myoglobin. It is therefore possibly an evolutionarily primitive form.

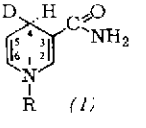
V. G. Allfrey (U.S.A.) investigated the differences between genetically active and inactive components of chromosomes. He found that only about 20 % of the genetic material in a mammalian cell is active. The remaining 80 % is balled together and is easier to remove from the cell than the active portion. The histone content of both fractions is the same, but the histones of the active portion are more strongly acetylated. It therefore appears that the minute structural changes induced by acetylation suffice to render a gene active without losing the protective and stabilizing action of the histones.

Mechanisms of Enzyme Action

The formation and stabilization of the three-dimensional structure of ribonuclease were the topics of the lecture by *C. B. Anfinson* (U.S.A.). Reduced ribonuclease contains 8 mercapto groups. The reduced enzyme is rapidly reconverted quantitatively into the native enzyme in dilute solution at a slightly alkaline pH in the presence of oxygen. The primary structure therefore appears to determine the tertiary structure of the protein. When the regeneration of the native enzyme is prevented by carrying out the oxidation at a low pH or in 8 M urea, an inactive protein is formed containing "incorrect" disulfide bridges. However, when this is incubated with traces of a mercapto compound, it undergoes disulfide exchange, and the active enzyme can be recovered. These reactions were used to test the extent to which the amino-acid side-chains influence the formation of the active tertiary structure. Attachment of polyalanyl residues onto the ε-amino groups of nine out of the ten lysine residues in the protein has no effect on the reoxidation, even when 60 molecules of alanine are incorporated into one molecule of RNase. It can therefore be concluded that the side-chains of these lysine residues are oriented outwards from the molecule. The ε-amino group of lysine-41 cannot be alanylated in the presence of polyanions (orthophosphate, cytidylate, or RNA). Polyanions also prevent alkylation of the histidine residues 12 and 119. It is therefore possible that there is a cluster of basic residues (induced or stabilized by polyanions) in the active center of the enzyme.

B. S. Hartley (England) reported the primary structure of beef chymotrypsinogen A. The molecule contains 245 amino acids and 5 disulfide bridges (Cys-1 to Cys-122, Cys-42 to Cys-58, Cys-135 to Cys-200, Cys-167 to Cys-181, and Cys-190 to Cys-219). The molecule is activated by tryptic cleavage of the bond between Arg-15 and Ileu-16. Subsequent chymotryptic cleavage of the bonds at residues Leu-13, Tyr-145, and Asp-NH_2-147 has only a slight effect on the activity of the enzyme and does not suffice alone to activate the enzyme. All 14 lysine residues, Cys-1, the *N*-terminal Ala-148, and the *C*-terminal Tyr-145 can be modified without loss of activity, hence these residues appear to be on the exterior of the molecule and to contribute only little to its catalytic effect or to maintenance of its tertiary structure. In contrast, the *N*-terminal Ileu-16 cannot be phenylated with fluorodinitrobenzene in the enzyme in the native state, and modification of this amino-acid residue can lead to alteration of the pH-dependence of the enzymatic activity. The *C*-terminal asparagine-245 also appears to reside within the molecule. There is much evidence that His-57 is involved in the active center. In this connection, it appears remarkable that the two histidine residues in positions 40 and 57 of the molecule are brought into close proximity by the disulfide bridge from Cys-42 to Cys-58, and that similar sequences are observed in trypsin and in chymotrypsinogen B.

The stereochemistry of enzymatic hydrogen transfer to pyridine nucleotides was discussed by *C. Donninger* (England). During the oxidation of substrates by pyridine coenzymes, the hydrogen from the substrate is transferred to C-4 of the pyridine ring. The reaction is stereospecific, the hydrogen transferred entering above [Formula *(1)*] or below [Formula*(2)*] the plane of the ring.The absolute configuration of the hydrogen introduced at C-4 was elucidated by means of deuterium labelling using a new ring degradation developed by *J. W. Cornforth*, which involves addition of methanol onto the 5,6-double bond, ozonization of the 2,3-double bond, and oxidation of the product with peroxyacetic acid. This treatment results in deuteriosuccinic acid *(3)* which is compared with synthetic deuteriosuccinic acid of known absolute configuration at C-2. It was thus shown that enzymes such as yeast alcohol oxidoreductase, which transfer a hydrogen to the "A" side of the pyridine ring produce *(4R)*-[4-D]DPHN *(1)*, *i.e.* the hydrogen is added onto that side of the nicotinamide ring from which the ring atoms 1–6 are viewed in an anticlockwise order.



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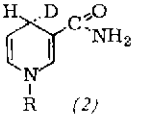

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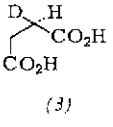

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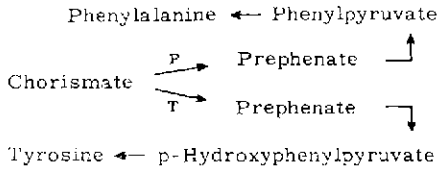
Hybrid isozymes of lactate dehydrogenase were obtained by *C. L. Markert* (U.S.A.). Lactate dehydrogenase (LDH) from vertebrates is generally a mixture of five isozymes formed by combination of two differing subunits into groups of four. These isozymes dissociate when they are dissolved and then frozen in the presence of certain salts. On thawing, statistical recombination of the subunits occurs. Mixtures of LDHs from different sources (fish, amphibia, reptiles, birds, mammals) gave hybrid isozymes after such treatment. Thirty-five isozymes were detected in mixtures containing four different subunits; three different subunits gave rise to 15 isozymes. All the hybrid isozymes exhibited enzymatic activity, but this was progressively less the greater the evolutionary distance between the species was whose LDHs were hybridized.

Special Topics in Biochemistry

F. Gibson and *R. Cotton* (Australia) detected two enzymes (prephenate synthetases) which convert chorismic acid into prephenic acid; these were obtained by chromatography of

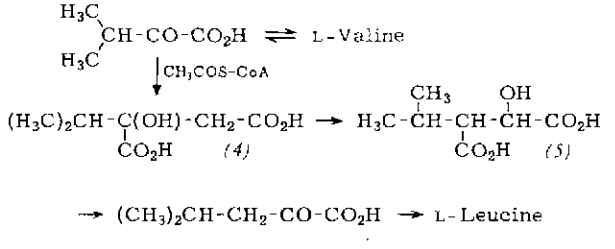
cell extracts from a wild type *Aerobacter aerogens* on DEAE-cellulose. End-product inhibition and repression tests with these enzymes demonstrated that one is responsible for phenylalanine synthesis (P), the other for tyrosine synthesis (T).



Mutants were obtained containing either one or neither of the prephenate synthetases. Strains which are auxotrophic for tyrosine have no enzyme T. Prephenate dehydrogenase, which catalyses the reaction prephenic acid → 4-hydroxyphenylpyruvate, passes through the column together with the prephenate synthetase T activity, and both activities may be lost and regained by single mutations. Similarly, prephenic aromatase (prephenic acid → phenylpyruvate) passes through with the prephenate synthetase P.

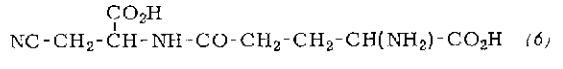
Washed cell suspensions of the anaerobic microorganism *Clostridium tetanomorphum* decompose tyrosine with formation of CO_2, H_2, and NH_3. Experiments to clarify the route of this anaerobic degradation were carried out by *N. Brot* and *H. Weissbach* (U.S.A.), who found that incubation of [u-^{14}C]tyrosine with growing or dormant cells of *Cl. tetanomorphum* yielded phenol containing 60 % of the radiocarbon. The degradation of L-tyrosine to phenol also occurs in cell-free systems, where the reaction is stimulated by pyridoxal phosphate. Another degradation product identified was pyruvic acid. Decomposition of the latter by phosphoroclastic cleavage could lead to the formation of CO_2 and H_2.

2-Isopropylmalic acid *(4)* and 3-isopropylmalic acid *(5)* are intermediates in the biosynthesis of leucine. *C. M. Stevens, J. M. Calvo,* and *M. G. Kalyanpur* (U.S.A.) investigated the mechanism of the rearrangement of *(4)* to *(5)*, which is comparable with the rearrangement of citric acid to isocitric acid. Following administration of [1-^{14}C]valine and [2-^{3}H]acetate to leucine-requiring mutants of *Neurospora crassa*, doubly labelled *(4)* and *(5)* are obtained, the radiocarbon:tritium ratio being the same in both compounds. α-Oxoisocaproic acid obtained from *(5)* by enzymatic or chemical oxidation contained no tritium.



Pyrolysis of *(5)* yielded 2-isopropylmaleic anhydride with an unchanged ^{14}C:T ratio. Enzymatic dehydration of *(5)* afforded the *cis*-acid. Measurement of the optical rotatory dispersion of the ethyl xanthate derivative of *(5)* proved that its carbinol carbon atom has the D_S-configuration. Furthermore, it can be concluded from the NMR spectrum of the *O*-acetyl anhydride of *(5)* that the natural compound is *erythro*-D_S-3-isopropylmalic acid. This implies that the enzymatic conversion of *(4)* to *(5)* proceeds *via* stereospecific *trans*-elimination and addition of water.

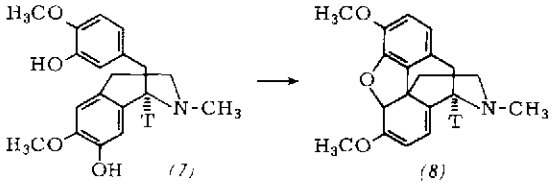
In various species of *Lathyrus* (sweet pea) and vetch, cyanide is a very efficient precursor for the cyano group in γ-glutamyl-β-cyanoalanine *(6)* which occurs in these plants. The formation of β-cyanoalanine was studied by *S. N. Nigam* and *C. Ressler* (U.S.A.). When [3-^{14}C]-L-serine was fed to seedlings of *Vicia sativa* (common vetch) through the roots, only 0.5 % of the radioactivity recurred in the dipeptide, but the degree of incorporation rose to 46 % when unlabelled KCN was administered simultaneously. The labelled dipeptide was hydrolysed with acid, and the aspartic acid formed converted into alanine with *Clostridium welchii*. The alanine still contained 90 % of the radioactivity. Hence serine in the presence of cyanide is an excellent precursor for carbon atoms 1–3 of β-cyanoalanine.



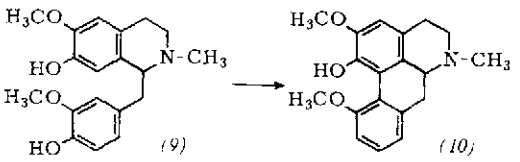
The formation of urea in tissues of ureide plants and in fruit bodies of higher basidiomycetes was examined by *H. Reinbothe* (Germany). Urea and glyoxylic acid are formed together in the course of aerobic degradation of purines. The glyoxylate can either form a ureide with the urea, as in ureide plants such as *Pelargonium zonale*, or participate to a large extent in the resynthesis of purines. There is thus a reaction cycle in operation in which the aerobic degradation of purines is connected *via* glyoxylate to the *de novo* synthesis of purines. There are at least three modes of urea formation in the fruit bodies of higher fungi (*Lycoperdon, Agaricus*) which accumulate urea: 1. the ornithine cycle, 2. aerobic degradation of purines, and 3. a hitherto unknown mode of pyrimidine catabolism. Two enzymes involved in arginine metabolism were found in the fruit bodies of *Lycoperdon*: arginase and an L-amino-acid oxidase. During oxidative degradation of arginine, γ-guanidobutyric acid is formed and can be partially degraded further to γ-aminobutyric acid and urea.

Earlier studies on the biosynthesis of the antibiotic cyclic decapeptide tyrocidin in intact cells of *Bacterium brevis* revealed that the synthesis of this peptide proceeds differently from the biosynthesis of proteins, since tyrocidin synthesis is unaffected by chloramphenicol and puromycin, whereas protein synthesis is completely inhibited. Actinomycin also causes total inhibition of RNA and protein synthesis but has no effect on the biosynthesis of tyrocidin, as *B. Mach* and *E. L. Tatum* (U.S.A.) were able to show. The synthesis of the decapeptide probably therefore requires no short-lived m-RNA. It was also found that in the biosynthesis of the tyrocidins A, B, C, and D the substitution of three single amino acids by others was dependent upon the concentration of these amino acids in the medium. This was attributed to a low specificity of the enzymes concerned and is also in contrast to the absolute specificity of such reactions during the biosynthesis of proteins.

A. R. Battersby (England) described some recent results on the biosynthesis of morphine alkaloids and of colchicine. [1-^{3}H]Reticuline was separated into its antipodes, and the incorporation of both forms into the thebaine in poppies was compared. It was found that only (−)-reticuline *(7)*, which has the tritium on C-1 in the same steric arrangement as the corresponding hydrogen atom in natural thebaine *(8)*, recurs in the thebaine isolated with about 60 % of its tritium activity. When (±)-reticuline is administered, the whole of the tritium is lost, since transformation to the (−)-antipode occurs before incorporation.



The ability to act as a precursor of thebaine also depends on the methylation pattern of the labelled compound. For example, the base *(9)* in which the hydroxyl and methoxyl groups in the benzyl residue are interchanged does not give rise to thebaine; instead, it is a precursor of isothebaine *(10)*.



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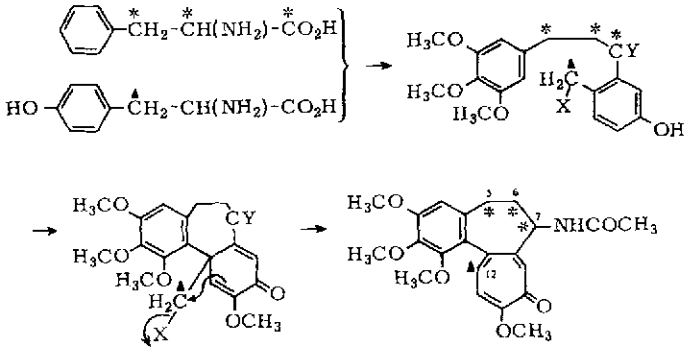
Although it was known from previous work that it is phenylalanine which gives rise to the phenyl residue and carbon atoms 5, 6, and 7 of colchicine, the mode of formation of the tropolone ring remained obscure. Experiments with [3-^{14}C]-tyrosine have now shown that when this compound was fed to *Colchicum autumnale*, 81 % of its radioactivity recurred in C-12 of the colchicine. It can therefore be concluded that colchicine is built up from phenylalanine and tyrosine, the 3-carbon atom of the tyrosine becoming C-12 of the tropolone ring *via* a ring expansion. Tyrosine and phenylalanine are therefore not equivalent precursors in this plant.



The biosynthesis of dideoxyhexoses in bacteria was investigated by *J. L. Strominger* et al. (U.S.A.). Ascarylose (3,6-dideoxy-L-mannose) is produced by extracts of *Pasteurella pseudotuberculosis*, Type V, by the following route: CTP + D-glucose-1-phosphate → CDP-D-glucose → CDP-4-keto-6-deoxy-D-glucose → CDP-ascarylose. TPNH is the reducing agent for the last step. CDP-3,6-dideoxy-D-glucose (CDP-paratose) is formed in a similar manner in extracts of *P. pseudotuberculosis*, Type III.

Lipids and Steroids

P. R. Vagelos et al. (U.S.A.) and *F. Lynen* et al. (Germany) gave reports on the course of the biosynthesis of fatty acids. Whereas the fatty-acid synthetase derived from yeast is a multienzyme complex, the synthetase from *E. coli* can be separated into its components. Three of these (E_I–E_{III}) are essential for the condensation of acetyl-CoA with malonyl-CoA:

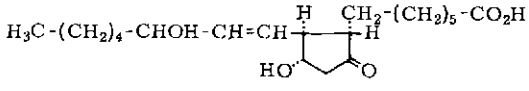
$$CH_3\text{-}CO\text{-}SCoA + HS\text{-}E_{II} \xrightarrow{HS\text{-}E_I} CH_3\text{-}CO\text{-}SE_{II} + CoA\text{-}SH$$

$$CH_3\text{-}CO\text{-}SE_{II} + HO_2C\text{-}CH_2\text{-}CO\text{-}SCoA \xrightleftharpoons{HS\text{-}E_{III}}$$

$$CO_2 + CoA\text{-}SH + CH_3\text{-}CO\text{-}CH_2\text{-}CO\text{-}SE_{II}$$

Fatty-acid transacylase (E_I) is extremely sensitive to SH inhibitors. E_{III} is the thermostable acyl transferase in the fatty-acid synthetase cycle; it has a molecular weight of 9500 and has been purified until chromatographically and electrophoretically uniform. It is also homogeneous in the analytical ultracentrifuge. E_{II} contains a cysteine residue. The enzyme E_{III} can also function as a transacylase, conveying the malonyl residue from malonyl-CoA to E_{II}. The main metabolic product of the fatty-acid synthetase in *E. coli* is *cis*-vaccenic acid, whose methyl-terminal carbon atoms are derived from acetyl-CoA, the remainder of the carbons in the chain being supplied in C_2 units by malonyl-CoA. *Lynen* and his collaborators concentrated fatty-acid synthetase from baker's yeast over one-hundredfold and obtained a preparation which was homogeneous when examined by electrophoresis or by electron microscopy. It had a molecular weight of 2.3×10^6, contained seven enzyme activities, and synthesized stearyl-CoA from acetyl-CoA and 8 moles of malonyl-CoA. Quantitative analysis of the terminal amino acids indicated the presence of seven polypeptide units in the complex. All the intermediates of fatty acid biosynthesis are attached covalently to the complex *via* mercapto groups which can be divided into peripheral groups (react readily with *N*-iodoacetamide or *N*-ethylmaleimide) and central groups (relatively resistant to these reagents). After saturated fatty acids containing 16–18 carbon atoms have been synthesized by the complex, they are transferred from a central to a peripheral SH group and are transferred from there to CoA, *i.e.* they are released from the complex.

Prostaglandines are complicated carboxylic acids of structure *(11)* which were investigated by *S. Bergström* (Sweden). They occur in mixtures in the seminal plasma of man and sheep, for example, and stimulate smooth muscle and depress the blood pressure. They also influence lipid metabolism. Prostaglandin E_1 in a concentration of 2.8×10^{-7} M counteracts the fat-mobilizing activity of adrenalin, noradrenalin, glucagon, and ACTH in rats. It also appears to inhibit the activity of a lipase in adipose tissue induced by adrenalin. However, injections of prostaglandin E_1 into humans increase the content of free fatty acids in arterial blood, and the fat-mobilizing effect of infused noradrenalin is not counteracted.



(11), Prostaglandine E_1

W. L. Byrne and *M. C. Ganoza* (U.S.A.) observed that the activity, stability, and substrate specificity of glucose-6-phosphatase is influenced by the phospholipids contained in the enzyme. If the lipids are removed, an inactive form of the enzyme is obtained which can be reactivated by addition of phospholipids, although complete identity of this preparation with the native form of the enzyme is not achieved.

Metabolism and Its Control

S. Granick (U.S.A.) discussed a repressed enzyme system in chicken liver. When 3,5-bisethoxycarbonyl-1,4-dihydrocollidine is added to a 16-day old primary culture of chick embryo liver, porphyrins can be detected in the cells within 3 h. The reason for this is *de novo* synthesis of rate-determining δ-aminolevulinic synthetase. Inhibitors of protein synthesis such as mitomycin C and actinomycin D prevent the formation of the enzyme.

W. E. Knox (U.S.A.) determined the degree of incorporation of [^{14}C]arginine into tryptophan pyrrolase following induction of the enzyme with tryptophan or cortisol. The enzyme was precipitated with antibodies, and its radiocarbon content was determined. Although the amount of enzyme rose after both types of induction, only that formed after induction with cortisol had a higher specific radioactivity in the protein. It therefore follows that only cortisol induces *de novo* syntbesis of the enzyme, whereas tryptophan apparently only slows down the degradation of the pyrrolase.

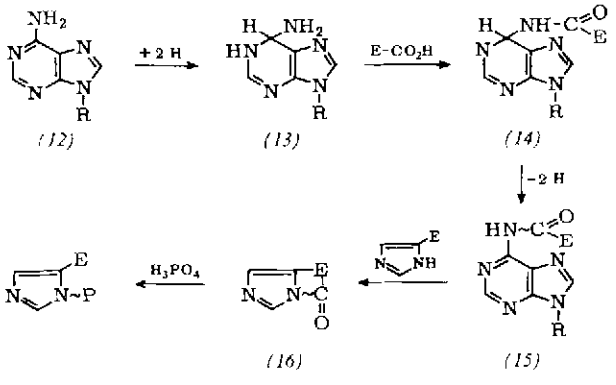
The effects of insulin on carbohydrate metabolism in the liver were studied by *J. S. Bishop* et al. (U.S.A.), who found that intravenous infusions of insulin (0.08–0.2 units/kg/h) into dogs decrease the release of glucose from the liver into the blood by 62 %, increase the glucose uptake of all tissues

threefold, and increase the synthesis in the liver of glycogen from blood glucose eightfold. The uptake of glucose into non-glycogenous liver constituents also increases.

Thyroid hormones influence the activity of mitochondrial enzymes. *B. Kadenbach* (Germany) observed an increase in the activity of glycerophosphate oxidase and succinic dehydrogenase in the mitochondria of rat liver, kidney, heart, muscle, brain, and spleen on passing from the hypo- to the hyperthyroid state. The cytochromes a, b, and c increase by a factor of 1.3–2.0, and DPN-specific isocitric dehydrogenase increases by a factor of 1.4–2.4, but not in brain and spleen mitochondria. On the other hand, TPN-dependent isocitric dehydrogenase, glutamate-oxaloacetate transaminase, and β-hydroxybutyric dehydrogenase in mitochondria from liver, heart, kidney, and muscle have lower activities in the hyperthyroid state. It follows from these results that thyroid hormones increase the activity of the oxidative system of mitochondria by induction of the enzymes of the citric acid cycle and of the respiratory chain, but inhibit the enzymes of the synthetic metabolism.

Bioenergetics

V. P. Skulachev (U.S.S.R.) reported on the function of adenine nucleotides in the respiratory chain. It appears that adenine nucleotides *(12)* not only function as energy-rich compounds (ATP) but, as the formulae show, are also substrates for redox reactions. The pyrimidine ring is first reduced to *(13)*, which is acylated at its amino group by the free carboxyl group of an enzyme (E–CO_2H) to give *(14)*, which is then reoxidized to *(15)*. The aromatic ring withdraws electrons from the amide nitrogen and thus increases the energy content of the amide bond. The energy from this bond could be utilized by imidazole catalysis for the formation of ATP.



The coupling factors involved in mitochondrial oxidative phosphorylation were discussed by *G. Webster* (U.S.A.). He isolated three proteins from the soluble protein fraction of mitochondria and found that these function as coupling factors, each being specific for a single coupling site. The DPNH coupling factor, which is required for phosphorylation in the DPNH-flavoprotein region, was obtained in crystalline form; it is homogeneous and has a molecular weight of about 30000. The QH_2 factor (specific for phosphorylation in the coenzyme Q-cytochrome b region) was highly purified and separates into two components in the ultracentrifuge. The coupling factor for reduced cytochrome c is homogeneous and has a molecular weight of about 35000.

It appears that all of these factors have a part to play in reaction sequences which may be written as follows:

a) Substrate + Particle → Particle ~ Substrate

b) Particle ~ Substrate + Factor → Factor ~ Substrate + Particle

c) Factor ~ Substrate + P_i → Factor ~ P + Oxidized substrate

d) Factor ~ P + ADP → Factor + ATP

The compounds Factor ~ Substrate (= DPNH ~ Factor) and Factor ~ P were isolated from the phosphorylation step coupled to DPNH oxidation. The Substrate ~ Particle component for the phosphorylation step coupled to cytochrome c oxidation was also isolated; it is labile above 5 °C. The compound Factor ~ Substrate (for cytochrome c) is red, has a molecular weight of about 50000, and appears to consist of 1 mole of factor and 1 mole of reduced cytochrome c. It reacts with orthophosphate to form colorless Factor ~ P with liberation of cytochrome c. The Factor ~ P compound is stable at neutral pH but decomposes at acid and alkaline pH. It reacts with ADP to form ATP. Inhibitors of oxidative phosphorylation affect various steps of the four-stage reaction sequence: 2,4-dinitrophenol and bicoumarol cause rapid disintegration of the Particle ~ Substrate complex, and oligomycin inhibits the formation of ATP from Factor ~ P.

[VB 868/173 IE]
German version: Angew. Chem. 77, 97 (1965)

Organic Photochemistry

The International Union for Pure and Applied Chemistry held an International Symposium on Organic Photochemistry in Strasbourg (France) on July 20th–24th, 1964. The conference was supported by NATO and admirably organized by *G. S. Hammond* and *J. Levisalles*, and was preceded by an introductory seminar lasting three days.

W. A. Noyes dealt with problems of the radiationless deactivation of excited molecular states with or without change in multiplicity (*i.e.* "intersystem crossover" or "internal conversion", respectively). In the case of diacetyl or benzene, all or nearly all molecules in the gas phase that are excited to the first singlet state are regarded as assuming the triplet state, unless they are previously stabilized by emission of fluorescence. There are indications, however, that the singlet-triplet-conversion requires only a low activation energy; in any case, deuteration of benzene increases the fluorescence yield considerably. This yield is not independent of the wavelength of the incident light; it approaches zero at 2350 Å. Presumably, a competing deactivation process plays a part, possibly an isomerization, which proceeds faster than the dissipation of the excess of vibrational energy, particularly if the latter is very large in the excited state.

Little has been done so far to investigate the radiationless transition: triplet → ground state; beyond its existence in principle, not very much is known. Here, isomerization may again play a role in the deactivation.

A survey of chemiluminescence in solution was given by *E.J. Bowen*. Chemiluminescence reactions are phenomena in which a potentially fluorescent molecule is excited by means of chemical energy into an electronically excited state. As a rule, typical radical reactions are involved, because the energy required per light emission in the visible region is 40–70 kcal/mole. Two of the most brilliant emissions are observed in the oxidation of the cyclic 3-aminopbthaloyl hydrazide and dimethyldiacridylium nitrate. In both cases, the final products (*viz.* aminophthalic acid or methylacridone) are the emitting species. In concentrated solutions of acridone, an energy transfer to the reacting molecules also appears possible. Organic hydroperoxides may be decomposed thermally to ketones; if a fluorescent organic molecule containing an

extended conjugated system is present, this is first oxidized in a one-electron process, and is then reduced in a second stage, with simultaneous conversion into the excited singlet state that is responsible for the luminescence. At least two additional, although less effective, mechanisms are possible. The mechanism of light emission that occurs in the thermal dissociation of cyclic peroxides of molecules containing conjugated systems (*e.g.* the peroxide of diphenylanthracene) is still not clear. The simple dissociation process

$$AO_2 \rightarrow A + O_2$$

does not provide sufficient energy for a visible quantum. Possibly the reaction

$$AO_2 \rightarrow {}^3A + {}^3O_2$$

is followed by

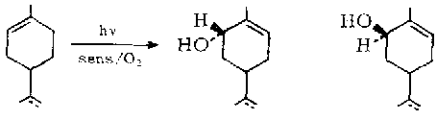
$${}^3A + {}^3A \rightarrow {}^1A^* + {}^1A$$

The subject of a survey by *G. Porter* was the reactivity of $n \rightarrow \pi^*$-, $\pi \rightarrow \pi^*$-, and charge-transfer states in benzophenone derivatives. It is wellknown that the photopinacolization of triplet-benzophenone is strongly influenced by substituents: certain *ortho*-substituents inhibit this reaction, due to intermediate tautomerization. The fact that *meta*- and *para*-substituents also exert a profound influence on the reactivity must be ascribed to their effect on the electronic energy levels. It has not yet been explained exactly how these effects operate. In particular, no explanation is yet available which accounts for the effectiveness of NH_2-substituents, for the lack of influence of halogens, or for the considerable reactivity of the *p*-methoxy derivative, and the contrasting inertness of the *p*-hydroxy derivative. An unequivocal interpretation of these phenomena is provided by new measurements of absorption and phosphorescence spectra, of quantum yields, and of lifetimes, together with new studies of intermediates by means of flash-photolysis. In addition to $n \rightarrow \pi^*$- and $\pi \rightarrow \pi^*$-states, charge-transfer states play a part in derivatives with electron-donating substituents (OH, OCH_3, NH_2); reactivity is always small when the charge-transfer levels are lowest, because in these cases the carbonyl group possesses a high electron density. The divergent effects of hydroxy and methoxy substituents is due to the rapid deprotonation of the hydroxy group in the excited state. This interpretation is supported by pK-measurements in the ground, triplet, and excited singlet states.

Confirmation of this interpretation of the different tendency of substituted benzophenones to photopinacolization is provided by the influence of solvents on the relative positions of the $n \rightarrow \pi^*$-, $\pi \rightarrow \pi^*$-, and charge-transfer transitions, and on the reactivities dependent thereon. Thus, certain photosensitized benzophenone derivatives abstract hydrogen from paraffins, but not from alcohols.

Results of recent investigations by *G. O. Schenck* and his coworkers were reported by *K. Gollnick*: The effectiveness of fluorescein (and its tetrabromo-, tetraiodo-, and tetraidotetrachloro derivatives) as sensitizers in the oxygen transfer to dimethylfuran: Spectroscopic data provide the basis for calculations of absolute rate-constants, and hence half-lives of the sensitizers in the excited singlet and triplet states, and for the computation of the quantum yields of the fluorescence, of the $^1S(O)$-transition and the oxygen-transfer reaction. Substitution by halogen in the sensitizer has practically no influence on the life-time of the excited singlet state, but increases considerably both the $^1S(O) \rightarrow S_0$- and the $^1S(O) \rightarrow {}^3S(O)$-transitions. Consequently, the quantum yield of triplet formation is considerably increased in fluorescein by heavy halogens. This effect is due to spin-orbit coupling. Because of the very short life-time of $^1S(O)$, the O_2-transferring species is formed almost exclusively by the reaction of $^3S(O)$ with oxygen.

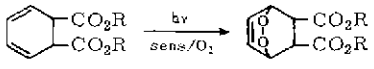
The mechanism and stereospecificity of the O_2-transfer to olefins having isolated double bonds and allylic hydrogen atoms, sensitized by methylene blue or Rose Bengal: oxygen transfer to (+)-limonene and (+)-carvomenthene *(1)* affords, in each case, after reduction of the hydroperoxides, six optically active alcohols. The fact that simultaneous inversion of configuration results in levorotatory *cis/trans*-carveoles and *cis/trans*-carvotanacetoles *(2)*, excludes direct O_2-insertion into the allylic C—H-bond, and emphasizes the contrast with thermal autoxidation. The actual composition of the product deviates from the statistical distribution and is interpreted in terms of the preferential removal of the quasi-axial hydrogen atoms. The stereoselectivity of the photo-oxidation of 1,1-dimethyl-2-alkylethylenes is ascribed to the same cause.



(+) (−) (−)

(1) *(2)*

The directive influence of very bulky substituents is demonstrated by (+)-Δ^3-carene (exclusive *trans*-attack), while the effect of purely electronic factors is shown by the cyclohexadiene derivatives *(3)* and *(4)*, and by various alkyl-substituted ethylene and cylohexene derivatives.



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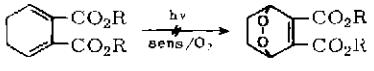
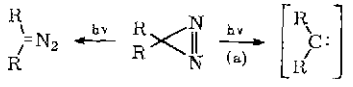


(4)

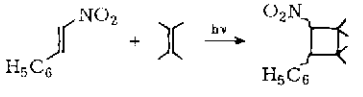
According to *H. M. Frey*, the photolysis of diazirines involves two primary reactions: the main reaction is the direct elimination of nitrogen with formation of a carbene *(6)*; in a parallel reaction, the diazirine is isomerized to the open-chain diazo compound *(7)*.



(7) *(6)*

The existence of a carbene intermediate is indicated by the composition of the hydrocarbon mixture originating in Reaction (a); this agrees satisfactorily with the result of the base-catalysed or thermal decomposition of *p*-toluenesulfonylhydrazones. However, attempts to trap carbenes in the photolysis of diazirines were unsuccessful.

New results concerning the photochemistry of unsaturated nitro compounds have been provided by *O. L. Chapman*. Irradiation of β-nitrostyrene in olefins results in the formation of 1:1-adducts in good yields; tetramethylethylene, for example, affords *(8)*. Surprisingly, β-methyl-β-nitrostyrene *(9)* does not add onto olefins, product *(10)*, isomeric with *(9)*, being obtained in 79 % yield.



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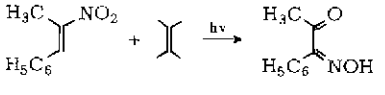
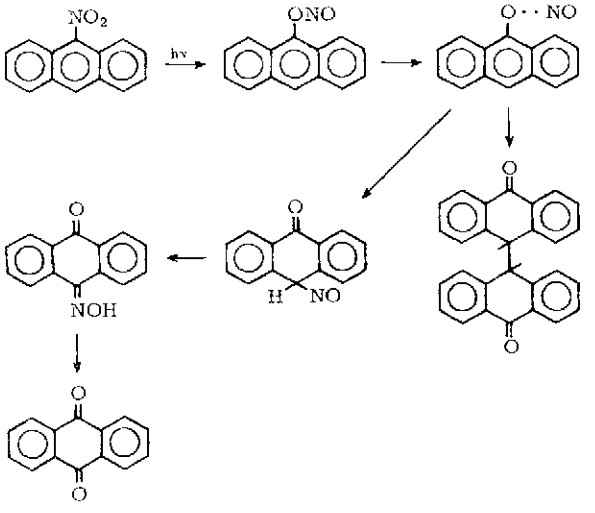


(9) *(10)*

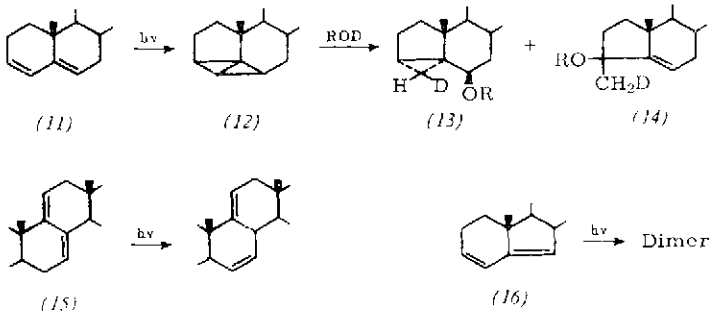
The mechansim of this rearrangement is closely related to photochemical transformations of aromatic nitro compounds. 10,10'-Bisanthrone, anthraquinone and its monoxime are the photochemical products of 9-nitroanthracene. Since anthraquinone arises also in the absence of oxygen, it is not the

product of a photo-oxidation (*Dufraisse*). On irradiation in the presence of nitric oxide, anthraquinone is formed in up to 77 % yield. These observations are interpreted by the following sequence of reactions:



A similar mechanism accounts for the isomerization of *(9)* to *(10)*.

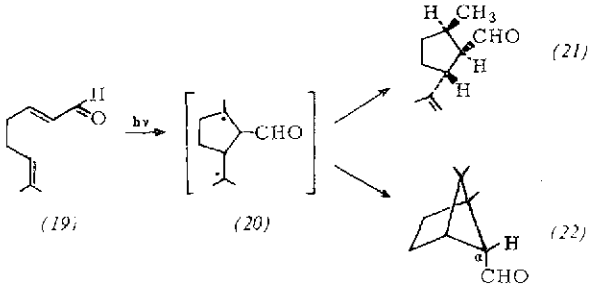
According to recent investigations by *W. G. Dauben*, the rigid *trans*-diene *(11)* is isomerized by irradiation in a hydrocarbon solvent to the [1,1,0]-bicyclic system *(12)* which reacts stereospecifically with protonic solvents to yield *(13)* [OR axial] and *(14)*.



Accordingly, in aqueous dioxane, the final photo-products are the appropriate alcohols. Sensitization by fluorscein causes dimerization of *(11)*. The sensitivity of the formation of the [1,1,0]-bicyclic system towards geometric factors is illustrated by examples *(15)* and *(16)*: hydrogen transfer or dimerization are the preferred reactions even in 10^{-4} M solution.

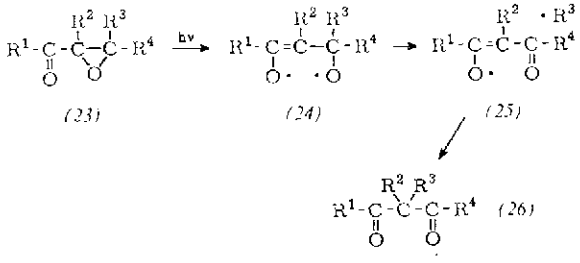
Mechanistic problems of photochemical reactions, particularly of carbonyl compounds, were the subject of a paper by *H. E. Zimmermann*. New sensitization studies suggest the high probability of a triplet mechanism for the rearrangement of the dienone *(17)* to *(18)*.

Spectroscopic data, measured in ethanol/petroleum ether at 77 °K, show that the reaction involves an $n \rightarrow \pi^*$-, and not a $\pi \rightarrow \pi^*$-triplet-state: the phosphorescence spectrum of *(17)* greatly resembles that of benzophenone in fine structure and in the position of the bands. For benzophenone the $n \rightarrow \pi^*$-character has been conclusively shown. The half-life of 0.5 msec measured at 77 °K is in agreement with this assignment.

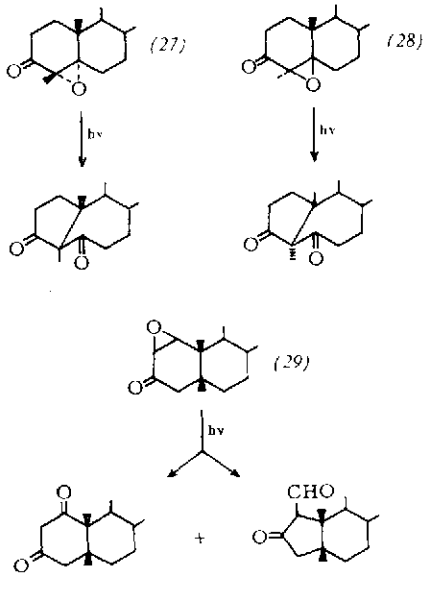


The mechanistic interpretation of photochemical reactions is often based, at least partially, upon stereochemical results. The reliability and limitations of such relationships were discussed by *R. C. Cookson*, with special emphasis on certain reactions of ketones, including the elimination of carbon monoxide, intramolecular ene-synthesis, and cleavage to ketenes. He stressed that stereospecificity is not an absolute proof of a synchronized process. The aldehydes resulting from the $n \rightarrow \pi^*$-excitation of citral *(19)* have configurations *(21)* and *(22)*. The *trans*-configuration of the alkyl groups in *(21)* and the α-position of the aldehyde group in *(22)* suggest the existence of a common intermediate *(20)* as singlet or triplet.

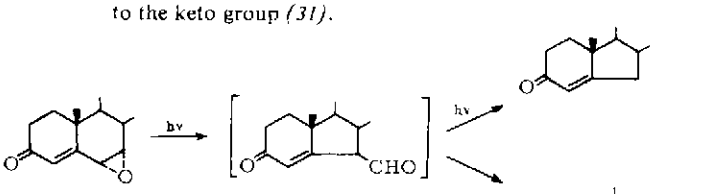
The importance of light-induced transformations of α,β-epoxyketones and related carbobyl systems in organic synthesis was demonstrated by *O. Jeger*. The isomerization of α,β-epoxyketones to β-diketones may be represented by formulae *(23)*–*(26)*.



Ultraviolet irradiation of numerous steroid α,β-epoxyketones illustrated the general nature of this photo-isomerization. Depending on the structure, it results in a 1,2-rearrangement of the carbon skeleton or in a 1,2-hydrogen migration. The reactions of *(27)*–*(29)* proceed stereospecifically.



α,β-Unsaturated γ,δ-epoxyketones *(30)* also undergo epoxyketone rearrangement. The function of the epoxy oxygen atom may be exerted by other oxygen functions in α-position to the keto group *(31)*.



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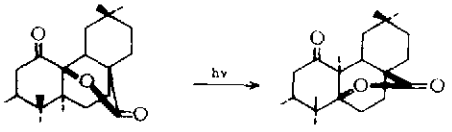
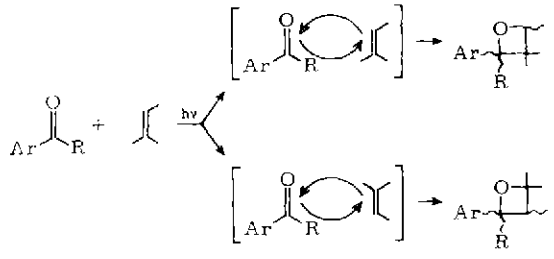


(31)

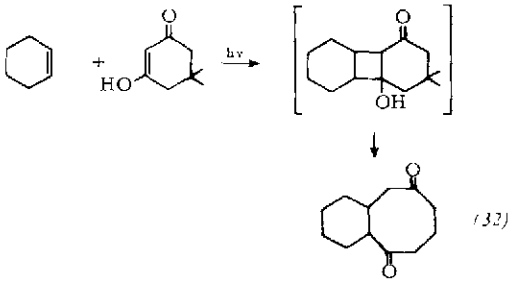
In addition to the C(α)-O bond, the C(α)–C(β) link may be cleaved during ultraviolet irradiation of α,β-epoxyketones. A process of this type is regarded to be operative in the photofragmentation of *O*-acetyljervine.

A paper by *N. C. Yang* dealt with new aspects of the Paterno-Büchi reaction. The oxetane mixture, isolated in 64 % yield in the photo-addition of benzaldehyde to 2-methylbut-2-ene, contains all four isomers, as expected. Attack by the carbonyl oxygen atom (which is electron-deficient in the excited state) at the C=C bond with formation of the most stable carbonium ion is more probable by a factor of 1.6.



Oxetane formation, occurring with a quantum yield of 0.45 ± 0.05, is suppressed by paramagnetic salts. The addition of benzophenone and acetophenone proceeds far more selectively: the two isomers of the favored addition are formed in yields exceeding 90 %. 1- and 2-Naphthaldehyde, 2-benzoylnaphthalene, and 9-anthraldehyde are employed with comparably good results, but the quantum yields are considerably lower than with benzaldehyde; however, 1- and 2-acetylnaphthalene and 9-acetylanthracene are inert. The use of α,β-unsaturated carbonyl compounds (*e.g.* cinnamic or crotonic aldehyde) results in 1,2-addition to the C=C and C=O bonds, but not in 1,4-addition to dihydropyran derivatives.

P. de Mayo dealt chiefly with photochemical cycloadditions of dicarbonyl compounds; their applicability to the synthesis of mono- and bicyclic systems is illustrated by the following examples. Dimethyl maleate reacts with cyclohexene to yield,

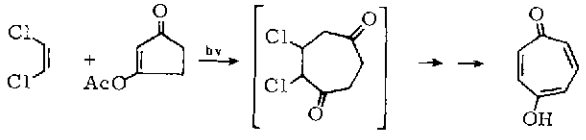


(33)

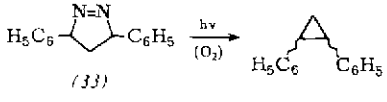
in addition to cyclohexenylsuccinic acid and bicyclohexenyl, at least four isomeric bicyclo[4,2,0]octanedicarboxylic esters. Two of these bicyclic products have the *trans*-configuration; this requires a two-stage process for the formation of at least these two compounds. The ratio of the *cis*/*trans* isomers is temperature-dependent, *i.e.* an intermediate is in thermal equilibrium with its environment. Since sensitizers (acetophenone, benzene) affect the result only slightly, the occurrence of triplet states (possibly of the $n \rightarrow \pi^*$-type) is possible.

The cycloaddition of cyclohexene to dimedone or of acrylic esters to cyclohexane-1,3-dione affords derivatives of cyclooctane-1,5-dione *(32)*; the perhydroazulene system is formed from cyclohexene and cyclohexane-1,3-dione.

One of three stereoisomeric addition products of dichloroethylene to the enol acetate of cyclopentane-1,3-dione yields γ-tropolone after methanolysis and treatment with bases.

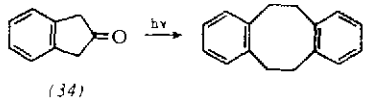


According to *G. Quinkert*, the most important types of photochemical reactions of saturated ketones in solution (epimerization, at least two modes of isomerization, elimination of carbon monoxide, and oxidative cleavage) probably proceed by way of intermediate acyl/alkyl biradicals which arise as dissociation products in the primary photochemical stage. Compared to monoradicals, these biradicals exhibit a considerably decreased intermolecular reactivity, particularly towards oxygen. Accordingly, the result of the photolysis of cyclic azo compounds such as *(33)* is not affected by oxygen.



(33)

Intramolecular recombination of these biradicals causes reversible epimerization of the ketones. In suitable environments, this recombination is inhibited by intramolecular hydrogen migration: the products of this photo-isomerization are open-chain ketenes (acids) and unsaturated aldehydes. The readiness of photo-decarbonylation – a valuable preparative method for the synthesis of certain hydrocarbons in the gas phase – depends in the liquid phase on the π-electron stabilization of the radicals formed.



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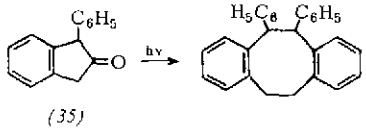

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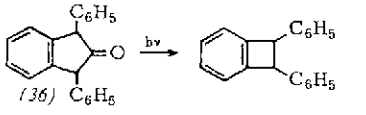
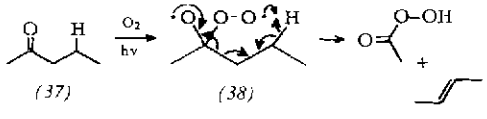


(36)

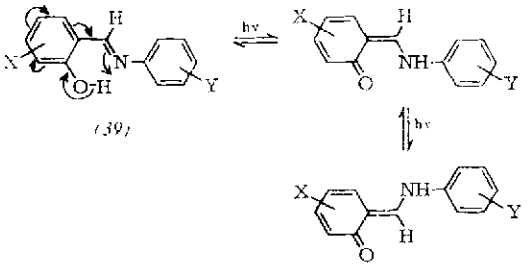
Thus, for example, *(34)* loses less than 10 % CO during irradiation, while *(35)* and *(36)* are almost completely decarbonylated.



(37) *(38)*

As shown by formulae *(37)* and *(38)*, all ketones containing a hydrogen atom in the β-position and in *cis*-configuration with respect to the carbonyl group, should be capable of undergoing this photo-oxidative cleavage.

Numerous photochemical reactions proceed differently in the solid state and in solution, possibly due to the high viscosity or the particular geometry of the crystal; in the latter case "topochemically controlled" reactions are involved. Two examples of this kind were discussed by *M. D. Cohen*. Photochromism (*i.e.* the reversible light-induced color change) of anils of salicylic aldehyde *(39)* may be ascribed to a two-stage process, *viz.* migration of hydrogen, followed by isomerization.



(39)

Crystallographic data account for the fact that photochromism and thermochromism are mutually exclusive in the case of these anils. When the crystal structure favors the hydrogen transfer, isomerization is prevented in the thermochromic crystals. The crystal lattice also determines the course of the photochemical reaction of cinnamic acids. Thus, the *trans*-acid will only dimerize when the distance between active centers is less than about 4 Å. [VB 865/172 IE]

German version: Angew. Chem. 77, 47 (1965)

Vth International Symposium on Gas Chromatography

The Fifth International Symposium on Gas Chromatography was held in Brighton (England) from September 8th to 10th, 1964. These symposia follow each other in alternate years, an interval which is too short for far-reaching advances to be expected from each symposium. This year the outstanding contributions were predominantly those extending knowledge and understanding of already known phenomena on the basis of critical and generalized examinations. The assimilation of innovations into established techniques of gas chromatography found expression in an extensive exhibition of apparatus.

Part of the proceedings showed that with the increasing technical perfection of gas-chromatographic apparatus, the production of rapid and high-efficiency columns has become a major problem, and that much effort will he required before the advantages inherent in gas-solid chromatography can be widely utilized.

The contributon by *I. Halász*, *K. Hartmann*, and *E. Heine* (Frankfurt/M.) on "Column types in gas chromatography" was of great theoretical and practical interest in this respect. The authors showed that column types are not sufficiently characterized on the basis of plate numbers. Of equal importance are permeability or the drop in carrier gas pressure at a given flow rate, which influence the time required for a given separation. The stability of the column and the technical difficulties involved in its preparation are also of practical importance. In a further development of the Golay performance index, *Halász* et al. propose a performance parameter (PP) for use in the characterization of column properties:

$$PP = h^2 \frac{(1+k')^5}{(k')^4} \cdot \frac{\eta}{K \cdot j'} \cdot \left(\frac{6 \cdot r_{12}}{r_{12}-1}\right)^4 = \Delta P_{ne} \cdot t_{ne}$$

(where ΔP_{ne} = pressure drop; r_{12} = relative retention; t_{ne} = analysis time; η = viscosity of the carrier gas; K = permeability; j' = pressure drop correction coefficient; k' = capacity factor; h = height equivalent of theoretical plate).

The authors attempted to combine the advantages of capillary columns (open tubular columns, low pressure drop) with those of packed columns (large surface area, small V/V_t-value), which has led to packed capillary columns and other transitional types.

C. Landault and *G. Guiochon* (Paris) described the preparation and properties of a packed capillary column. Like *Halász* et al., they used a capillary column (50 m long; 0.5 mm internal diameter; 1.5 mm external diameter) filled with firebrick C-22 (particle size from 100 to 250 μ, various packing densities). The liquid phase was applied as in the classical capillary column technique. With squalane as stationary phase a complete separation of the isomeric hexanes, including separation of the pair 2,3-dimethylbutane and 2-methylpentane, which is difficult, was obtained within 8 minutes.

Gas-solid chromatography has distinct advantages over gas-liquid chromatography only in the field of hydrocarbon separations, for which alone it is possible to obtain linear isotherms without the use of extremely high operating temperatures. *C. G. Scott* and *C. S. G. Philips* (Oxford) stated that:

1. Gas-solid elution chromatography can accomplish the same separations of hydrocarbons and relatively non-polar substances as can gas-liquid elution chromatography.
2. The selectivity of gas-solid chromatography can equal, if not surpass, that of gas-liquid elution chromatography.
3. A combination of gas-solid displacement chromatography and gas-liquid elution chromatography is a powerful method for trace analysis.
4. Gas-solid displacement chromatography has considerable use in preparative chromatography.

A. V. Kiselev (Moscow) discussed types of intermolecular interaction. Compounds which are not capable of specific interactions contain only π-bonds or have a symmetrical electron density distribution; while molecules capable of specific interactions have local concentration of positive or negative charge (lone-pair electrons, π-bonds, active hydrogen). On this basis adsorbents were classified into four groups:

1. Adsorbents with a chemically saturated surface (*e.g.* graphited soot). The surface contains no ions, functional groups, or π-bonds. The operative forces are dispersion forces, depending only on the geometry of the molecule. On such surfaces the energies of adsorption of water, ammonia, alcohol, etc. are smaller than their energies of condensation, because the surface coverage is so sparse that the adsorbed molecules do not interact with one another. Gas-solid chromatography columns employing graphitized carbon black as stationary phase were first used by *Halász* and *Horvath*. High adsorption energies are disadvantageous as they require very high working temperatures.
2. Adsorbents with local concentrations of positive charge (protons, small-radius cations). They adsorb molecules with lone-pair electrons and π-bonds.
3. Adsorbents with π-bonds and anions of small ionic radii.
4. Non-specific adsorbents bearing cations and anions.

J. J. Kirkland (Wilmington, Del.) described investigations with boehmite-modified firebrick carriers, treated with stearic acid. Dibutyl maleate (1 %) was used as liquid phase. As compared with a column containing dibutyl maleate (20 %) as

liquid phase on normal firebrick, a better separation of the low boiling fractions of a fluorinated hydrocarbon mixture, and a marked reduction of bleeding as a result of adsorption of the dibutyl maleate on the (active) boehmite, was obtained. Similar boehmite-modified carrier surfaces were produced by *Kirkland* on glass beads and in glass capillaries, for which purpose coatings with silicone oils were generally used.

A. B. Littlewood (Newcastle-upon-Tyne) calculated (according to *Giddings*) the increase in width of gas-chromatographic zones over the whole cross-sectional area of a packed column, resulting from non-uniform flow. The results obtained were confirmed on intentionally badly-packed columns, and the effects with alkaline or acidic vapors were made visible by the use of indicators. The effect is also observed in properly packed columns, and here also the theory is compatible with the experimental results. *Littlewood* found that inhomogeneity of the flow profile decreases the separating efficiency especially in preparative columns of diameters between 3 and 10 cm.

In their contribution on "The theory and design of preparative-scale columns", *C. M. C. Higgins* and *J. F. Smith* (Welwyn Garden City, Herts.) discussed the difficulties involved in obtaining definite and reproducible packings of preparative columns. The authors favor what they term a "mountain-packing" method of column filling, where the stationary phase is slowly introduced through a narrow tube so as to form a mound in the center of the column. This method of filling leads to a strong fractionation of particle sizes across the column, which is advantageous in smoothing the flow profile. Particular attention was given by the authors to overloading phenomena in gas-chromatographic columns. On the basis of their observations they propose the following requirements in preparative gas chromatography:

1. A stable liquid phase with a low γ_0-value must be chosen.

2. The carrier material should consist of a very narrow sieve fraction and be as uniformly coated as possible. Of all the carriers examined, firebrick had the best properties (good mechanical durability, easy to coat, easy to pack).

3. Carrier and packing technique should be chosen so that a high radial diffusivity and, as far as possible, a flat intrinsic-profile is obtained.

4. The heat conductivity and specific heat of the packing should be greater than that of the apparatus (column, injection block, etc.).

5. A change of carrier gas has no great influence on separation. Only the time necessary for a given separation is dependent on the diffusivity of the carrier gas.

6. The method of sample injection should allow for control of the sample volume in order that a good compromise between sample size and overloading phenomena can be obtained.

7. The detection system should be rapid in operation and have a large dynamic range.

K. P. Hupe and *E. Bayer* (Tübingen) dealt with problems of temperature programming of preparative columns. In large-diameter columns considerable temperature differentials arise between the walls and the center of the column. These influence the separation very unfavorably and make rapid temperature programming over a large temperature range impracticable. Temperature profiles were calculated by the method of *Giddings*. In large-diameter columns the experimental findings did not agree with the calculations.

According to *R. P. W. Scott* (Sharnbrook, Bedford) flow programming is superior to temperature programming for the shortening of analysis time in the following respects:

1. Flow programming can be used with any chromatograph without regard to oven construction.

2. The thermal stability of the liquid phase is not important.

3. The long cooling-down period after temperature programming is avoided.

Finally, flow programming has a very favorable effect on overloading phenomena and makes "preparative" loads possible even on analytical columns.

Two contributions described new detector systems for liquid-solid chromatography. In both methods an endless metal wire is run past the end of the column where it is moistened by the eluate. The wire then runs into an oven where the solvent is evaporated, leaving only the non-volatile material. In the experimental arrangement of *A. T. James* et al. (Sharnbrook, Bedford) the material on the wire is then led into a pyrolysis oven and cracked. The cracked gases are detected in an argon macrodetector. In the arrangement reported by *E. Haahti* et al. (Turku, Finland) the wire is led directly into the flame of a flame-ionization detector.

Finally, the presentation of gas-chromatographic data was discussed. New recommendations of the Gas Chromatography Discussion Group are that:

1. Relative retentio data should only be derived from chromatograms containing a standard substance.

2. As far as possible n-alkanes should be used as standard substances.

3. Where this is not possible, secondary substances whose retention data relative to n-alkanes are known should be used.

4. All data should be corrected for the dead volume of the apparatus.

5. The retention of an unknown substance x relative to a n-alkane with N C-atoms should be indicated as R_{xN}, and the relative retention should be regarded as the primary unit.

6. Relative retention data should be published preferably in the form of *Kovat*'s retention indices or as R_{x9} values. It has been shown that the Kovats' retention index shows the least variation from a standard value.

7. The gradient b of the linear plot of log R against C-number of the n-alkane, determined from at least three alkanes, should be given together with the retention data.

8. Full experimental details of the apparatus used should be given.

The exhibition of apparatus provided a survey of new developments. Prominent among these were a microcoulometric detector (Messrs. Dohrmann), which can be used with any chromatograph for the analysis of halogen-, phosphorus-, and sulfur-containing compounds, and a flow-programming apparatus (designed by *Scott*) (Messrs. Pye). In the integration field, a new digital integrator (Messrs. Infotronics) for use in amino-acid analysis, and a digital integrator (Messrs. Siemens), were shown. An important development is the Atlas curve-evaluator (patented for Farbenfabriken Bayer) which achieves the integration of a recorded chromatogram by means of an optical tracer system. This apparatus also gives the results in digital form. [VB 862/167 IE]

German version: Angew. Chem. 77, 104 (1965)

Under the joint auspices of the Czechoslovakian Chemical Society and the University of Prague, a "Symposium on the Chemistry of Organic Sulfur Compounds" was held in the Castle of Liblice, near Prague, between June 15 and 17, 1964.

From the agenda:

O. Exner, Prague, surveyed the attempts to gain semiquantitative relations for the originally qualitative concepts of the inductive, mesomeric, and steric effects. These effects were studied on model compounds, and relative data were obtained either from kinetic data or from equilibrium constants. The (-I) effect of alkylthio groups is significantly weaker than that of alkoxy groups. However, groups containing multivalent sulfur are strong electron-acceptors. The (-I) effect decreases in the order:

$$SO_2Cl > SO_2F > SO_2CF_3 > SO_2OC_2H_5 \approx SO_2NH_2 \gg SO_2O^-.$$

The (+M) effect of the SR-group is about half as great as that of the OR-group.

The application of infrared spectroscopy to the investigation of organic sulfur compounds was discussed by *M. Horac*, Prague. He dealt especially with the "insulation effect" due to the relatively great mass of sulfur. Empirical relations were found between the vibration frequencies of the SO and SO_2 groups on the one hand, and the effects of polar substituents on the other. The force constants of these groups were estimated. The intermolecular interaction of different S-containing compounds in donor-acceptor systems was examined in detail. The ability to take up protons is about the same for sulfides as for ethers, while the SH group forms appreciably weaker hydrogen bonds than the OH group.

According to *E. A. C. Lucken*, Geneva (Switzerland), investigations of the nuclear magnetic resonance and the nuclear quadrupole resonance of organic sulfur compounds are restricted by the relatively low occurrence of the natural ^{33}S isotope (0.75 %); nevertheless, the halogen coupling constants of sulfur-containing halogen compounds can be used for structural investigations.

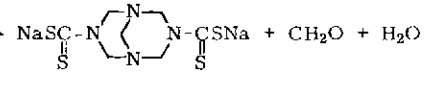
H. W. Prinzler, Leuna-Merseburg (Germany), discussed the formation of the sulfur compounds present in petroleum. Evidently, sulfur compounds were formed simultaneously with the formation of the crude oil by anaerobic microbial reduction of sulfates. With progressive exhaustion of the sulfur content of the mineral deposits, disproportionation occurred with a hydrogen transfer, as a result of which some H_2S escaped and the sulfur content of the crude oil decreased. The hydrogen deficient fraction then gave rise to the sulfur-containing fused compounds found in crude oil today.

P. Zuman, Prague, illustrated the application of polarographic methods to the investigation of organic sulfur compounds. The C–S–R bond is cleaved reductively when activating groups, such as phenacyl, are present, or when the sulfur is in the form of a sulfonium salt. Aryl sulfones are reduced to aryl sulfines and aryl sulfoxides form aryl thioethers. On the other hand, in α,β-unsaturated sulfones the C=C bond is reduced preferentially. In disulfides, 1,2-disulfones, and thiosulfates, the S–S bond is reduced. Homolytic or heterolytic reactions occur, depending on the potential and the structure of the compounds.

According to *J. Cech*, Ustí (Czechoslovakia), the reaction of carbon disulfide with hexamethylenetetramine in alkaline medium gives pentamethylenetetraminebisdithiocarboxylates *(1)*. The ammonium salt can also be prepared from a mixture of aqueous ammonia, CS_2, and formaldehyde. The heavy metal salts of the acid are distinguished by characteristic colors.

According to *W. Fürst*, *W. Kretzschmann*, and *W. Göbel*, Dresden (Germany), pyridine-3-sulfochloride can now be prepared in 70 % yield since pyridine-3-sulfonic acid is obtainable in more than 90 % yield from pyridine and SO_3 at 180 °C.

$$2\ CS_2 + 2\ NaOH + N_4(CH_2)_6$$



(1)

J. Gosselck, Gießen (Germany), found that the inductive and mesomeric effects of the hetero-atoms O, S, and Se may be estimated from the differences in the C=O bond-frequencies $[\Delta\nu_{CO}\ (A-B)]$ and p_k values of isologous carboxylic acids and esters of the general formula $R-C_6H_4-X-CH_2-COOR'$ (A) and $R-C_6H_4-CH_2-X-CH_2-COOR'$ (B), where R = H, NO_2; R' = H, OC_2H_5; X = O, S, Se. Resonance between the limiting structures $Ar-X- \leftrightarrow \overset{\ominus}{Ar}=\overset{\oplus}{X}-$ decreases in the direction O > S > Se in the ratio 8:3:1. The chemical shift of the α-methylene protons in the NMR spectrum is proportional to the C=O frequency of the same compounds.

J. Horac, Prague, investigated the reaction between trichloromethanesulfenic acid (and its derivatives) with alkoxides and aliphatic or aromatic thiolates, which leads (a) to orthocarbonates and (b) to trithiocarbonates, respectively.

$$\text{(a)}\quad CCl_3SX + 4\ RO^{\ominus} \rightarrow C(OR)_4 + S + 3\ Cl^{\ominus} + X^{\ominus}$$

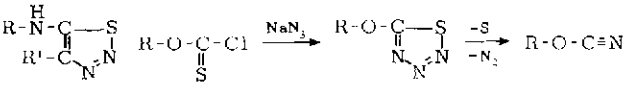
$$\text{(b)}\quad CCl_3SX + 4\ RS^{\ominus} \rightarrow SC(SR)_2 + R-S-S-R + 3\ Cl^{\ominus} + X^{\ominus}$$

The first step in the reaction is the bimolecular nucleophilic substitution of the Cl atoms of the CCl_3-group. In phenyl esters on the other hand, the first step is substitution at the sulfur:

$$CCl_3SOAr + RO^{\ominus} \rightarrow CCl_3SOR + ArO^{\ominus}$$

G. Kresze, München (Germany), has shown that the nitrogen-sulfur bond in *N*-sulfinyl compounds and especially in *N*-sulfinylsulfonamides, is capable of cycloaddition to multiple bonds (C=C, C–O, N=O) to form four-, five-, or six-membered rings. Compounds of the form HX (alcohols, mercaptans, amines) can also be added.

According to *D. Martin*, Berlin-Adlershof (Germany), the reaction between isothiocyanates and diazo compounds yields amino-substituted 1,2,3-thiadiazoles *(2)* by an 1,3-dipolar addition. The corresponding 1,2,3,4-thiatriazoles *(4)*, which are formed from chlorothioformates *(3)* and sodium azide, undergo exothermic decomposition to give nitrogen, sulfur, and aryl cyanates *(5)*, which so far had not been described.

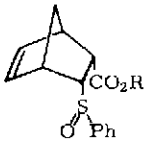


(2) *(3)* *(4)* *(5)*

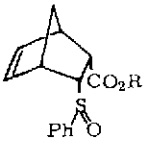
According to *R. Mayer*, Dresden (Germany), carbonyl compounds or their analogues do not yield thiols or thioketones with hydrogen sulfide, if electron-attracting groups are in positions adjacent to the carbonyl group. Instead, reduction products, *viz.* –CH(OH)– or $-CH_2-$, are formed quantitatively. Compounds of the type R–S–X can be similarly desulfurized to give R–X. Numerous examples illustrate the range of application of this reaction.

F. Montanari, Modena (Italy), has described methods for the preparation of optically active sulfoxides, *e.g.* by oxidation of sulfides R–S–R' with optically active peroxyacids.

Relationships can be established between the absolute configuration of the sulfur atom in the enantiomer formed in excess and the optically active reagent used. Diastereomeric sulfoxides are reduced by hydrogen iodide at different rates. Diene syntheses with α-ethylenesulfoxides yield isomeric adducts *(6)* and *(7)* differing only in the configuration of the sulfur atom. The syn- and anti-forms have been distinguished by means of NMR and infrared spectroscopy.

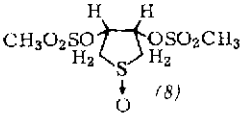


(6), syn



(7), anti

By kinetic studies on the oxidation of sulfoxides to sulfones with peroxyacids in alkaline medium, *G. Modena*, Bari (Italy), has shown that nucleophilic attack by the peroxyacid on the SO group occurs besides the known electrophilic oxidation. The positive ρ-value (*Hammett*) for the reaction indicates that oxidation is favored by an increase in charge density on the SO group brought about by substituent effects. In its dependence on steric effects, the oxidation in alkaline media does not differ appreciably from that in neutral or acidic media.



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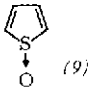
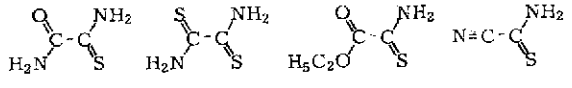


(9)

M. Procházka, Prague, obtained thiophene 1-oxide *(9)* by the action of sodium methoxide on the bis-methanesulfonate of 3,4-dihydroxytetrahydrothiophene 1-oxide *(8)*. The product *(9)* is a very reactive diene and dimerizes or trimerizes in concentrated solutions.

M. Rajsner, Prague, reported on the reactions of lactones of the phthalide type with mercapto compounds. The bicyclic 4,9-dihydrobenzo[e]thieno[2,3-*b*]thiepin-4-one, formed by ring closure from 2-(2'-thienylthiomethyl)benzoic acid, gave the strongly anti-histaminic 4-(3-dimethylaminopropylidene)-4,9-dihydrobenzo[e]thieno[2,3-*b*]thiepine ("Dithiadene") by reaction with 3-dimethylaminopropylmagnesium chloride, followed by dehydration.

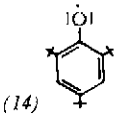
D. H. Reid, St. Andrews (Great Britain) reported on the synthesis of pyrrolo[2,1-*b*]thiazoles. These compounds are thermally stable and form stable charge-transfer complexes. They are protonated reversibly on C-5 and can undergo electrophilic substitution on the same carbon atom. Their spectroscopic behavior corresponds to that of hetero-aromatic compounds. *J. Sandström*, Lund (Sweden), obtained information by spectroscopic methods on conjugation and steric effects in the amide of thiooxalic acid and related compounds. According to this work, *(10)* and *(12)* exist in the trans-form. The effects brought about by conjugation in *(10)*, *(12)*, and



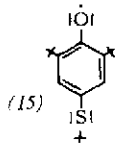
(10) *(11)* *(12)* *(13)*

(13) are in satisfactory agreement with the results of LCAO calculations. The spectra of *N*-monomethyl compounds resemble those of the amides, while those of dimethylamino compounds exhibit considerable hypsochromic shifts of the $n \rightarrow \pi^*$ and $\pi \rightarrow \pi^*$ bands; this behavior is attributed to bond displacement and consequently decreasing conjugation.

K. Scheffler and *H. B. Stegmann*, Tübingen (Germany), demonstrated the participation of sulfur in the free-radical state of aroxyls, by the determination of the g-factor from EPR spectra and by the examination of the EPR hyperfine structure (HFS). The g-factor of the sulfur-free aroxyl *(14)* has a value of 2.00447, whereas that of *(15)* is 2.00529. Since g should be 0.0129 when only the $-\overset{\oplus}{\underset{\cdot}{S}}-$ structure is present, the actual participation of the S-radical form can be estimated at 6.3 % from the difference in the g-factors of *(14)* and *(15)*.



(14)



(15)

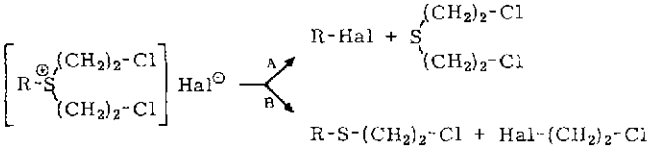
Similarly, a certain free-electron density on the sulfur emerges from the hyperfine structure investigations. If groups capable of conjugation ($-\overset{\alpha}{C}H=\overset{\beta}{C}H-R$) are introduced and the molecule is deuterated a spin density can be detected in the α- and β-positions. The compounds are therefore mesomeric O–C–S radicals.

E. N. Prilezhaeva et al., Moscow, investigated the steric course of the addition of thiols and alcohols to *cis*-1-alkylthio-1-butene-3-ynes and to *cis*-1-alkoxy-1-butene-3-ynes. Thiolate ions add stereospecifically to the triple bonds of the alkylthio compounds forming *cis,cis*-1,4-bisalkylthio-1,3-butadienes. The addition of alkoxide ions to the alkoxy compounds leads to propiolaldehyde acetals.

•SR-Radicals add non-stereospecifically to the triple bond of the en-yne system to give 1,4-disubstituted *cis,cis*- and *cis,trans*-butadienes. PCl_4^+ is added to the triple bond when the en-yne system reacts with PCl_5.

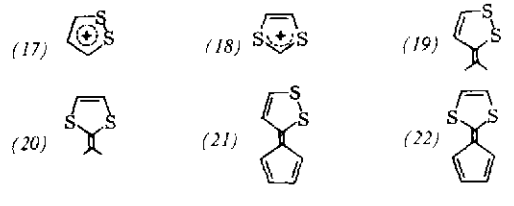
The decomposition of the primary complex results in the formation of the chlorides of 1-alkoxy- or 1-alkylthio-3-chloro-1,3-butadiene-4-phosphinic acid, respectively.

To improve the cytostatic activity of tris-(β-chloroethyl)-sulfonium salts, *A. Lüttringhaus* and *J. Ringhartz*, Freiburg (Germany), reacted cholestanethiols with two moles of ethylene bromohydrin and obtained the corresponding bis-(β-hydroxyethyl)sulfonium salts. Chlorination with thionyl chloride, however, gave β-chloroethyl sulfides instead of the



expected bis-(β-chloroethyl)sulfonium salts. It has been shown that the sulfonium salts *(16)*, with R = benzyl or alkyl, decompose according to (A) exclusively. If, on the other hand, R = t-butyl or cyclohexyl, the decomposition partly follows route (B). Br^- or I^- ions increase the tendency to decompose by route (B).

Comparative proton resonance measurements were carried out on 1,2- and 1,3-dithiolium salts by *H. Prinzbach*, *E. Futterer*, *H. Berger*, and *A. Lüttringhaus*, Freiburg (Germany).



(17) *(18)* *(19)* *(20)* *(21)* *(22)*

Compounds *(17)* and *(18)* are iso-π-electronic with the tropylium ion, while the dithiafulvenes *(19)* and *(20)* and the dithiafulvalenes *(21)* and *(22)* are analogous to heptafulvene and sesquifulvalene.

The chemical shifts of the proton signals of *(17)* and *(18)* reflect the marked local electron deficiency at the corresponding carbon atoms. From the influence of substituents in the 3- and 4-positions in *(17)*, or in the 4-position in *(18)*, on the chemical shift of H-4 and H-5 or H-2 it can be deduced that a cyclic delocalization of the π-electron system occurs in *(17)* and *(18)*, involving in each case a pair of p_π-electrons of the ring sulfur atoms.

The H-signals in the analogously substituted compounds *(19)–(22)* are displaced diamagnetically by about 2–2.5 ppm. These data are compatible only with extensively localized bond systems, dipolar structures having no importance.

[VB 844/163 IE]

German version: Angew. Chem. 77, 51 (1965)
Translated by Express Translation Service, London

Structure and Properties of Coordination Compounds

In connection with the Eighth International Conference on Coordination Chemistry in Vienna from September 7th to 11th 1964, the Czechoslovakian Chemical Society, together with the Slovakian and the Czechoslovakian Academies of Sciences and the Slovakian Technical University, Bratislava, arranged a Symposium on the Structure and Properties of Coordination Compounds in Bratislava (Czechoslovakia) from September 2nd to 4th, 1964. The congress had about 200 participants, and 80 lectures were given in Englisch (55 %), German (35 %), or Russian (10 %).

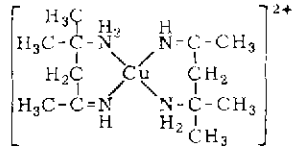
Investigations of Crystal Structure

L. Kutschabsky (Berlin, Germany) showed that $SrB_2O_4 \cdot 4\,H_2O$ consists of discrete $[B(OH)_4]^-$ tetrahedra and Sr^{2+} ions.

H. Dunken and *W. Haase* (Jena, Germany) examined the polytetrafluoroarsenates $(MAsF_4O)_n$ prepared by *L. Kolditz* and coworkers and found dimeric units $(As_2F_8O_2)^{2-}$ consisting of two octahedra with common oxygen edges. Shielding of the susceptible As–O bond leads to a remarkable stability of the complexes.

By passing NH_3 into a solution of $Cu(NO_3)_2$ in acetone, condensation and complex formation occur. In the violet chelate complex *(1)* the octahedral coordination of the copper is achieved through the nitrate groups (*F. Hanic* and *G. Lundgren*, Bratislava).

(1)



In $Cu(SCN)_2(NH_3)_2$ (*J. Garaj* and *J. Gažo*, Bratislava), which always crystallizes in the *trans*-form from aqueous solution, the Cu atom is surrounded by four nitrogen atoms in a distorted square; the two sulfur atoms complete the coordination polyhedron to form an inclined bipyramid.

According to *B. Hajek* (Prague, Czechoslovakia) fluoroscandates always contain ScF_6 octahedra, which are discrete units in M_3ScF_6 and are joined at the corners to form two-dimensional layers in $MScF_4$.

J. Zemann (Göttingen, Germany) reviewed the stereochemistry of tellurites and tellurates. While in tellurites the lone-electron pair occupies a coordination site, TeO_5-octahedra are present in tellurates. They are joined to form chain-complexes having common edges in $KTeO_3(OH)$ and common corners in $KTeO_2(OH)_3$.

From structural investigations on pentacarbonylmanganese hydride and other hydrides *J. A. Ibers* (Upton, N.Y., U.S.A.) concluded that the metal-hydrogen distance was the length for a covalent bond and that the hydrogen atom completed the coordination polyhedron, having a definite position in it.

K. Dornberger-Schiff (Berlin, Germany) investigated the structure of $Sr_3(GeO_3)_3$ as a model for β-wollastonite. It consists of layers of $(GeO_3)_3$ rings, between which Sr atoms with an eightfold coordination are located.

In lithium *o*-chlorobenzoate, $ClC_6H_4COOLi \cdot H_2O$, lithium is surrounded tetrahedrally by three carboxyl-oxygen atoms and a hydrogen atom. One carboxyl-oxygen atom is always common to two tetrahedra (*H. H. Worch*, Berlin, Germany).

New Complexes

Biphosphines, $R_2P{-}PR_2$, according to *K. Issleib* (Halle, Germany) react not only with metal salts to form complexes, but also with metal carbonyls by substitution. In this way compounds of the types *(2)* to *(5)* result.

$$(R_2P\text{-}PR_2)MX_2 \quad (2) \qquad (R_2P\text{-}PR_2)_2MX_2 \quad (3)$$

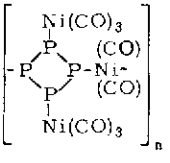
$$(R_2P\text{-}PR_2)\underset{X}{Cu}(R_2P\text{-}PR_2)\underset{X}{Cu}(R_2P\text{-}PR_2) \quad (4)$$

$$(CO)_nM(R_2P\text{-}PR_2)M(CO)_n \quad (5)$$

With M = Ni, Co, Pd, and others the halogen-containing complexes (X = halogen) are more easily formed when R is aliphatic than when it is aromatic. The stability of CO-containing complexes with M = Ni, or Fe does not depend on the nature of R. $Fe(CO)_5$ and $Ni(CO)_4$ react also with tetraorganylcyclotetraphosphines. Highly polymerized complexes *(6)* and *(7)* are probably formed. Alkali metals add onto cyclophosphines without cleavage of the P–P bonds.

$(RP)_4[Fe(CO)_4]_2$ *(6)*

(7)

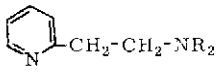


M. H. B. Stiddard (London, England) obtained diphosphine carbonyl complexes with M = Mn, and prepared diarsine carbonyl complexes with M = Re. The central atoms can be oxidized to Mn^+, or Re^{3+} and Re^{4+}.

G. Schwarzenbach (Zurich, Switzerland) spoke about complex formation with mercaptophosphines $R_{3-x}P(CH_2{-}CH_2{-}SH)_x$ [x = 1, 2, and 3]. 1:2, 2:4 and 3:4-complexes result with Ni, Pd, and Pt. If the sulfur atoms are not coordinated they can take up protons and the usual acidity of mercaptans is found. The protons can be replaced by CH_3Hg-groups. The 1:2-complexes, having *trans*-configuration according to their dipole moments, dissolve in aqueous $NiCl_2$ solution to form 3:4-complexes and are converted into *cis*-1:2-complexes by addition of EDTA. In this way polynuclear complexes with different central atoms can also be obtained.

If in Pt complexes P or As together with olefinic groups are present in a ligand such as $CH_2=CH-CH_2-(CH_2)_2-L$ [L = $As(CH_3)_2$ or PPh_2], then, according to *M. A. Bennett* (London, England) the double bond is only weakly held by the platinum atom. When the $-CH_2-$ bridge in the ligand is replaced by a phenylene group, the double bond no longer participates in complex formation, but increased reactivity results.

E. Uhlig (Jena, Germany) reported on the formation of complexes *(8)* with NiX_2 (X = halogen). If R is large,



(8)

Ni(amine)X_2 complexes result, which are tetrahedral or octahedral and polymeric. If R = H or at the most CH_3, then octahedral compounds Ni(amine)$_2X_2$ form; with X = iodide a yellow tetragonal and a dark green tetrahedral isomer exist.

Phthalocyanines of Ni, Co, Fe, and Mn, according to *R. Taube* (Greifswald, Germany), can be reduced in four stages by Li or Na in tetrahydrofuran. The Li salts from the first two stages were obtained on a preparative scale.

K. Madeja (Greifswald, Germany) found that $[Fe(phenanthroline)_3]^{2+}$ in hot pyridine easily loses a ligand to form $[Fe(phenanthroline)_2X_2]$. The magnetic properties of these complexes markedly depend on the nature of X.

Alkylchromium compounds of various compositions can be obtained, according to *E. Kurras* (Jena, Germany), by reaction of Grignard or organolithium compounds with $CrCl_3$ and $CrCl_2$.

R. Ripan (Cluj, Rumania) reported on salts *(9)* and *(10)* of two new heteropolyacids.

$(NH_4)_6\,[Co_2(II)W_{12}O_{42}]\,[Ni(II)(NH_3)_2(H_2O)_2]\cdot x\,H_2O$ *(9)*

$(NH_4)_7\,[Co(III)W_{12}O_{42}]\cdot x\,H_2O$ *(10)*

α-Amino acids as bidentate ligands can replace four nitro groups in hexacobaltates(III) according to *M. B. Celap* (Belgrade, Yugoslavia).

Physicochemical Investigations

T. Šramko (Bratislava, Czechoslovakia) made a spectrophotometric investigation of various $NiClO_4$/thiourea systems and confirmed the existence of $[Ni(thiourea)_6]^{2+}$. *Z. Valtr* (Bratislava) proved the existence of cyanato complexes $K_2[M(OCN)_4]$ with M = Cu, Fe, Ni, and Mn in methanolic solution. *V. Holba* (Bratislava) followed the course of hydration of *trans*-$[Cr(en)_2(SCN)_2]^{2+}$ and *M. Bartušek* and *L. Sommer* (Brno, Czechoslovakia) studied the complex formation of UO_2^{2+} ions with ligands containing phenolic hydroxy groups.

By polarographic examination *E. Fischerová* (Brno, Czechoslovakia) found that Cr(III) and Cr(II) complexes with ethylenediamine behave analogously to the cobalt complexes. *D. I. Bustin* and *A. A. Vlček* (Prague, Czechoslovakia) observed near the first reduction step for the $[Cr(CN)_5(NO)]^{3-}$ ion a second and a third step at lower pH values. *V. Novák*, *M. Svičekova*, and *J. Majer* (Bratislava) determined the stability constants of the lanthanide complexes of 2,3-diaminobutane-N,N,N′,N′-tetra-acetic acid.

The reduction of $[Cu(CN)_4]^{2-}$ complexes in methanolic solution at −45 °C is slowed down so much that *J. Bjerrum* and *R. Paterson* (Copenhagen, Denmark) could determine the complex-formation constants potentiometrically.

The proton magnetic resonance spectrum of σ-cyclopentadienyl complexes of Si, Ge, Sn, and Pb contains, according to *H. P. Fritz* (Munich, Germany), at high temperatures only one signal, indicating that valence-tautomeric systems are probably present.

[VB 858/165 IE]

German version: Angew. Chem. 77, 44 (1965)

VIIth European Peptide Symposium

The Seventh European Peptide Symposium was held from September 3rd to 8th, 1964 in Budapest (Hungary).

From the agenda:

Protective Groups

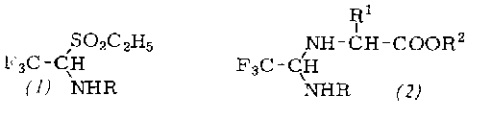
T. Wieland (Frankfurt/Main, Germany) emphasized that even today further new protective groups, selectively removable under mild conditions, are needed in peptide chemistry. Starting from the observation that some *Amanita* toxins are cleaved [1] specifically at the γ-hydroxyleucyl bond even by aqueous trifluoroacetic acid at room temperature, the γ-hydroxyisocaproyl residue (HIC-residue) was used as an amino-protective group. HIC-amino acids may be prepared by heating amino acids with γ,γ-dimethylbutyrolactone in the presence of imidazole. After peptide synthesis the protective group can be split off with dilute acids, *e.g.* in the case of HIC–Gly–L–Leu–OBz (Bz = benzyl) with 50 % trifluoroacetic acid (20 °C, 2 h) [2].

m-Nitrophenoxycarbonylamino acids can be deacylated by irradiation with a mercury lamp (λ > 300 mμ) (1 mmole in 2–3 h) or even with triethylamine/water at room temperature. Unfortunately, hydantoins are always formed in the deacylation of peptide derivatives, so that the protective group is not suitable for peptide syntheses.

K. and *H. Medzihradszky* (Budapest, Hungary) found that with Z-peptides (Z = carbobenzoxy), which do not contain *N*-terminal methionine, the carbobenzoxy residue may be removed by hydrogenation, if the fourfold amount (by mole) of cyclohexylamine is added and about 0.1 to 1 times the amount by weight of catalyst is used. In the presence of sensitive ester groups, triethylamine can also be added as base. The method fails with carbobenzoxydipeptide esters, since here diketopiperazines are formed.

F. Weygand, *W. Steglich*, and *I. Lengyel* (Munich, Germany) reported on a new CF_3-containing protective group. 2,2,2-Trifluoro-1-ethylmercaptoethylamine hydrobromide [3], easily accessible from 2-trifluoromethylpseudooxazol-5-one and ethyl mercaptan in HBr/glacial acetic acid, can be acylated on the nitrogen atom and oxidized to the sulfone *(1)*.

Compound *(1)* exchanges the sulfonyl residue easily for other nucleophilic groups like −OR, −SR and −NHR. If a



(1) *(2)*

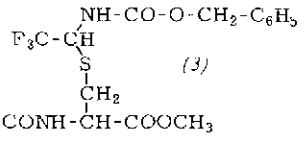
(a): R = F_3CCO-

(b): R = $H_5C_6CH_2$-O-CO-

[1] *T. Wieland*, Helv. chim. Acta *44*, 919 (1961).

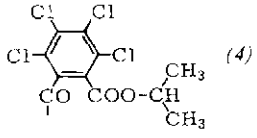
[2] Cleavage of a peptide bond under mild conditions: *T. Wieland* and *D. Rehbinder*, Liebigs Ann. Chem. *670*, 149 (1963).

sulfone like *(1a)* or *(1b)*, that contains a removable acyl residue, is used, then derivatives of the type *(2a)* or *(2b)*, respectively, are obtained by reaction with amino-acid esters. Compound *(3)* is formed in good yield from *N*-trifluoroacetyl-L-cysteine methyl ester and *(1b)* in presence of triethylamine (1 mole) at room temperature.



(3)

S. Guttmann and *J. Pless* (Basel, Switzerland) used acyl residues for the reversible protection of the guanidino group of arginine. The tetrachloroisopropoxyphthaloyl group (TIP-group) *(4)* and the *p*-nitrobenzyloxycarbonyl group [Z(NO_2)-group] proved particularly suitable.



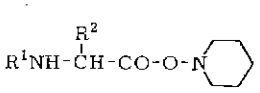
(4)

For the preparation of Z-(ω-TIP)-L-arginine, Z-L-arginine was treated with TIP-2,4,5-trichlorophenyl ester. The TIP-residue can be split off quantitatively with aqueous acetic acid at 100 °C. It is stable to HBr/glacial acetic acid, trifluoroacetic acid and H_2/Pt. Z-[ω-Z(NO_2)]-L-arginine is also suitable for peptide synthesis. The guanidino-protective group, which may be selectively removed by controlled catalytic hydrogenation, is exceptionally stable to HBr/glacial acetic acid and caustic alkali.

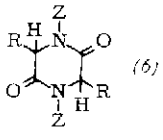
p-Chlorobenzyl esters of *N*-carbobenzoxyamino acids are attacked less than benzyl esters in the cleavage of the Z-residue with HBr/glacial acetic acid, as *L. Kisfaludy* and *N. Löw* (Budapest, Hungary) found. With 17 % HBr/glacial acetic acid, the Z-di-*p*-chlorobenzyl esters of aspartic and glutamic acids may be converted in more than 60 % yield into the di-*p*-chlorobenzyl ester hydrobromides. If instead of HBr/glacial acetic acid, 1 N NaOH in dioxane is used, Z-aspartic acid β-*p*-chlorobenzyl ester or Z-glutamic acid γ-*p*-chlorobenzyl ester are obtained in 60 and 33 per cent yield, respectively.

Formation of the Peptide Bond, Racemization

Of special interest for peptide chemistry are the *N*-acylamino acid 1-piperidyl esters *(5)* investigated by *I. Antonovics*, *S. Beaumont*, *B. O. Handford*, and *G. T. Young* (Oxford, England).



(5)



(6)

Z = $H_5C_6CH_2$-O-CO-

They may be prepared from the *N*-acylamino acids and 1-hydroxypiperidine with dicyclohexylcarbodiimide (DCC). While Z-L-Leu-O-Pip (Pip = piperidyl) and Gly-OC_2H_5 afforded Z-L-Leu-Gly-OC_2H_5 in good yield only after 5 days, 84 % of the dipeptide derivative were obtained 36 h after addition of 1 mole of glacial acetic acid. If the glycine ester was liberated from the hydrochloride with water-containing sodium acetate, the dipeptide derivative (85 % yield) was formed even after 2 h. In these cases, as well as in the synthesis of benzoyl-L-Leu-Gly-OC_2H_5 under different conditions, no racemization could be found (detection limit about 2 % DL-compound). Also from free glycine and 1 mole of base in dioxane/water, optically pure benzoyl-L-Leu-Gly was formed in high yield. In chloroform/triethylamine benzoyl-L-Leu-O-Pip showed no racemization and no oxazolone formation, in contrast to the *p*-nitrophenyl ester.

As *E. Taschner*, *A. Kuziel*, *T. Vajda* and, *B. Rzeszotarska* (Danzig) showed, the amount of dicyclohexylcarbodiimide determines what kind of products are formed in the reaction with Z-amino acids. While according to *Schüssler* and *Zahn* [4], Z-amino-acid anhydrides are formed with 1/2 mole of DCC, a mixture of *N*-acylurea and the bisbenzyloxycarbonyldiketopiperazine derivative *(6)* was obtained using 1 mole of DCC in ethyl acetate at 20 °C in addition to dicyclohexylurea (45–100 %). Anhydrides or oxazolones could not be detected.

E. Taschner, *B. Rzeszotarska*, and *A. Kuziel* (Danzig) recommend bromoacetonitrile in place of the customary chloroacetonitrile [5] for the preparation of cyanomethyl esters. The esters are formed already at room temperature and can be reacted, without isolation, with amino-acid esters. The addition of 0.2 equivalents of glacial acetic acid markedly decreases the reaction time. The dipeptide derivatives *(7)* and *(8)* were examined for racemization by paper chromatography (For = formyl, TFA = trifluoroacetyl, tBu = t-butyl).

	activation with	DL-dipeptide [%]
For-L-Val-L-Val-OtBu *(7)*	$ClCH_2CN$	30
	$BrCH_2CN$	< 1
TFA-L-Phe-L-Val-OtBu *(8)*	$ClCH_2CN$	40
	$BrCH_2CN$	25
	$BrCH_2CN$ + 0.2 equiv. AcOH	< 1

B. Liberek and *A. Michalik* (Danzig) used Z-β-cyano-L-alanine to study the degree of racemization in the synthesis of Z-dipeptide esters. Although in the reaction with glycine methyl ester by the *p*-nitrophenylester, DCC-, phosphorazo- and phosphorus oxide chloride-methods, no racemization occurred (even 2 % racemate detectable), it was observed in considerable amount in the reaction of the thiophenyl ester.

The degree of racemization greatly depends on the solvent: it is highest in dimethylformamide (DMF) and dimethylsulfoxide and lowest in tetrahydrofuran (THF). The degree of racemization increases with greater dilution. While *Beyerman*'s bifunctional catalysts [6] have no influence in DMF, and while acetic acid reduces the degree of racemization only slightly, the racemization in ethyl acetate is lowered from 27 to 2 % DL-compound by 2-hydroxypyridine or acetic acid.

D. G. Knorre and *T. N. Shubina* (Novosibirsk, U.S.S.R.) reported on peptide syntheses in aqueous solution without isolation of intermediate peptides. An activated intermediate (probably *O*-acylurea) is formed in the reaction of formylamino acids with water-soluble carbodiimides in water in a narrow pH range with an optimum at pH 5. In addition, a non-reactive product, presumably the *N*-acylurea, is formed. After the addition of amino-acid ester, peptides are formed at pH 7.

Since all by-products are easily removed with ion exchangers, the formyldipeptide produced can be used afresh for synthesis without isolation after hydrolysis of the ester. The method was used for preparing simple tetrapeptides; the yields amounted to 60–85 % at each step. It is of advantage to work with a 2- to 5-fold excess of carbodiimide.

M. Brenner (Basel, Switzerland) studied the rate of the aminodiacylhydrazine rearrangement [7] in which *e.g.*

[3] *F. Weygand*, *W. Steglich*, and *H. Tanner*, Liebigs Ann. Chem. *658*, 128 (1962).

[4] *H. Zahn* and *H. Schüssler*, Chem. Ber. *95*, 1076 (1962).

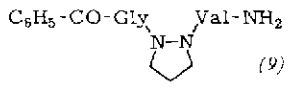
[5] *R. Schwyzer*, *M. Feurer*, *B. Iselin*, and *H. Kägi*, Helv. chim. Acta *38*, 80 (1955).

[6] *H. C. Beyerman* and *W. Maassen van den Brink*, Proc. chem. Soc. (London) *1963*, 266.

[7] *M. Brenner* and *W. Hofer*, Helv. chim. Acta *44*, 1794 (1961).

Z-Gly-Gly-Phe-NH-NH_2 is formed from Z-Gly-Gly-NH-NH-Phe. Only those acids, which carry a doubly bound oxygen atom and an OH-group on the same atom, *e.g.* carboxylic acids, phosphoric acid and sulfuric acid, act as catalysts. Pivalic acid is by far the best catalyst; activity decreases in the series propionic acid > acetic acid > formic acid.

The rate of rearrangement strongly depends on the solvent. It decreases in the series THF, dimethoxyethane, methanol. Besides, it depends markedly on the constitution. While *e.g.* benzoyl-Gly-NHNH-Phe in 10 % propionic acid in THF at 40 °C rearranges within 25 min, Z-Val-NHNH-Val required 40 days under similar conditions. Substitution of the hydrazine-hydrogen atoms by alkyl groups increased the rate of rearrangement. Derivatives of the type *(9)* rearrange instantaneously. Unfortunately the NH-group liberated can no longer be acylated.



(9)

New results on the effects of bifunctional catalysts were communicated by *H. C. Beyerman* and *W. Maassen van den Brink* (Delft, Holland). With slow reactions, *e.g.* the reaction of Z-Gly-OCH_2CN with cyclohexylamine at 20 °C, the yield of amide amounts to 11 % after 30 min without catalyst, but to more than 60 % after addition of pyrazole, 1,2,4-triazole or 2-hydroxypyridine. A mixture of phenol and pyridine showed no effect. Also, in the reaction of Z-Gly-OCH_3 with cyclohexylamine in boiling acetonitrile, bifunctional catalysts increased the yields of amide 10- to 12-fold. In peptide synthesis with cyanomethyl esters, *p*-nitrophenyl esters and vinyl esters, no racemization occurred in the presence of 1,2,4-triazole, while imidazole yielded some racemate in most cases.

A. T. Moore and *H. N. Rydon* (Exeter, England) polymerized ε-TFA-Lys-Gly-Glu-(γ-OCH_3)-Gly and ε-TFA-Lys-Gly-Gly-Glu-(γ-OCH_3)-Gly-Gly with DCC in DMF obtaining as main products the protected octa- and dodecacyclopeptides, respectively. It was shown that even with peptides containing an even number of amino acids the dimerizing cyclization is the main reaction. The possibility for the non-parallel arrangement of the initial peptide appears, therefore, to be more important for the course of the reaction than the stabilization of the end product by hydrogen bonding.

Synthesis of Natural Peptides

R. A. Boissonnas and *E. Sandrin* (Basel, Switzerland) prepared many eledoisine analogues and showed that the *C*-terminal amino acids are responsible for the biological action [8].

K. Lübke (Berlin) found that on degrading eledoisine from the amino-end, the octapeptide (amino acids 4–11) still exhibited 50 % activity, and on passing to the pentapeptide (amino acids 7–11) the activity decreased further [9].

S. Guttmann, J. Pless, and *R. A. Boissonnas* (Basel, Switzerland) reported on the synthesis of ACTH analogues (ACTH = adrenocorticotropic hormone). For this purpose, in the case of arginine, the tosyl- and, in the case of lysine, the formyl-residue was used for protection of the ω-amino groups, so that cleavage of the Lys-Pro bond was avoided on reduction with sodium in liquid ammonia. Here, however, partial cleavage of a Tyr-Pro bond was observed. *M. Löw* and *L. Kisfaludy* (Budapest, Hungary) constructed an ACTH-sequence using hydroxysuccinimide esters. As novel protected amino-acid derivatives Z-Asp-(β-OtBu)-OSU, Z-Glu-(γ-OtBu)-OSU, Z-(ε-BOC)Lys-OSU, and Z-(OBz)Tyr-OSU were prepared (SU = succinimidyl, BOC = t-butyloxycarbonyl). On reaction of these with higher peptides the reaction times increased considerably. An excess of hydroxysuccinimide ester was then used, which after reaction with $NH_2-CH_2-CH_2-N(CH_3)_2$, could be easily removed by dissolving in acid.

K. Poduska (Prague, Czechoslovakia) described the synthesis of the partial trypsin sequence Asp(NH_2)-Ser-Cys-Glu(NH_2)-Gly-Gly-Asp-Ser-Gly-Pro-Val-Val-Cys-Ser-Gly-Lys (which, however, according to the latest findings is slightly different in trypsin). The required intermediate, Z-Ser-(OtBu)-Gly-OCH_3, was prepared directly from the Z-dipeptide ester and isobutylene in the presence of some sulfuric acid. Apparently the etherification succeeds only, if glycine is adjacent to serine [10].

D. Theodoropoulos (Athens, Greece) synthesized the peptide part of cytochrome c. For this, Try-(imBz)His-Thr-Val-Gu-$(OBz)_2$ [imBz = imidazole benzyl], after saponification with 2 equivalents of caustic alkali, was converted into the *p*-nitrobenzyl ester by warming with *p*-nitrobenzyl tosylate and triethylamine in acetone or DMF. In the synthesis of glutamine-containing peptides, ring closures to pyroglutamic or glutamic imide derivatives occurred as side reactions.

The hormone stimulating the secretion of stomach juice consists of the closely related gastrins I and II. Gastrin II is a heptadecapeptide [11]: pyroGlu-Gly-Pro-Try-Met-Glu-Glu-Glu-Glu-Glu-Ala-Tyr-Gly-Try-Met-Asp-Phe-NH_2. *R. C. Sheppard* (Liverpool, England) reported on the synthesis of this peptide from *(10)*, *(11)*, and *(12)*.

pyroGlu-Gly-Pro-Try-Met-OCH_3 *(10)*

Z-Glu-(OtBu)-Glu-(OtBu)-Glu-(OtBu)-Glu-(OtBu)-Glu-(OtBu)-Glu-(OtBu)-Ala-Tyr-Gly-OCH_3 *(11)*

Try-Met-Asp-(OtBu)-Phe-NH_2 *(12)*

After splitting off the protective groups the peptide proved to be physiologically fully active, but was identical in its chemical and physical behavior with Gastrin I; this contradiction has not yet been explained.

Special Problems

C. Nicot and *E. Bricas* (Paris, France) were able to protect *meso*-diaminopimelyl-(D)L-alanine with carbobenzoxy chloride in 47 % yield selectively at the L-center of the *meso*-diaminopimelic acid. The compound is a useful intermediate for the synthesis of unsymmetrical tripeptides of *meso*-diaminopimelic acid.

The acylation of substituted hydrazines employing methods common to peptide chemistry was investigated by *H. Niedrich* (Berlin-Buch, Germany). Reaction of hydrazinoacetic ester with t-butyloxycarbonyl *p*-nitrophenolate afforded a mixture of the two isomeric BOC-compounds, which may be separated by distillation. Both could be acylated with carbobenzoxyglycine and DCC on the free NH-group; after removal of the protecting group, one compound gave the *N*-aminodipeptide *(13)* and the other gave the hydrazinopeptide *(14)*.

Z-Gly-CO-$\overset{\overset{NH_2}{|}}{N}$-$CH_2COOC_2H_5$ *(13)*

Z-Gly-CO-NHNH-$CH_2COOC_2H_5$ *(14)*

[VB 861/166 IE]
German version: Angew. Chem. 77, 53 (1965)

[8] *E. Sandrin* and *R. A. Boissonnas*, Helv. chim. Acta *47*, 1294 (1964).

[9] Cf. *E. Schröder* and *K. Lübke*, Experientia *20*, 19 (1964).

[10] Discussion remarks by *E. Schröder*.

[11] *R. A. Gregory, G. W. Kenner, R. C. Sheppard* et al., unpublished work.

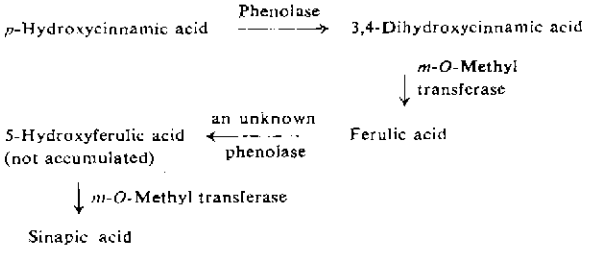
An international symposium "sur la Chimie et la Biochemie de la Lignine, de la Cellulose et des Hemicelluloses" was held in the Ecole Francaise de Papeterie, Grenoble (France), from June 29th–July 4th, 1964.

K. Freudenberg, Heidelberg (Germany), used selected data from the work carried out over the past 15 years on the biosynthesis, degradation, and analysis of lignin [1] to construct a schematic structural formula for lignin comprising 18 main and 7 alternative C_6–C_3 units; this formula is able to account for all the properties of lignin both qualitatively and quantitatively [2]. Spruce lignin can be formed *in vitro* by enzymatic dehydrogenation of a mixture of *p*-coumaryl alcohol, coniferyl alcohol, and sinapyl alcohol (14:6:80) via di-, tri-, tetra-, and oligolignols, many of which have been isolated and identified. Diverse reactions of quinone methides, which occur as intermediates in this polycondensation process, contribute significantly to molecular growth. The three major dilignols (dehydrodiconiferyl alcohol, (±)-pinoresinol, and guaiacylglycerol-β-coniferyl ether) have been isolated from spruce wood by chemical degradation of its lignin. The elemental composition of pure lignin from any woody plant fits the formula – based on C_9 – $(C_9H_{8-}OCH_3O_2(H_2O)_{0\ 1}(OCH_3)_{0-1.5}]_n$, *i.e.* about 2 atoms of hydrogen have been abstracted from every C_9 unit during the formation of lignin. For thioglycolic acid lignin, the group $(C_2H_{3.33}O_{1.67}S)_{<1}$ per C_9 unit has to be added.

E. Adler et al., Göteborg (Sweden), acidolysed spruce lignin (0.2 N HCl, dioxane:water 9:1, 4 h reflux) and obtained crystalline monomeric [3] and dimeric products after chromatography on Sephadex columns; these proved the presence of dehydrodiconiferyl-alcohol and guaiacylglycerol-β-coniferyl-ether groupings in lignin. Cleavage of the guaiacylglycerol-β-coniferyl-ether entities in lignin is promoted by S^2 ions during cooking of wood with $NaOH/Na_2S$ [4]. During kraft pulping, some of the phenylcoumaran structures in lignin are converted via quinone methides into stilbenes, with liberation of HCHO. This reaction was examined on dehydrodiisoeugenol as a model.

F. F. Nord and *W. J. Schubert*, Fordham University, New York (U.S.A.), treated softwood lignins and lignin models with various white-rot fungi [5]. About 15 substances, including vanillin, vanillic acid, *p*-hydroxybenzoic acid, ferulic acid, 4-hydroxy-3-methoxyphenylpyruvic acid, *p*-hydroxycinnamic acid, guaiacylglycerol, coniferaldehyde, *p*-hydroxycinnamaldehyde, and guaiacylglycerol-β-coniferyl ether were detected as degradation products by paper chromatography. A hitherto unknown etherase is thought to be responsible for the liberation of the ether (yield from ultraviolet measurements 0.1 %).

S. A. Brown, Peterborough, Ont. (Canada), reviewed work on the biogenesis of the C_6–C_3 alcohols [6] from which lignin arises by dehydrogenative polycondensation. His latest labelling experiments with wheat have revealed the following paths for some of the steps:



The acids are reduced to the alcohols via their CoA derivatives. When radioactive coniferyl alcohol is administered to wheat, it is partly converted into dehydrodiconiferyl alcohol and (±)-pinoresinol.

T. Higuchi, Gifu (Japan), and *F. Barnoud*, Grenoble (France), studied lignin formation from labelled precursors and the requisite enzyme systems in plant tissue cultures. Tyrase was detected in numerous Gramineae and phenylalanine deaminase in many higher plants. These enzymes catalyse the transformation of the amino acids into the correspondingly hydroxylated cinnamic acids during the biosynthesis of the C_6–C_3 alcohols. It appears that only peroxidase is responsible for the phenol dehydrogenation reactions involved in lignification in tissue cultures.

J. C. Pew, Madison, Wis. (U.S.A.), dehydrogenated 4-propylguaiacol and other guaiacyl derivatives with peroxidase/H_2O_2 as simple models for lignification. Apart from biphenyl compounds [7], he found *inter alia* diphenyl ethers, quinone methides, 1-guaiacylpropan-1-ols, and guaiacyl ethyl ketones as dehydrogenation products. Dehydrogenation of eugenol gives rise to a quinone methide which adds on a molecule of water to form coniferyl alcohol; this explains the formation of the lignin-like products obtained by *S. M. Siegel* [7a] on dehydrogenation of eugenol. In the discussion, *J. M. Harkin*, Heidelberg (Germany), pointed out that these dehydrogenations lead not only to *o*- and *p*-quinone methides, but also to benzoquinones, diphenoquinones, quinhydrones, and semiquinones. When embedded in the lignin macromolecule, these structures are restrained from undergoing the addition and polymerization reactions observed with simple models. These groups serve to explain part of the carbonyl and free radical (term "caged radical" proposed by *K. Kratzl*; cf. [8]) contents of lignin.

K. Sarkanen et al., Seattle, Wash. (U.S.A.), prepared specifically deuterated and tritiated guaiacols, veratrols, and creosols and used these to study the reactivities of the various positions in the aromatic ring towards electrophilic attack, *e.g.* by Cl_2, NO_2, H^+, or HCHO. C–6 in lignin units reacts faster than C–5 or C–2. [2,6-$^3H_2$]Glucovanillin is incorporated into the lignin of the middle lamellae when administered to spruce.

A. von Wacek, Graz (Austria), attempted to work out a micromethod for the determination of lignin in wood using its total methoxyl content and applying corrections for the carbohydrate methoxyl content determined by liberation of methanol with alkali. However, it was found that methanol is also liberated by alkali from certain lignin models and from similar structures in natural and in *Freudenberg*'s artificial lignin via quinone methide intermediates. This complicates the determination of the sugar methoxyl content.

[1] Cf. for example *K. Freudenberg*, Fortschr. Chem. org. Naturstoffe *20*, 41 (1962).

[2] Cf. *K. Freudenberg*, Holzforschung *18*, 3 (1964); Science (Washington), in the press; *K. Freudenberg* and *J. M. Harkin*, Holzforschung *18* (1964), in the press.

[3] *K. Lundquist*, Acta chem. scand. *16*, 2303 (1962).

[4] *E. Adler*, *J. Marton*, *I. Falkehag*, and *H. Halvarson*, unpublished results.

[5] *H. Ishikawa*, *W. J. Schubert*, and *F. F. Nord*, Arch. Biochem. Biophys. *100*, 131, 140 (1963). Cf. *T. Fukuzumi*, Bull. agric. chem. Soc. Japan *24*, 728 (1960).

[6] Cf. *S. A. Brown*, Science (Washington) *134*, 305 (1962); *S. A. Brown* and *T. Higuchi*, Canad. J. Biochem. Physiol. *41*, 613, 621 (1963), and earlier work.

[7] *J. C. Pew*, Nature (London) *193*, 250 (1962).

[7a] See J. Amer. chem. Soc. *78*, 1753 (1956); *79*, 1628 (1957).

[8] *C. Steelink*, *T. Ried*, and *G. Tollin*, J. Amer. chem. Soc. *85*, 4048 (1963); *T. N. Kleinert*, Holzforschung *18* (1964), in the press.

T. Enkvist and *J. Turunen*, Helsinki (Finland), reported on attempts to obtain low molecular-weight products from spent sulfite liquor by means of demethylation and degradation. The liquor is treated with fresh Na_2S/NaOH at 250 to 295 °C for 15–60 min [9], but now at normal pressure or *in vacuo*. A simple S_N2 reaction with HS^- or CH_3S^- effects specific cleavage of certain ether and C–C linkages. The products include phenol, alkylphenols, catechol, alkylcatechols, phenolic carboxylic acids, $(CH_3)_2S$, and $(CH_3)_2S \rightarrow O$.

K. Kratzl and *E. Risnyovszky*, Vienna (Austria), conducted alkaline hydrolyses of about 20 model substances in order to obtain information of the reaction mechanisms involved in the anaerobic alkaline cleavage of lignosulfonic acids from gymnosperms. The sulfonic acid grouping is absolutely necessary for reaction to occur. Sulfonic acids derived from aldols give rise to ketones; those derived from acyloins yield carboxylic acids. A twofold β-elimination is assumed to explain the reaction. Considerable yields of vanillin, acetaldehyde, acetovanillone, and formaldehyde were obtained in this way from lignin.

C. de Choudens and *R. A. Quiles*, Grenoble (France), oxidized 2 % solutions of lignin in NaOH at 100 °C and 5–30 atm of oxygen. CO_2, formic and acetic acids, acetovanillone, vanillin, *p*-hydroxybenzaldehyde, syringaaldehyde, and the corresponding acids were detected as products by chromatography.

Studies of the influence of the physical properties, particularly the melting point, of lignin either as such or in sawdust of various grain size on the speed of sulfonation at 70, 95, and 135 °C and pH 3 or 7 were carried out by *A. Björkman*, Copenhagen (Denmark). Chemical reactions are not rate-determining. Kinetic expressions for the rate of dissolution of the lignin – a first-order process – were evolved. About 10 % of isolated lignin dissolves immediately, however. Methylated lignin or lignin reduced with $NaBH_4$ dissolves slower than untreated lignin.

D. A. I. Goring, Montreal (Canada), determined the molecular weights and molecular configuration of 5 fractions of lignosulfonate from spruce. The values obtained by light-scattering and sedimentation-pattern measurements lay between 5000 and 130000. $M_w/M_n = 3.1$, *i.e.* there is a wide range of molecular weights present. Dialysis through graded micropore filters gave 9 subfractions with molecular weights between 37000 and 1270000. The molecules are spherical aggregates of random coils. Electron micrographs indicate a molecular diameter of 60 Å; the dialysis experiments suggest 47 Å. Heating of the molecules does not bring about any greater change in molecular weight, *i.e.* the random C_9 chains must be interlinked by covalent bonds, and the spherical aggregates are not merely micelles.

[VB 842/155 IE]

German version: Angew. Chem. 77, 56 (1965)

[9] Cf. *A. Rezanowich, W. Q. Yean*, and *D. A. I. Goring*, Svensk Pappertid. 66, 141 (1963).

Annual Conference of the German Mineralogical Society

The Deutsche Mineralogische Gesellschaft held its session of lectures in Wiesbaden (Germany) from September 7th to 10th, 1964.

From the agenda:

H. Kirsch (Gummersbach, Germany) reported on the examination of tubes from high-pressure steam-power stations. The crystallites of layers of magnetite, formed by corrosion inside the tubes, grow at the area of contact with one of their octahedral faces orientated on the metal crystallites. The degree of orientation and the density of these magnetite layers depend on the amount of oxygen dissolved in the water, on the temperature and on the rate of flow of water or steam in the tubes. Since well-orientated and defect-free magnetite layers effectively protect the tubes against further corrosion, the conditions in the first hours after installation of new tubes are very important as regards resistance to corrosion.

J.-H. Hiller (Stuttgart, Germany) carried out X-ray investigations on rusting of sheet iron in sea air, woodland air, and in the air (containing SO_2) of industrial regions, and showed that fresh rust originally contains an amorphous component which is transformed in a few hours into γ-FeOOH, lepidocrocite, which sometimes forms hexagonal platelets 0.5 mm across. The lepidocrocite is transformed, while retaining its external crystal form, into α-FeOOH (goethite) or magnetite (Fe_3O_4). Magnetite forms rapidly, especially in moist industrial air, but only very slowly in woodland air.

Another problem in industry is the quantitative X-ray determination of cristobalite, which is difficult due to the different degrees of order of the crystals. According to *I. Patzak* (Bonn, Germany) the "disorder number", which is defined as the ratio of the half-widths of two of the closest possible adjoining X-ray interferences and is easily determined experimentally, is a measure of the degree of order of the cristobalite under investigation. Calibration curves, obtained by using cristobalite of a known "disorder number", permit determination of the relative state of order and also of the quantity of cristobalite contained in a mixture.

The importance of the electron microprobe for microanalytical work and for chemical phase analysis was mentioned in two papers. *E. F. Stumpfl* and *A. M. Clark* (London, Great Britain) found that orientated lamellar crystals in naturally occurring linneite, Co_3S_4, were not of the common hexagonal CoS type, but a cubic phase of composition Co_9S_8 ($a_0 = 9.928 \pm 0.001$ Å). Furthermore, the authors found new rhodium-platinum minerals in South African platinum ores, which had escaped detection till then, since they occur only in very small quantities in the ores and are of small particle size. The work of *D. D. Klemm* (Munich, Germany) on zonally formed skutterudites (Fe, Co, Ni)As_x, where $x = 2.0$ to 3.5, gave some indication of the limits of this method due to limitations in the resolving power of the microprobe. The resolving power is determined by the diameter of the electron beam which in this case is about 1 μ.

H. Schloemer (Saarbrücken, Germany) has studied the effect of alkali concentration and species of alkali ions on the properties of boehmite γ-AlOOH, which had been precipitated using purest aluminum powder (5 ppm impurities) with 0.1, 0.01, and 0.001 N alkali-metal hydroxide solutions and triply distilled water. He observed that the crystallite size and state of order of the boehmite increased not only with increasing alkali concentration but also in the order H_2O, CsOH, KOH, LiOH, as precipitating agent, while the specific surface area decreased in this order. The observed decrease in magnitude of the lattice constants of the boehmite with increasing radius of the alkali ion used needs further investigation.

While nowadays it is usually assumed that precipitation of silica dissolved in sea-water proceeds *via* its incorporation into the shells and skeletons of marine organisms, the experiments of *H. Harder* (Münster, Germany) show that deposition of dissolved silica is possible by precipitation

of aluminum hydroxide. The SiO_2 content of the amorphous hydroxide precipitate is higher, the lower the temperature during precipitation. With a high $Al_2O_3:SiO_2$ ratio in solution the dissolved silica is almost completely precipitated. The pH of the solution has only a slight effect on the $Al_2O_3:SiO_2$ ratio of the precipitate. When using sea water, the X-ray amorphous precipitates contain other ions, especially magnesium; this could be of significance in the diagenesis of clay minerals from these hydroxide-silica precipitates.

On attempting to prepare the dihydrate $MgSO_4 \cdot 2\ H_2O$ (sanderite) *R. v. Hodenberg* and *R. Kühn* (Hannover, Germany) repeatedly obtained two hydrate phases, of still uncertain composition, whose crystals grew together with the same orientation. For one of the two phases the lattice constants $a_0 = 12.35$ Å, $b_0 = 12.40$ Å, $c_0 = 13.25$ Å, $\beta = 91.5°$ (C2/c) were found. Moreover, the authors prepared an orthorhombic trihydrate $MgSO_4 \cdot 3\ H_2O$, not described before, with lattice constants $a_0 = 8.18$ Å, $b_0 = 10.93$ Å, $c_0 = 12.42$ Å (Pbca, $\rho_{exp.} = 2.06$ g cm^{-3}).

W. Eysel, M. Behruzi, and *T. Hahn* (Aachen, Germany) investigated the system $LiGaSiO_4/LiGaGeO_4/LiAlGeO_4/LiAlSiO_4$. While $LiAlSiO_4$ has the β-quartz structure at normal pressure, the first three compounds crystallize as the phenakite type and are completely miscible. Cd_2GeO_4 is isotypic with γ-Ca_2SiO_4 and γ-Ca_2GeO_4 (olivine type); however, Cd_2SiO_4 crystallizes as the Na_2SO_4 (V)-type. Therefore, at high temperatures only limited mixed-crystal formation between the two cadmium compounds was observed. Cd_3SiO_5 is orthorhombic-pseudotetragonal and structurally related to Ca_3SiO_5; however, Sr_3SiO_5, Ba_3SiO_5 and Ba_3GeO_5, K_3BeF_5 and Rb_3BeF_5 possess full tetragonal symmetry. Sr_3GeO_5 and Cd_3GeO_5 could not be synthesized.

G. H. Moh (Heidelberg, Germany) investigated the binary system tin/sulfur and found that Sn_2S_3 and SnS_2 exist as stable phases as well as Sn, SnS, and S. The hexagonal layer structure of the disulfide is transformed sluggishly at 692 °C into the cubic structure which is stable up to the melting point. Also Sn_2S_3 has a transition point at 738 °C and melts incongruently at 758 °C. Knowledge of the stability relationships finally brought about the discovery of Sn_2O_3 in Bolivian tin ores.

An investigation of cadmium titanate at high pressures (up to 50×10^3 atm) by *J. Liebertz* (Aachen, Germany) and *C. J. M. Rooymans* (Eindhoven, Netherlands) lead to the unexpected result that the temperature of transition from the low-temperature form α-$CdTiO_3$ (ilmenite type) to the high-temperature form β-$CdTiO_3$ (perovskite type) decreased with increasing pressure. This implies that α-$CdTiO_3$ is less dense than the β-form. While the phase transition $\alpha \rightarrow \beta$ in air above 925 °C is irreversible and very slow, the reverse reaction can be observed under hydrothermal conditions at 850 °C.

G. Bayer and *W. Hoffmann* (Zurich, Switzerland) prepared, by solid state reactions, compounds with the formulae $Na_x(B_yTi_{8-y})O_{16}$ where B = Mg, Co, Ni, Zn, Al, Ti(II), Ti(III), Cr(III), Fe(III), and Ga. The range of phases extended, for the compounds with trivalent B ions, from $Na_2B_2Ti_6O_{16}$ to $Na_{1.33}B_{1.33}Ti_{6.67}O_{16}$, and for those with bivalent B ions from $Na_2BTi_7O_{16}$ to $Na_{1.6}B_{0.8}Ti_{7.2}O_{16}$. All these compounds are isotypic with the titanium bronzes Na_xTiO_2, described by *Wadsley*. The Ti and B ions are statistically distributed over the octahedral sites in the crystal lattice, while the Na ions are surrounded by eight oxygen atoms for valence reasons. Substitution for Na by K, Rb, and Ba leads eventually to non-stoichiometric compounds isotypic with priderite.

The painstaking investigation of the structure of the mineral denningite (Mn, Ca, Zn, Mg)Te_2O_5 by *E. M. Walitzi* (Graz, Austria, and Göttingen, Germany) gives information concerning the structure of tellurites. In this structure the Te atom forms a trigonal pyramid with three oxygen atoms. Two such TeO_3 pyramids are joined by a common oxygen atom into a Te_2O_5 group, such that the Te–O distance within the Te_2O_5 group is, on average, 1.92 Å. The coordination of each Te atom is completed by a fourth oxygen atom, at a distance of 2.36 Å, belonging to another Te_2O_5 group. The coordination of the Te atoms as well as the Te–O–Te bond angle of 120° indicate considerable covalent character of the Te–O bond.

$Li_2ZnCl_4 \cdot 2\ H_2O$ contains, according to *H. Jacobi* and *B. Brehler* (Clausthal-Zellerfeld, Germany), $[ZnCl_4]^{2-}$ tetrahedra, while each Li^+ ion is surrounded by four Cl^- ions and two H_2O molecules. In half of the $[LiCl_4(H_2O)_2]^{3-}$ octahedra the water molecules occupy the *cis*-positions, and in the other half they occupy the *trans*-positions.

S. Ghose, M. Fehlmann (Zurich, Switzerland) and *J. J. Finney* (Golden, Colorado, U.S.A.) found two types of copper polyhedra in the crystal structure of cornetite, $Cu_3PO_4(OH)_3$. Two thirds of the Cu atoms have tetragonal-pyramidal [4 + 1]-coordination, and the others have very distorted tetragonal-bipyramidal [4 + 2]-coordination. These polyhedra are combined by common corners and edges into a three-dimensional network, in which the $[PO_4]$ groups are found.

Of great interest was a comprehensive paper by *W. Gentner* (Heidelberg, Germany) on the determination of the age of planetary materials, in which he showed that, contrary to popular opinion, methods by which the concentration of a gaseous decomposition product is measured (K–Ar methods, U/Th–He methods) offer advantages over those using solid decomposition products, because the isotopic composition of the original lead is unknown, while the original rare gases are practically no longer available on Earth. Measurement of the K–Ar age of a large number of chondrites frequently showed that they had an age of ca. 0.5×10^9 or ca. 4×10^9 years. Presumably then, these stony meteorites from our planetary system originated from two heavenly bodies which solidified 0.5×10^9 and 4×10^9 years ago. The so-called "radiation age", obtained by examination of the outer crust of the meteorite which has been exposed to cosmic radiation, enables the point of time of disintegration of a heavenly body to be established. For stony and for iron meteorites the "radiation age" is usually 2×10^7 to 3×10^7 and 5×10^7 years, but the small number of meteorites examined yields little definite information about how many cosmic catastrophies the meteorites which reach Earth have passed through. There has been much controversy as to whether tektites are glasses of volcanic or of meteoric origin. The determination of their "radiation age" gave $(14.9 \pm 1) \times 10^6$ years for tektites from the Nördlinger Ries, and $(14.8 \pm 0.6) \times 10^6$ years for the moldavites found in Czechoslavakia, which, together with other findings, indicates a genetic linkage between the two. The isotopic composition of argon contained in the many blow-holes in the tektites indicates that the material is terrestrial matter which probably melted when striken by a meteor.

[VB 859/169 IE]

German version: Angew. Chem. 77, 45 (1965)

Synergic Effects in Solvent Extraction

H. Irving, Leeds (England)

Synergism in the liquid-liquid extraction of inorganic cations, *i.e.* the phenomenon wherehy a mixture of two reagents produces a larger value for the extraction coefficient than either reagent taken alone, was originally believed to occur only with uranium(VI) and certain mixtures of phosphorus-containing extractants. In 1959, *Irving* predicted that the effect would be much more general and demonstrated the very large synergic effect in the extraction of uranium(VI) by mixtures of TTA (thenoyltrifluoroacetone) and TBP (tributylphosphate) or TBPO (tributylphosphine oxide). The effect was later demonstrated with other actinides in various

oxidation states, with lanthanides, with transition metals of the first series, and even with alkaline earths.

In the lecture, examples were given of synergism in the solvent extraction of indium, protactinium, and plutonium by various combinations of reagents and solvents. An account was also given of other unpublished work on the uses of heterocyclic amines and diamines to promote the extraction of copper(II) by acetylacetone, cobalt(II) by TTA, and nickel by diacetylbisbenzoylhydrazone. The compositions of the extractable adducts have been determined in various ways and a reduction of the synergic effect caused by α-substitution in pyridines can be attributed to steric hindrance of coordination.

Where the solvent extraction of the bischelate CoT_2 [*] is enhanced by either of two bases A or B due to the formation of the extractable adducts CoT_2A_2 and CoT_2B_2, an additional synergic effect may arise from a mixed complex CoT_2AB, and evidence for such mixed complexes can be obtained in this way.

[VB 839/188 IE]

German version: Angew. Chem. 77, 57 (1965)

[*] T=Thenoyltrifluoroacetone.

SELECTED ABSTRACTS

An apparatus for maintaining the pH of unbufferd solutions has been constructed by *C. W. Cotman* and *D. M. Smith*. A pH-meter with a simple combination of a glass electrode and a reference electrode gives a signal indicating any change in pH through a servo system which, depending on the sign of the pH difference relative to the desired constant value, discharges strong acid or strong base (of a concentration dependent upon the pH value to be maintained) from one of two syringes. The instrument can maintain any pH value between 2 and 10 constant to better than ±0.05 unit for 48 h, provided that the temperature of the unbuffered solution is kept constant. / Rev. sci. Instruments *41*, 561 (1964) / –Hz.

[Rd 110/297 IE]

Pure difluoroborane HBF_2 has been prepared for the first time by *T. D. Coyle, J. J. Ritter*, and *T. C. Farrar*. HBF_2 was already suspected as an intermediate in the reaction of diborane with fluoro-olefins; here it is best obtained from BF_3 and dialkoxyboranes at 0 °C; the product is frozen out as a mixture with BF_3 and a little diborane. The products are separated by vacuum distillation, but this leads to considerable loss of HBF_2. The compound disproportionates gradually at room temperature into BF_3 and diborane; addition of diborane slows down the disproportionation. HBF_2 reacts smoothly with ethylene at room temperature to give ethylboron difluoride. / Proc. chem. Soc. (London) *1964*, 25 / –Gn.

[Rd 145/332 IE]

Novel complexes of metallocenes with π-acceptors were isolated by *J. C. Goan, E. Berg*, and *H. E. Podall*. (1:2)-Nickelocene-*p*-chloranil *(1)* is formed from its components in benzene in 76 % yield as a dark brown solid which is stable in air and up to 350 °C under argon; it is soluble in water and benzene. (1:1)-Cobaltocene-*p*-chloranil *(2)* [92 % yield] is olive green and decomposes at 105–110 °C; the (1:2)-complex *(3)* [78 % yield] is dark green and decomposes at 228 °C. (1:1)-Cobaltocene-1,3,5-trinitrobenzene *(4)* [95 % yield] is brown and stable in air; its m. p. is 125 °C. Ferrocene forms complexes in the melt and in some solvents with *p*-benzoquinone, tetrachlorophthalic anhydride, 1,2,4,5-tetracyanobenzene, *etc.*, but these cannot be isolated.

$\pi\text{-}Cp_2Ni^{2\oplus}CA^{2\ominus}CA$ *(1)*

$\pi\text{-}Cp_2Co^{\delta\oplus}CA^{\bullet\delta\ominus}$ *(2)*

$\pi\text{-}Cp_2Co^{\delta\oplus}TNB^{\delta\ominus} \rightleftharpoons \pi\text{-}Cp_2Co^{\oplus} + TNB^{\bullet\ominus}$ *(4)*

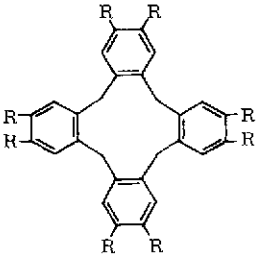
$\pi\text{-}Cp_2Co^{\oplus}CA^{\bullet\ominus}CA$ *(3)*

Cp = Cyclopentadienyl, CA = p-Chloranil,
TNB = 1,3,5-Trinitrobenzol

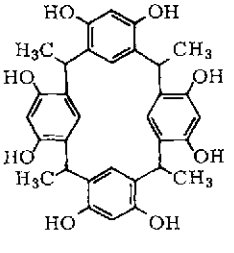
Complexes of this kind are the intermediates sought for in the preparation of metallocinium salts of aromatic acids by oxidation of metallocenes, *e.g.* with benzoquinone in the presence of acid [1]. Infrared and ultraviolet spectra reveal that it is the central metal ion and not a π-cyclopentadienyl ring which functions as π-electron donor. This ion combines with the aromatic radical anion (detected by ESR spectroscopy) to form either a charge-transfer complex with partial charge separation such as *(2)* or *(4)* – which can dissociate into ions in polar solvents such as methanol – or a charge-transfer radical ion salt such as *(3)*. Because of the weakness of its ESR signal, *(1)* is formulated as a nickelocinium salt in which the primary radical ions have undergone disproportionation. / J. org. Chemistry *29*, 975 (1964) / –Bi.

[Rd 156/343 IE]

The structures of macrocyclic condensation products obtained from veratrole and resorcinol with aldehydes were elucidated by *H. Erdtman, F. Haglid*, and *R. Ryhage*. Acid-catalysed condensation of veratrole with formaldehyde affords two crystalline compounds. It was confirmed by mass spectrometric and NMR studies that one of these does in fact possess the structure already assumed by *Lindsey* [2] with three veratrole rings and a "crown" conformation of the nine-membered ring. The second compound has the structure *(1)*. A crystalline product obtained by condensing resorcinol with acetaldehyde in the presence of sulfuric acid has the



R = OCH_3 *(1)*



(2)

structure *(2)*. / Acta chem. scand. *18*, 1249 (1964) / –Ma.

[Rd 150/337 IE]

Prismatic samples can give wrong transparency values in the infrared, as *A. L. Olsen, K. B. LaBaw*, and *L. W. Nichols* have found. The prismatic form of the sample causes the beam of light that has passed through it to enter the monochromator at an oblique angle and therefore disturbs the conditions of the optical beam balance. The magnitude of the error in the transparency is given in terms of the angle of the prismatic layer and index of refraction of the sample; the error increases with increasing prism angle and with increasing refractive index. / J. opt. Soc. American *54*, 813 (1964) / –Hz.

[Rd 112/299 IE]

[1] Cf. *G. Wilkinson* et al., J. Amer. chem. Soc. *74*, 2125 (1952).

[2] *A. S. Lindsey*, Chem. and Ind. *1963*, 823.

A new Landoldt reaction which is catalysed by vanadium(V), iron(III), or osmium(VIII) has been discovered by *J. Bognár* and *O. Jellinek*. The reaction can be used for the detection and semiquantitative estimation of small amounts of these ions.

$$ClO_3^{\ominus} + 6\ Br^{\ominus} + 6\ H^{\oplus} = Cl^{\ominus} + 3\ Br_2 + 3\ H_2O \qquad (a)$$

$$Br_2 + C_6H_8O_6\ (1) = 2\ Br^{\ominus} + 2\ H^{\oplus} + C_6H_6O_6 \qquad (b)$$

$$ClO_3^{\ominus} + 3\ C_6H_8O_6\ (1) = Cl^{\ominus} + 3\ C_6H_6O_6 + 3\ H_2O \qquad (c)$$

Reaction (b) goes faster than Reaction (a), so that bromine is reduced by ascorbic acid *(1)* as soon as it is formed. It is only when the ascrobic acid has been entirely consumed by Reactions (b) and (c) that bromine formed by Reaction (a) remains in the solution and is indicated by its brown coloration with *o*-toluidine. The time required for the bromine to appear is shortened by the catalytic effect of traces of some elements; this phenomenon can be used to detect 0.1 μg of V(V), 0.5 μg of Fe(III), or 0.2 μg of Os(VIII) in 5 ml of solution. An excess of Ti(IV), Mo(VI), and Cu(II) interferes with the test by causing additional catalysis. / Mikrochim. Acta. *1964*, 317 / –Gn. [Rd 147/334 IE]

A gravimetric procedure for estimating cyclopentadiene and the cyclopentadienyl anion has been worked out by *G. W. Watt* and *L. J. Baye*; the method is based on the reaction with $HgCl_2$ [1]. A few milligrams of C_5H_6 or KC_5H_5 in anhydrous methanol are mixed with an excess of a 40 % solution of $HgCl_2$ in methanol and saturated methanolic sodium acetate. A yellow precipitate separates almost immediately and is completely coagulated after 16 h. Dilution of the supernatant with water precipitates another small quantity of $C_5(HgCl)_6$. The precipitate is filtered off and washed. The solid gives no X-ray diffraction diagram. In unbuffered solutions C_5H_5HgCl, contaminated with a little Hg_2Cl_2 is precipitated. From buffered solutions $C_5(HgCH_3COO)_6$ and a minute amount of CH_3COOHg are obtained almost quantitatively. / J. inorg. nuclear Chem. *26*, 1531 (1964) / –Kr. [Rd 119/306 IE]

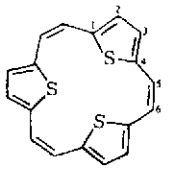
A rapid determination of CO_2, particularly for purposes of organic elemental analysis, can be achieved using relative conductometric procedures according to *W. Bartscher* and *W. Schmidts*. The ratio of the conductivities of a solution of sodium hydroxide used to absorb CO_2 and of an unaltered standard solution is measured; the relationship of these ratios to the CO_2 content is non-linear, but a suitable circuit is used to achieve a linear response when the sample cell and reference solution are kept at the same temperature. The concentration of the sodium hydroxide solution must be kept low in order to estimate small amounts of CO_2; this can lead to incomplete absorption in the solution. However, this difficulty can be avoided by addition of the enzyme carboanhydrase to the solution or by buffering it with amino compounds, *e.g.* aminoethanol. The increase in accuracy obtained in this way makes it possible to determine carbon in organic substances, for example, in samples of even less than 1/mg with the precision of conventional methods. / Z. analyt. Chem. *203*, 168 (1964) / –Gn. [Rd 146/ 333 IE]

A covalent metal-metal bond in mixed metal carbonyls was proven by *R. F. Bryan* using X-ray analysis. In the complex $(C_6H_5)_3SnMn(CO)_4P(C_6H_5)_3$, which crystallizes in a monoclinic ($P2_1/n$) lattice (a = 10.453; b = 26.477; c = 12.646 Å; β = 99°34'), the three atoms Sn, Mn, and P are in a linear arrangement with the interatomic distances $d_{Sn-Mn} = 2.55 \pm 0.02$ and $d_{Mn-P} = 2.36 \pm 0.02$ Å. / Proc. chem. Soc. (London) *1964*, 232 / –Jg. [Rd 157/344 IE]

[1] *K. Issleib* and *A. Brack*, Z. Naturforsch. *11b*, 420 (1956).

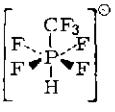
The structure of [18]-annulene trisulfide was made the subject of HMO calculations by *C. A. Coulson* and *M. D. Poole* (in order to compare its aromaticity with that of [18]-annulene itself). Working on the assumptions of a planar D_{3h} molecule, equality of all α_c, and of $\beta_{cc} = \beta_0$, they varied two parameters: $\alpha_s - \alpha_c = 1.5(2.0; 1.5)\beta_0$; and $\beta_{cs} = 1(1.0; 0.8)\beta_0$. The π-bond order [S–(C–1): 0.368; (C 1)–(C–2): 0.630; (C–2)–(C–3): 0.658; (C–4)–(C–5): 0.548; (C–5)–(C–6): 0.715] and π-charge densities: [S: 1.776; C–1: 1.009; C–2: 1.067; C–5: 1.037] given for the third case differ only slightly from those obtained for the first and second assumptions. The most important result is that the (C–5)–(C–6)

(1)



honds have a significantly higher double-hond character than the other C–C bonds. The trisulfide *(1)* is thus less aromatic than [18]-annulene, being more like three thiophene rings coupled by olefinic double bonds; this result is supported by the ultraviolet spectrum of *(1)*. The thiophene rings may be twisted somewhat out of the common plane. / Proc. chem. Soc. (London) *1964*, 220 / –Jg. [Rd 158/345 IE]

The hydridotetrafluoro(trifluoromethyl)phosphate anion *(1)* has been detected and characterized by NMR and infrared spectroscopy by *R. G. Cavell* and *J. F. Nixon*.



(1)

Its dimethylammonium salt *(2)* is formed as follows:

$$3\ F_3C{-}PF_2 + 3\ HN(CH_3)_2 \rightarrow 2\ F_3C{-}PF{-}N(CH_3)_2 + (H_3C)_2NH_2^{\oplus}[F_3C{-}PF_4H]^{\ominus}$$

(2)

Dry *(2)* is stable at room temperature; on alkaline hydrolysis, it forms a quantitative yield of fluoroform. / Proc. chem. Soc. (London) *1964*, 229 / –Jg. [Rd 159/346 IE]

Fluorinated imines were studied by *W. J. Middleton* and *C. G. Krespan*. Perfluorinated ketones do not yield imino derivatives under the usual conditions. The reactive imine *(1)* was, however, obtained in 70 % yield from hexafluoroacetone by treating it with NH_3 and then with $POCl_3$ in pyridine. *N*-Alkylimines are obtained if primary amines are used instead of the NH_3. The synthesis is generally applicable for the preparation of fluorinated imines from fluoro ketones. Compound *(1)* reacts with ammonia or amines to give adducts such as *(2)*. With hydrazine it forms the aminohydrazine *(3)*, which is converted into the hydrazone *(4)* by P_2O_5. The adducts *(5)* and *(6)* are obtained with HCN and HN_3, respectively. Cyclopentadiene, too, gives an adduct. The lithium salt of the imine can be converted into the bromo derivative, which reacts with the Li salt to form the azine *(7)*.

$(CF_3)_2C{=}NH$ *(1)* $(CF_3)_2C(NH_2)_2$ *(2)*

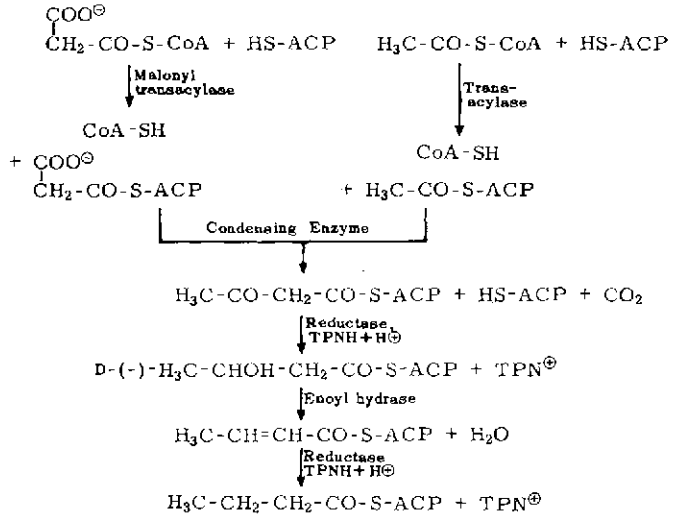
$(CF_3)_2C(NH_2)NHNH_2$ *(3)* $(CF_3)_2C{=}NNH_2$ *(4)*

$(CF_3)_2C(NH_2)CN$ *(5)* $(CF_3)_2C(NH_2)N_3$ *(6)*

$(CF_3)_2C{=}N{-}N{=}C(CF_3)_2$ *(7)*

Abstracts, 148th Meeting Amer. chem. Soc. 1964, 24 K / –Ma. [Rd 148/335 IE]

The protein carrier responsible for the biosynthesis of fatty acids has been isolated from *Escherichia coli* by *P. J. Majerus, A. W. Alberts*, and *P. R. Vagelos*. Since the coenzyme A derivatives of the intermediates in the β-oxidation of fatty acids are not the same as those of the intermediates in fatty acid synthesis, it was assumed that all these intermediates are linked to a protein. This thermostable protein, previously called enzyme II, is now termed acyl-carrier protein (ACP) and was concentrated 410-fold by heating incubates at 80 °C, followed by precipitation with 0.1 N HCl, treatment with streptomycin, and repeated chromatography on DEAE-cellulose and DEAE-Sephadex. The protein was practically pure and has a molecular weight of 9500; its amino-acid composition was also determined. It contains a mercapto group which can bind an acyl residue as a thioester grouping. The carrier protein from *E. coli* does not appear to be species-specific. The synthesis of fatty acids in *E. coli* proceeds by the following scheme:



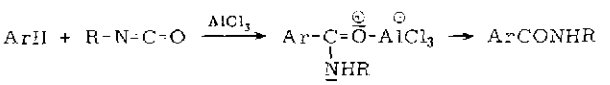
Proc. nat. Acad. Sci. USA *51*, 1231 (1964) / –Sch. [Rd 136/323 IE]

An asymmetric synthesis of optically active alcohols from carbonyl compounds was achieved by *S. R. Landor, B. J. Miller*, and *A. R. Tatchell* using $LiAlH_4$. An asymmetric complex is prepared in ether from a suspension of $LiAlH_4$ with 1,2-*O*-cyclohexylidene-D-glucofuranose *(1)* or methyl 4,6-*O*-benzylidene-α-D-glucopyranoside *(2)*, and the ketone to be reduced is added to this dropwise with stirring.

Ketone	Yield of alcohol [%]	Stereo-specificity [%]	$LiAlH_4$-complex with
C_6H_5–CO–CH_3	66	14.3	*(1)*
	58	7.6	*(2)*
$(H_3C)_2C$=CH–CO–CH_3	60	9.6	*(1)*
	56	3.9	*(2)*

The method is simple and cheap to apply. It is hoped that higher stereospecificity will be achieved with cyclic asymmetric complexes in which the aluminum hydride portion can approach closer to the center of asymmetry. / Proc. chem. Soc. (London) *1964*, 227 / –Jg. [Rd 160/347 IE]

The Friedel-Crafts reaction of isocyanates and benzene derivatives was investigated by *F. Effenberger* and *R. Gleiter*. Isocyanates react with aromatic compounds according to the scheme



to form *N*-substituted benzamides. The reactivity of the aromatic compounds decreases along the series anisole ≈ mesitylene > toluene > benzene ≈ fluorobenzene > chlorobenzene > *m*-dichlorobenzene. The heat of formation of the alkyl isocyanate complexes is greater than that of the aryl complexes, but the alkyl isocyanate/$AlCl_3$ complexes are less reactive than the aromatic complexes. Di-isocyanates give rise to bis-anilides. The highly reactive compound *p*-toluenesulfonyl isocyanate yields the diphenylsulfone derivative as well as the amide. Aromatic compounds with second-order substituents, *e.g.* acetylmesitylene, dimesitylsulfone, and nitromesitylene, do not react to give anilides. Some of the reactions give quantitative yields. / Chem. Ber. *97*, 472 (1964) / –Ma. [Rd 6/283 IE]

Intermolecular association of liquid nitriles is indicated by the temperature dependence of their dielectric constants, according to *W. Dannhauser* and *A. F. Flueckinger*. The equation of *Cole* [Equation (a)] derived from the Kirkwood-Frohlich theory was used to calculate the correlation factor, g, which is a measure of short-range dipole-dipole interaction.

$$\varepsilon_0 \varepsilon_\infty + \frac{3\varepsilon_0}{2\varepsilon_0 + \varepsilon_\infty}\left(\frac{\varepsilon_\infty + 2}{3}\right)^2 \frac{4\pi N \rho \mu_0^2}{3MkT} \cdot g \qquad (a)$$

[ε_0 = experimental dielectric constant at $\nu = \infty$ (as a measure of the polarization), ρ = density, μ_0 = dipole moment in vacuo, M = molecular weight]

If the association is assumed to be due merely to the dimerization of molecules of antiparallel dipole, an equilibrium constant $K = (1-g)/g^2$ can be calculated. The values calculated from the temperature dependence of K and the ranges of ε_0 are given in the table.

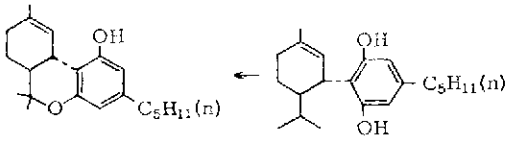
Nitrile	$K^\circ_{25\,°C}$	$\Delta H^\circ_{25\,°C}$ [kcal/mole]	$\Delta S^\circ_{25\,°C}$ [e.u.]	Range of T [°C]	Range of ε_0
Acrylo-	0.34	−0.73	−4.63	−80–+160	55.2–16.1
Propio-	0.46	−1.00	−4.94	−60–200	41.6–12.4
2,2-Dimethylpropio-	0.34	−1.11	−5.90	20–180	21.1–10.9
Benzo-	1.12	−1.18	−3.72	0 –180	27.8–15.0
2,6-Dimethylbenzo-	0.23	≈0	−2.92	100–200	16.8–11.2

J. physic. Chem. *68*, 1814 (1964) / –Jg. [Rd 118/305 IE]

Ozone is stabilized by strong bases, according to a report by *L. J. Heidt* and *R. Landi*. The half-life of ozone at room temperature is 2 min in 1 N NaOH, 40 min in 5 N NaOH, and 83 h in 20 N NaOH. In addition, ozone does not decompose explosively in strongly alkaline solutions. The causes of these effects are still unknown. It is also unexplained why the half-life of ozone decreases about 18-fold on passing from 10^{-6} to 10^{-4} N NaOH and then increases again in stronger NaOH. / Chem. Engng. News *42*, No. 30, p. 38 (1964) / –Kr. [Rd 120/307 IE]

The effect of sodium γ-hydroxybutyrate on the activity of anesthetics in mice was studied by *L. A. Serebryakov*. Sodium γ-hydroxybutyrate intensifies the anesthetic action of hexobarbital, sodium thiopental, and ethanol two- to three-fold and of diethyl ether and fluorothan to a smaller extent. The lethal dose of sodium γ-hydroxybutyrate applied by intraperitoneal injection is 3.7 g/kg. Simultaneous application of sodium γ-hydroxybutyrate and either hexobarbital or ethanol did not increase the toxicity of either substance. / Pharm. and Toxicol. USSR *3*, 275 (1964) / –Kr. [Rd 121/308 IE]

The isolation, structure, and partial synthesis of an active constituent of hashish (marihuana) are described by *Y. Gaoni* and *R. Mechoulam*. Δ^1-3,4-*trans*-Tetrahydrocannabinol *(1)* was isolated by chromatography of a hexane extract of hashish on florisil. The structure of *(1)* was derived from the properties of its crystalline derivatives, from its ultraviolet, infrared, and NMR spectra, and from its partial synthesis by refluxing cannabidiol *(2)* in ethanol plus HCl. Compound *(1)* exhibits high activity in the ataxia test on dogs.



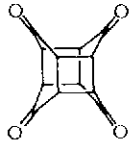
(1) *(2)*

J. Amer. chem. Soc. *86*, 1646 (1964) / –Sch.
[Rd 139/326 IE]

Cystathionine is absent from the brains of patients suffering from homocystinuria, as *T. Gerritsen* and *H. A. Waisman* showed for several persons. Homocystinuria is a congenital disturbance of the metabolism of amino acids containing sulfur, its symptoms including mental retardedness. The human brain normally contains 0.022–0.056 % cystathionine, which is formed in the liver from homocysteine and serine through the action of cystathionine synthetase. Homocystinuria is thought to be caused by a lack of cystathionine synthetase. In earlier studies no cystathionine synthetase could be detected in the liver of a homocystinuria patient. Since a very minute excretion of cystathionine in urine was observed after administration of L-serine and since the excretion of homocystine was reduced, the pathogenic symptoms are probably due only to a strongly inhibited formation of cystathionine, and not to complete blockage of the process. / Science (Wahington) *145*, 588 (1964) / –De. [Rd 107/294 IE]

A quantitative separation of inorganic orthophosphate from pyrophosphate and organic phosphates was achieved by *Y. Sugino* and *Y. Miyoshi*. Addition of ammonium molybdate and triethylamine hydrochloride to an acidic solution of the phosphates (0.05–1.0 N at pH 0.5–2.0) gives a precipitate consisting of orthophosphoric acid, ammonium molybdate, and triethylammonium chloride (1:2:3). Inorganic pyrophosphate, sugar phosphates, and nucleoside phosphates remain in the supernatant. Acid-labile phosphates are partially hydrolysed. Concentrations of orthophosphate ions down to 5×10^{-6} M can be removed. / J. biol. Chemistry *238*, 2360 (1964) / –Sch. [Rd 138/325 IE]

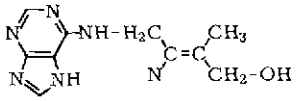
A three-dimensionally bonded dimer of *p*-benzoquinone *(1)* was obtained by *D. Bryce-Smith* and *A. Gilbert* by ultraviolet irradiation of *p*-benzoquinone in molten maleic anhydride; the yield was 30 mg or 0.2 % after 1 h at 60–65 °C. The same pale yellow dimer *(1)*, m.p. 248 °C, is formed when molten benzoquinone is irradiated, although the yield is lower. Irradiation of benzoquinone in cyclohexane yields *(1)* as by-product and



(1)

quinhydrone as main product. Surprisingly, no photoadduct of *p*-benzoquinone onto benzene, naphthalene, anthracene, or phenanthrene was found. Irradiation of a mixture of *p*-benzoquinone and acenaphthylene afforded a copolymer with the approximate formula (*p*-benzoquinone)$_{14}$(acenaphthylene)$_{15}$. / J. chem. Soc. (London) *1964*, 2428 / –Kr.
[Rd 122/309 IE]

Zeatine, a factor which induces cell division, has been isolated in crystalline form (1 mg from 70 kg of grain) by *D. S. Letham*, *J. S. Shannon*, and *I. R. McDonald*. Zeatine *(1)* was identified on chromatograms as a purine derivative; its oxidation with HNO_3 or MnO_2 yielded adenine. Physical investigations and



(1)

its identity with zeatine synthesized by *G. Shaw* and *D. V. Wilson* from γ-bromotiglate (m.p. 207–208 °C) led to structure *(1)* for the compound. As little as 0.1 μg/l of the substance suffices to activate cell division. / Proc. chem. Soc. (London) *1964*, 230, 231 / –De. [Rd 106/293 IE]

The repressor for the alkaline phosphatase in Escherichia coli is a metabolically unstable protein, judging from the results of studies by *J. Gallant* and *R. Stapleton* on the synthesis of the alkaline phosphatase in an *E. coli* mutant in which repression by inorganic phosphate increases with decreasing temperature. The repression depends on the presence of a specific amino acid which is essential for the mutant, and can be eliminated by chloramphenicol (an inhibitor of protein biosynthesis), but is not affected by 5-fluorouracil (an inhibitor of RNA biosynthesis), and occurs even in the absence of the DNA constituent thymine. This indicates that the repressor is a protein, and since a *de novo* synthesis is essential following every derepression, it must be a metabolically unstable protein. Inorganic phosphate appears to be required as corepressor for its synthesis. / J. molecular Biol. *8*, 431 (1964) / –Sch. [Rd 140/327 IE]

The size of the binding site of messenger RNA on ribosomes was determined by *M. Takanami* and *G. Zuber* by degrading polyribosomes containing the synthetic messenger poly(uridylic acid) [poly-U] with ribonuclease. Since only free poly-U is degraded rapidly by the enzyme, it was to be expected that the nucleic acid in or at the 30-S subunit of the ribosome would not be attacked. The isolation and characterization of a relatively homogenous oligonucleotide fraction consisting of heptadecameric UMP suggests that sequences of about 17 bases of the messenger RNA are attached to the ribosomes. When stretched, an oligonucleotide of this type is 184 Å long and is thus just as large as the diameter of the 30-S subunit of the ribosomes (160–180 Å). Poly-U has no secondary structure; it forms polyribosomes immediately on mixing with a ribosome preparation. All other types of RNA require preincubation or denaturation. The attachment to the ribosomes therefore occurs in the stretched form. / Proc. nat. Acad. Sci. USA *51*, 834 (1964) / –Sch. [Rd 143/330 IE]

The entropy of micelle formation in aqueous potassium perfluorocaprylate has been evaluated by *K. Shinoda* and *K. Katsura*. The entropy in solutions free from foreign electrolytes can be calculated from the critical micelle concentration c^0 using Equation (a), for example, assuming that the micelle behaves as a separate phase.

$$\Delta S = \Delta H/T = -(1 + k)RT \cdot d \ln c^0/dT \quad (a)$$

c^0 is obtained from the electrical conductivity; the constant k is found by adding a foreign salt (KNO_3); c_3 is the concentration of the counter-ion belonging to the surfactant per-

T [°C]	ΔS [e.u.]	c_3 [mole/l]	ΔS [e.u.]	c_3 [mole/l]
27.5	9.9	0.028	–	–
47.5	−2.5	0.027	− 2.9	0.063
77.5	−9.6	0.033	−10.5	0.063

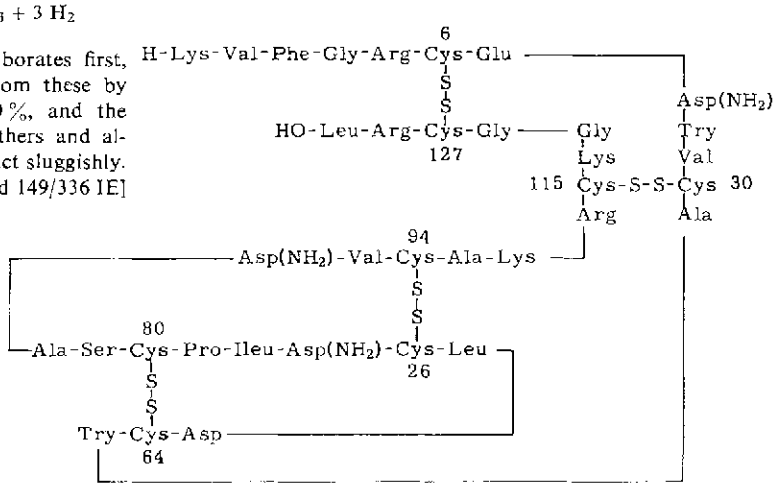
fluorocaprylate anion. / J. physic. Chem. *68*, 1568 (1964) / –Jg. [Rd 115/302 IE]

A new method for preparing organic iodides has been described by *G. F. Freeguard* and *L. H. Long*. Compounds of the type R–O–R′, where R = alkyl, substituted alkyl, R′ = H, alkyl, aryl, or another organic ligand, react with iodine in the presence of small amounts of diborane (or other boranes) to form organic iodides.

$$6\ R{-}O{-}R' + 3\ I_2 + B_2H_6 \rightarrow 6\ RI + 2\ B(OR')_3 + 3\ H_2$$

Cyclic ethers, *e.g.* epoxides, form iodinated borates first, but the iodo compounds can be liberated from these by hydrolysis. The yields are generally over 70%, and the products obtained are very pure. Diphenyl ethers and alcohols with vicinal halogen atoms generally react sluggishly. / Chem. and Ind. *1964*, 1582 / –Ma. [Rd 149/336 IE]

The positions of the disulfide bridges in lysozyme from hen's egg-white were determined by *P. Jollès*, *J. Jauregui-Adell*, and *J. Jollès* by isolating the four peptides containing cystine after hydrolysis of the native protein with pepsin and chymotrypsin. The protein molecule is a chain consisting of 129 amino acids [1] and can be represented schematically as follows:



C. R. hebd. Seances Acad. Sci. *258*, 3920 (1964) / –Sch. [Rd 144/331 IE]

Addition of sodium alkyl sulfates to water alters the chemical shift of the signals of water protons in the NMR spectrum; *J. Clifford* and *B. A. Pethica* observed that the resonance is shifted to higher field strengths. The first four methylene groups in the alkyl chain have but little influence; here the effect of the sulfate group on the structure of the water still predominates. With alkyl sulfates containing (4 + n) methylene groups, the shift is proportional to n. As soon as micelles are formed, the effect disappears, since contact between water and the alkyl chains is lost; micelles produce the same shifts as an equivalent number of free sulfate groups. The results can be interpreted by assuming that the dissolved alkyl chains break hydrogen bridges. / Trans. Faraday Soc. *60*, 1483 (1964) / –Hz. [Rd 111/298 IE]

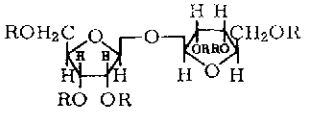
Ion-pair formation in aqueous solutions was detected by *H. Lee* and *J. K. Wilmshurst* using Raman spectroscopy. Degenerate natural vibrations of nitrates, sulfates, carbonates, perchlorates, and ammonium salts are resolved at high concentrations. It is thought that the ion-pairs which can be observed in this fashion share one molecule of water between the anion and cation in the first hydration shell. Attention is called to the difference between the high "spectroscopic" and low "kinetic" concentration of ion-pairs, which is due to the fact that the time of observation involved in vibrational spectroscopy is of the order of 10^{-12} sec. / Austral. J. Chem. *17*, 943 (1964) / –Hz. [Rd 109/296 IE]

The formation of negative ions in alkali halide vapors has been investigated by *H. Ehinghaus* using mass spectrometry. Ions of the form $M^{\ominus}$, $X^{\odot}$, $MX^{\ominus}$, and $M_2X^{\odot}$ were found, where M = Li, Na, K, and Cs and X = F, Cl, Br, and I. Some of the ions are formed from dimers M_2X_2. The results of the measurements were used to evaluate the electron affinities of the alkali metal atoms; the values obtained lie around 0.5 eV and agree well with those obtained by quantum-mechanical calculations. The electron affinities of the MX molecules were calculated to be 1.1–1.5 eV, but these values are to be considered as minima. / Z. Naturforsch. *19a*, 727 (1964) / –Hz. [Rd 114/301 IE]

A protein as the product of a regulator gene was isolated by *A. Garen* and *N. Otsuji*. A protein which is absent in mutants of *Escherichia coli* effecting constitutive synthesis of alkaline phosphatase, but which is present in a wild strain whose enzyme is repressed by phosphate was identified by electrophoresis and isolated by precipitation with ammonium sulfate and repeated chromatography on DEAE-cellulose. The amino-acid composition of the protein was determined. Its biosynthesis is dictated by one of the three genes which regulate the alkaline phosphatase, *viz.* the R2b locus. Like the phosphatase, it is subject to genetic regulation, and is therefore not the repressor as such, though it is probably essential for formation of the latter. / J. molecular Biol. *8*, 841 (1964) / –Sch. [Rd 141/328 IE]

β-Galactosidase subunits have no enzymatic activity, as *S. Lederberg*, *B. Rotman*, and *V. Lederberg* found from estimations of individual enzyme molecules on active ribosomes. In non-induced *E. coli* cells, there is one molecule of β-galactosidase for 4×10^7 ribosomes, *i.e.* less than one molecule per 100 cells. Molecules with intermediate activity could not be detected; the subunits or enzyme fragments are therefore enzymatically inactive. Galactosidase antibodies double the activity bound to ribosomes in experiments *in vitro*, but do not affect the activity of the free enzyme. The antibody becomes attached to an allosteric center on the enzyme and appears to form a model for the hypothetical protein which produces the active enzyme from inactive β-galactosidase *in vivo* by altering the conformation of the latter. / J. biol. Chemistry *239*, 54 (1964) / –Sch. [Rd 65/353 IE]

A new diriboside synthesis developed by *J. A. Zderic* has led to the first preparation of crystalline β-D-ribofuranosyl-β-D-ribofuranoside *(1b)*. 1-*O*-Acetyl-2,3,5-tri-*O*-benzoyl-β-D-ribofuranoside was treated with boron trifluoride etherate in benzene to give *(1a)*. Removal of the benzoyl group with sodium



(1a) R = CO-C_6H_5
(1b) R = H

methoxide in methanol and recrystallization from ethanol afforded *(1b)*, m.p. 158–160 °C, $[\alpha]_D = -102°$ (c = 0.47 in water). The β,β′-configuration was proved by NMR spectroscopy. / Experientia (Basel) *20*, 48 (1964) / –Re. [Rd 133/320 IE]

[1] *P. Jollès*, Angew. Chem. *76*, 20 (1964); Angew. Chem. internat. Edit. *3*, 28 (1964).

Justus von Liebig in eigenen Zeugnissen und solchen seiner Zeitgenossen (Justus von Liebig in his own Memoirs and those of his Contemporaries). Edited by *Hertha von Dechend*, with a foreword by *W. Hartner*. Verlag Chemie, Weinheim/Bergstrasse, 2nd revised edition, 1963. 159 pp., 4 plates, DM 14.80 (about $ 3.75).

Much has been written about *Liebig* in the past, and numerous are the works in which his correspondence with certain of his contemporaries such as *Berzelius*, *Merck*, *Mohr*, *Reuning*, *Schönbein*, or his friend *Wöhler* has appeared in print. Like so many eminent figures who ardently defended that which was recognized as right, during his lifetime he had not only admirers but also sworn adversaries; it therefore speaks highly of *Liebig*'s fascinating personality that, in the ninety years which have elapsed since his death, contributions have continually appeared dealing with his life or certain of his ideas and achievements. The present book, issued by the Frankfurt Institute for the History of Natural Sciences and first published in 1953 by the Giessen Society of the Liebig Museum to commemorate the 150th anniversary of *Liebig's* birth, is a further proof that "he who has once been seriously involved with him will never escape him". The book opens with *Liebig*'s autobiographical notes, first published in 1926 by *E. Esselhorn*; the main section, arranged in chronological order, consists of his discourses on scientific, personal, or political questions alongside comparison with the opinions of his friends or adversaries. From the discourses and discussions, there thus ensues a very impressive picture of the personality of this scientist and of the period in which he lived. This is better suited to following *Liebig*'s pathway than a biographical presentation which is always influenced by the temperament of its author.

W. Ruske [NB 217/96 IE]

Zonenschmelzen (Zone Melting). By *H. Schildknecht*. Monograph No. 75 of "Angewandte Chemie" and "Chemie-Ingenieur-Technik". Verlag Chemie, GmbH., Weinheim/Bergstraße, 1964. 1st Edit., XII + 226 pp., 220 figs., 29 tables, linen, DM 26.– (about $ 8.50) [*].

Although originally developed for the purification of semiconductors because of the high demands placed upon their purity, the technique of zone melting has also earned an important status within the past few years in preparative inorganic and organic chemistry. Not unimportant in this connection is the fact that this process can frequently be applied to separate mixtures even of chemically related compounds with good success and yields without requiring chemical transformations. Once a suitable apparatus is available, the main advantage of the method, namely its low demand of man-hours, is fully accrued.

In the present monograph, the author has given a concise and very comprehensive review of the process of zone melting and its applications.

The fundamentals of the subject are dealt with in a general section. The liquid-solid phase equilibrium, eutectic systems, and the formation of solid-solutions are described, and the behavior of these systems on zone melting is discussed in pregnant but justifiably terse terms. The author intentionally does not place too much emphasis on a mathematical analysis of the phenomenon of zone melting in the various systems; instead, he restricts his treatment to the most important formulae, and in keeping with this general policy, allots only a qualitative treatment to a few complicated cases. In the second instrumentation section, apparatus for zone melting and the various methods of heating and cooling are described. This section will provide many a valuable suggestion especially to the organic chemist engaged in preparative work.

In the third specialized section, the author goes into the subject of the purification by zone melting of semiconductor elements and compounds, of metals, and of organic, aromatic and aliphatic compounds, *etc.* The relatively extensive treatment of organic compounds here – about half of this section – is not surprising considering that the author himself is a prominent worker in this field who has published a number of important fundamental articles on the subject and has contributed significantly to the applications of zone melting, *e.g.* for the isolation of natural products. In addition, the importance which this separatory procedure has attained for the preparation of organic compounds and the possibilities which are still open for extending its use in this direction are impressively revealed.

The monograph is written in a clear and lucid style and from its content and organization is directed primarily towards the practical chemist.

Anyone who desires to learn about this elegant purification technique is advised to acquire this book. Even those who are already working in this field will find the volume to be profitable reading.

In conclusion, it should be pointed out that an extensive literature coverage (360 references) and author index are provided to facilitate research into specialized literature on this topic.

Th. Renner [NB 318/156 IE]

Die coulometrische Analyse (Coulometric Analysis). By *K. Abresch* and *I. Claassen*. Monograph No. 71 of "Angewandte Chemie" and "Chemie-Ingenieur-Technik". Verlag Chemie GmbH., Weinheim/Bergstraße 1961. 1st Edit., 228 pp., numerous illustrs., paperback, DM 24.– (about $ 6.00).

The significant advances that have been made within recent times in electrochemical analytical procedures thanks to electronics have only partially been recorded in German scientific literature. It is therefore all the more welcome that the present volume has appeared to fill a gap in one branch of this discipline.

No exceptionally great knowledge of theoretical principles is required in order to understand coulometric analysis. The method is based solely upon Faraday's laws, and the only prerequisites for determining the end points are knowledge of the Nernst equation for an electrode potential and some familiarity with the treatment of transport processes. Accordingly, this book concentrates upon the technical execution of the various procedures and gives illustrations with practical examples which at the same time indicate the limits of detection and the accuracy of the method. An extensive table is given in which almost all of the procedures developed to date are listed. The book is thus an excellent source of information for anyone who wishes to solve a special analytical problem using this technique. The text is easy to read and orderly arranged, so that the book can be warmly recommended to the experimenting analyst.

H. Gerischer [NB 314/172 IE]

Medizin und Chemie, Vol. VII (Medicine and Chemistry). Essays from the medical-chemical research laboratories of Farbenfabriken Bayer AG. Verlag Chemie, Weinheim/Bergstr. 1963. 1st Edit., 822 pp., 122 illustr., 135 tables, 12 color plates, half-leather, DM 45.– (about $ 11.50).

The new (VIIth) volume of the series "Medizin und Chemie" has been published for the centenary of Farbenfabriken Bayer AG and dedicated to the memory of *Fritz Mietzsch*. The scientific contributions are arranged according to their content in 10 groups following a survey of the history of Farbenfabriken Bayer, especially of the pharmaceutical division

[*] An English edition will be published jointly by Verlag Chemie and Academic Press in 1965.

founded 75 years ago after the discovery of phenacetin. The first group, "Pharmacology", is the most extensive. A substantial part of the papers report on drugs with effects on the nervous system. Other contributions include the application of the Mann-Whitney test to the examination of pharmacological activities. In the field of chemotherapy, reports are given on thiochromes with schistomicidal activity and 8-hydroxyquinoline derivatives with activity against *Trypanosoma cruzi* infections. A series of articles deals with the production, properties, and activities of semisynthetic penicillins, *e.g.* the preparation of 6-aminopenicillanic acid by enzymatic cleavage of penicillin G. In the salicyl anilide series, parallelism between cestocidal activity and the uncoupling of oxidative phosphorylation was observed. One of the contributions of the virus research group describes the cultivation of the foot-and-mouth-disease virus in kidney-cell cultures for obtaining antigen. Three contributions are concerned with the synthesis of ethyleneiminoquinones, their toxicity and effect on tumor cells. Chemical papers on a new vitamin A synthesis and a determination of the vitamin B_{12} components in injectable liver extract follow. The 47 contributions provide a clear picture of the range and intensity of research in the laboratories of Bayer's pharmaceutical division. Several contributions not only describe special results, but also sketch the current status of the knowledge and problems of the fields concerned, so that they offer information to a wider circle of interested scientists.

M. Kiese [NB 190/83 IE]

Advances in Inorganic Chemistry and Radiochemistry, Vol. 5. Edited by *H. J. Emeléus* and *A. G. Sharpe*. Academic Press Inc., New York 1963. 1st Edit., IX + 429 pp., numerous illustrs. and tables, linen, $ 14.50.

The book "Modern Aspects of Inorganic Chemistry" by *H. J. Emeléus* and *J. S. Anderson* published for the first time in 1938 was received with great enthusiasm by professional colleagues, research chemists, and even by students, for it gave short pregnant summaries of various special fields of the then current research in inorganic chemistry, called attention to deficiencies and probable errors, and provided numerous directives and incentives. It is clear that this undertaking, which was started under the influence of the youthful zeal and dedication of the main author, would surpass his capacities as the extent of his non-scientific duties increased. The only alternative available for him was to act as editor of a series of monographs in which prominent research chemists would report on the newest developments in their particular fields. It was with this background that the series on "Advances in Inorganic Chemistry and Radiochemistry" was commenced in 1959; the fifth volume of the series has now appeared. In the first five years of its existence, the series has achieved high recognition, and it is probably nowhere lacking in institutes dealing with problems of inorganic chemistry or in the libraries of academic teachers and research workers associated with the fields discussed.

It is perhaps seemly, now that 39 articles covering about 2000 pages of text have appeared, to give a critical survey of the complete work. By applying a loose classification, eleven monographs on the chemistry of non-metals, six on the chemistry of complexes, three on organometallic compounds, three on structural chemistry, eight on nuclear chemistry and radiochemistry, three on physical inorganic chemistry, and five on inorganic systems in unusual states (fused oxides, gaseous hydroxides, *etc.*) can be differentiated; naturally there are often no sharp distinctions between the individual groups of topics. Striking omissions include discourses on systems and structures of metals and alloys, the chemistry of semiconductors, and the inert gases. These lapses will certainly be compensated in later volumes.

There are a few factors which have an unfavorable influence on the quality of the series. For example, there is generally an interim of two years between compilation of the manuscripts and the appearance of the printed volumes, and articles on rapidly advancing subjects give the impression of being outdated despite the insertion of important addenda during proof - reading. Again, the editor may perhaps not always have been able to secure the services of the most knowledgeable experts or at least of the most gifted authors on certain subjects for the "Advances"; there are pronounced differences in the quality of the individual monographs. It detracts from the homogeneity of the work that the editor has tended to allow the authors to describe their fields from their own viewpoint and has handled the articles with magnanimous tolerance: nomenclature, physical symbols, *etc.* often vary from monograph to monograph. Furthermore, restriction of the pages allocated to each monograph to approximately 50 sometimes incites the authors to communicate only superficial or abridged information on their fields. The expert soon recognizes that such monographs cannot be complete, while on the other hand, those who wish to become acquainted with only the main themes of a specialized field are shied off by the maze of abundant and disordered information. In effect, therefore, the "Advances in Inorganic Chemistry and Radiochemistry" are not essentially different from review journals. The hope that the "Modern Aspects of Inorganic Chemistry" would evolve into a promising 3000-page textbook of specialized inorganic chemistry in the "Advances" series seems as far from fulfillment as that of the timely appearance of updated – or at least only three years outdated – volumes of Gmelin's Handbook. It appears as if we shall probably have to forbear any survey over the whole of modern inorganic chemistry, even only in broad outline, and no one is spared the task of undertaking strenuous literature searches for information on more limited research topics.

The principle benefit of the "Advances" is to be culled from their use for preparing lecture series on specialized subjects and for preliminary literature work for commencement in new fields. Careful perusal of the articles will call so many gaps, discrepancies, and parallels in our knowledge to the attention of the reader that many may feel inclined to start off their own research studies at such points.

Volume 5 of "Advances in Inorganic Chemistry and Radiochemistry" contains eight monographs: 1. "The Stabilization of Oxidation States of the Transition Metals" (40 pp., 77 references) by *R. S. Nyholm* and *M. L. Tobe*, an article written with fluent (too fluent?) a style; 2. "Oxides and Oxyfluorides of the Halogens" (49 pp., 211 refs.), in which *M. Schmeisser* and *K. Brändle* have incorporated numerous unpublished results from their own and other research into a chapter on classical preparative chemistry – [here inclusion of the compounds O_3ClOF and O_2NOF in the treatment would have been desirable; moreover, the krypto-ionic approach adopted, whereby compounds such as $ClONO_2$ ("chloronitrate", which has a Cl–O bond) or $ClNO_2$ ("nitryl chloride", which has an N–Cl bond) are written simply as $ClNO_3$ and NO_2Cl, is somewhat confusing]; 3. "The Chemistry of Gallium" (44 pp., 310 refs.,) in which *N. N. Greenwood* describes unusual chemical properties of this element, but principally its adducts with halides; 4. "Chemical Effects of Nuclear Activation in Gases and Liquids" (80 pp., 349 refs.) by *J. G. Campbell*, for those interested in radiochemistry; 5. "Gaseous Hydroxides", where *O. Glemser* and *H. G. Wendlandt* give a supreme description of hydroxides of Li, Na, Be, B, Al, Si, Zn, Mo, and W in the gas phase at high temperatures (up to 2000 °C); 6. "The Borazines" (47 pp., 197 refs.) by *E. K. Mellon* and *J. J. Lagowski*, where about 200 derivatives of the borazole ring system [the nomenclature preferred by these authors, viz. "borazines", is just as trivial as the name "borazoles" and is not derived systematically] are described, stressing the differences between the aromatic system of benzene and that of borazole; opinions are expressed which appear to be derived more from studies of the pertinent literature and from theoretical estimations than from the authors' own experimental work; 7. "Decaborane-14 and its Derivatives" (39 pp., 88 refs.) by *M. F. Hawthorne* is a stimulating and informative chapter, whose length for the description of a

single compound shows the enormous development of boron hydride chemistry; and finally 8. "The Structure and Reactivity of Organophosphorus Compounds" (52 pp., 192 refs.) by *R. F. Hudson*, which ought to interest the organic chemist more than the inorganic or organometallic chemist.

Without wishing to depreciate the value of the other contributions, the reviewer finds that the treatises by *Schmeisser*, *Glemser*, and *Hawthorne* will prove to be most the fruitful reading for the inorganic chemist, for whom the series is actually intended. The quality of this fifth volume is not only in the same high class as that of its predecessors, but it can compete favorably with the best of them.

A few errors might be quoted in conclusion. Page 43, line 3: O_4F_2 is not an oxide; page 51: read $Cl_3Ti\ Cl^{\delta-}$ and $ClO-Cl^{\delta+}$ instead of Cl_3Ti-Cl^- and $ClO-Cl^-$; page 63: the rearrangement equilibrium $O_2NNO_2 \rightleftharpoons NO^+NO_3^-$ is incorrectly formulated; page 66, line 17: $FClO_3$ was prepared in a pure state for the first time in 1952 by *Engelbrecht* (ref. 52); *Bode* (1951) formulated his product as $FOClO_3$, but he was actually dealing with a mixture of $FClO_2$ and $FClO_3$; page 69, line 29: O_3ClF and O_3ClO^- are not isosteric; page 219, Figure 3: there should be ⊕ instead of OH; page 268, line 14: $(R-C\equiv H-NBRH)_3$ is inconceivable; page 274, line 21: potassium thiocyanate is $K^{\oplus}[\overline{N}=C=\overline{S}]^{\ominus}$, not K[CNS] (= thiofulminate); the reaction of KNCS with $\rangle BCl$ can lead only to $\rangle B\ \overline{N}=$ or $\rangle B-\overline{S}-$, never to $\rangle B\ C\equiv$ bonds.

U. Wannagat [NB 300/159 IE]

Neutronenaktivierung als analytisches Hilfsmittel (Neutron Activation as an Analytical Tool). By *Werner Schulze*, in co-operation with *W. Bock-Werthmann*. Vol. 50 of the series "Die chemische Analyse" edited by *G. Jander*. Ferdinand Enke Verlag, Stuttgart 1962. 1st Edit., X + 323 pp., 28 figs., numerous tables, linen, DM 79.-- (about $20.00).

Following a short introduction explaining the principle and modes of application of activation analysis, the authors describe the methods of producing neutrons, the nuclear reactions that can be effected by neutrons, and procedures for irradiating samples with neutrons. Further chapters deal with modes of decay, scaling methods, and the principles of radiochemical separations. The second part of the book contains important measuring data and an extensive collection (with 1010 references) of known applications of activation analysis.

Despite the vast amount of material covered, the authors have succeeded in giving a lucid representative survey of the field. The diversity of the various aspects of the subject naturally requires fuller consideration of certain topics. Thus, for example, the counting methods might have been discussed more critically in order to help users of the book to decide which method best fits his particular needs. A more intensive discussion of the precision of the analytical methods would have been useful. In addition, some corrections are necessary; for example, the activity measured for an infinitely thick sample is proportional to the specific activity, and not to the weight of the sample. Despite these slight flaws, the book can be recommended as an introduction to the methods of activation analysis. The book contains many tables and these will make it a valuable work of reference for the specialist in this field.

H. Münzel [NB 253/111 IE]

Non-stoichiometric Compounds. Edited by *L. Mandelcorn*. Academic Press, New York-London 1964. 1st Edit., xiii + 674 pp., numerous illustrations and tables, linen, $22.50.

This monograph surveys the properties of organic and inorganic compounds having slight deviations from stoichiometric proportions of their constituent atoms and of compounds having no definite connections with the laws of stoichiometry. The boundaries between these two groups are naturally not always clear-cut. The first group includes numerous inorganic oxides and chalcogenides, the second group includes inorganic addition, inclusion, and complex compounds, *e.g.* the zeolites. Organic representatives of the latter group include some molecular compounds and adducts, *e.g.* clathrates.

The book is divided up as follows. *J. M. Robertson* discusses the analysis of the structures of these compounds using X-ray diffraction methods. *H. Eyring* and *D. Henderson* consider statistical thermodynamics and the theory of absolute rates of reaction, particular attention being paid to non-stoichiometric compounds. A comprehensive survey of the lattice structures of inorganic compounds that exhibit deviations from stoichiometric composition is given by *A. D. Wadsley*. *O. M. Katz* and *E. A. Gulbransen* report on the dissolution and occlusion of gases, particularly hydrogen, in metals. A contribution by *E. C. Subbarao* is devoted to the physical properties of non-stoichiometric inorganic compounds. *R. M. Barrer* reports on iorganic inclusion complexes. The next three chapters are allotted to non-stoichiometric organic compounds, *H. M. Powell* reporting on clathrates, *L. P. C. Fetterly* on organic adducts, and *F. R. Senti* and *S. R. Erlander* on hydrates of carbon. *L. A. K. Stavely* then deals with the physical, thermodynamic, and chemical properties of organic molecular compounds in a chapter entitled "The Physics and Chemistry of Inclusion Compounds".

This book will stimulate the interest of everyone who works with non-stoichiometric compounds.

H.-J. Engell [NB 248/106 IE]

From Vital Force to Structural Formulas. By *O. T. Benfey*. Classic Researches in Organic Chemistry. Houghton Mifflin Co., Boston-New York-Atlanta-Geneva, Ill.-Dallas-Palo Alto 1964. 1st Edit., xi + 115 pp., 4 figs., paperback, $1.95.

For the young student who finds that his textbooks present only the current position of his science, this book uses narrative style to impress upon him the answer to the question how it came about that a particular structural formula was allotted to each particular compound. The approach adopted in describing this evolution which culminates in the structural formulae proposed by *Kekulé* and *Couper*, is didactically very clever: references to original publications, indications of sources of more detailed discussions – mostly articles in the Journal of Chemical Education – on particular questions for the interested reader, and the author's fluent mode of expression combine to give the beginner the impression of participating in the construction of the edifice of organic chemistry upward from the foundations that were laid by the "great" chemists. In a country like Germany, where the history of science is regarded mainly as a "hobby" for emeritus professors, it should be pointed out that the author wrote his mansucript during a sabbatical year. The book belongs to the series "Classic Researches in Organic Chemistry" edited by *H. Hart*. The idea of bringing the student of chemistry into contact with classical investigations in this way is certainly a most welcome innovation.

W. Ruske [NB 258/116 IE]

Fortschritte der Arzneimittelforschung (Advances in Drug Research) Vol. 6. Edited by *E. Jucker*. Birkhäuser Verlag, Basel-Stuttgart, 1963. 1st Edit., 423 pp,. 35 illustr., numerous tables, linen, DM 108.– (about $27.50).

Vol. 6 of this series once again contains detailed reviews on particular aspects of drug research. "Metabolism of drugs and other foreign compounds by enzymatic mechanisms" is reviewed by *J. R. Gilette* (60 pp.). The principal mechanisms for the conversion of foreign substances in the body are first described by means of instructive examples, and then the agents, either inherent in or foreign to the body, which enhance or inhibit such metabolism, are discussed (413 references).

The next review, by *R. V. Heinzelman* and *J. Szemuszkevicz*, is entitled "Recent studies in the field of indole compounds"

(76 pp.). The authors supplement the earlier reviews by *Cerletti* in Vol. 2 and *Erspamer* in Vol. 5 with discussions of the synthesis and biological activity of tryptamine derivatives, the conversion of tryptamines into β-carbolines, the enzyme-inhibiting activity of 3-(2-aminobutyl)indoles, indole compounds with ketonic and alcoholic side-chains, and indole derivatives containing sulfur. Finally, syntheses of tetrahydrobenzindole, bufotenine and uroroseine are described (218 references and numerous tables).

H. G. Leemann, K. Stich, and *M. Thomas* provide a detailed review (128 pp.) of "Physico-chemical methods in pharmaceutical chemistry. I. Spectrofluorometry". After a theoretical discussion of the basic principles of fluorometry, examples of the relationship between fluorescence and chemical constitution are discussed. The main section of the report reviews the relevant work published in about 400 journals during the period 1950–1961. The wavelengths of the exciting and fluorescent light, the detection limits, and literature references are presented in tabular form.

The "Biological activity of the terpenoids and their derivatives" is reviewed by *M. Martin-Smith* and *Towhida Khatoon*. After an introduction on classification, some terpenoids with specific activities, those used in clinical and non-clinical practice, and the role of active groups are discussed. The fate of terpenoids in the body and their side effects are briefly described (867 references).

"Neue Arzneimittel" (New drugs), by *W. Kunz*, covers in 60 pp. materials introduced since publication of the earlier reviews in Vols. 2 and 3, classified according to field of indication (365 references).

A detailed subject index again makes the volume a useful work of reference, and the numerous structural formulae substantially contribute to its usefulness. The presentation is once again excellent.

O. Schaumann [NB 221/98 IE]

Progress in the Science and Technology of the Rare Earths. Vol. 1. Edited by *LeRoy Eyring*. Pergamon Press, Oxford London-New York-Paris 1964. 1st Edit., 532 pp., numerous illustrations and tables, linen, £6.0.0 (about $16.00).

Interest in the rare earths was reawakened about 20 years ago, because these elements were found to be products from the nuclear fission of uranium, and secondly because they held promise as good models for predictions about the actinides. Furthermore, thorium had gained importance because of its use as a source of nuclear energy. During the isolation of thorium from monazite sand, several times its weight of rare earths are obtained as by-product and – as in *Auer von Welsbach*'s time – are lying in vast stock-piles until some profitable method of utilizing them is discovered. Hence industry is also now interested in extending basic research in this field. In the USA, congresses concerned exclusively with the chemistry and metallurgy of these elements are held from time to time, and in Russia, a whole institute is devoted to the study of them.

Bearing this in mind, it is understandable that the editor and publishers are planning to produce a series of monographic reports on the rare earths. This first volume covers publications which appeared between the years 1955 and 1961 and reproduces in 500 pages 16 excellent articles written by experts from six different countries. The topics dealt with range from geochemistry and the technical recovery and separation of rare earths to their alloys and organometallic compounds. One contribution gives an 85-page review of potential applications, and two other articles evaluate Russian literature in this field.

The survey volume presented here is to be followed annually by other volumes of the series, a highly useful practice that has already been adopted in some other fields. This practice may evolve into the future form of abstract literature and thus replace the classical abstract journals which threaten to become too expensive and too extensive to read.

Werner Fischer [NB 244/102 IE]

Methoden der organischen Chemie (Houben-Weyl-Müller) [Methods in Organic Chemistry], Vol. VI, Part 2: Sauerstoffverbindungen I (Oxygen Compounds). Georg Thieme Verlag, Stuttgart, 1963. 4th Edit., edited by *Eugen Müller*. xlviii + 952 pp., 4 figs., 1 portrait, 161 tables, price per volume DM 220.– (about $ 56.00).

This is the first part of the projected volumes VI/2 and VI/3 on organic oxygen compounds. Its first chapter contains methods for preparing metal alkoxides, enoxides, and phenoxides and also an appendix (20 pp.) on the most important chelates, including a section on the technically interesting technique of "oxidative coppering of azo dyes". This is followed by chapters on the preparation of organic derivatives of silicic and boric acids. It is of great advantage to the reader that terms are defined in the preliminary chapters, thus avoiding confusion and ensuring consistency throughout the book. The authors have taken the trouble to record the names of the compounds in accordance with the old and new rules of nomenclature – occasionally with references to the English names.

The procedures for preparation of the numerous compounds described are based mainly on a few fundamental chemical operations such as partial and complete solvolysis of readily available halogeno derivatives, comproportionation and disproportionation reactions, and esterification and transesterification, all of which are arranged in orderly fashion. Next come chapters that are organized in a similar manner on organic derivatives of oxyacids of nitrogen, arsenic, antimony, sulfur, and halogens, followed by chapters on the production of β-lactones and on the preparation and reactions of other lactones. The recency of the closing date for literature coverage varies; it is only in the chapter on organic boric acid derivatives that the deadline of 1962–1963 mentioned in the preface has been respected.

After careful perusal [*] of the whole volume applying highly critical standards, the reviewer considers it worthwhile to call attention to the following points.

1. The trimethylsilazadichloralane formed fromh examethyldisilazane and aluminum trichloride (p. 167/2) is apparently dimeric [cf. *M. Schmidt* and *H. Schmidbauer*, Angew. Chem. *74*, 372 (1962); Angew. Chem. internat. Edit. *1*, 327 (1962)].

2. In connection with the reaction of N_2O_5 with cycloparaffins (p. 346), the publication by *F. Asinger* [Chem. Ber. *94*, 84 (1961)] in which he corrects earlier erroneous reports should have been cited.

3. Since attention is called to the sensitivity towards light of alkyl nitrites (p. 338), it would have been useful to have gone into the preparatively important Barton reaction [J. Amer. chem. Soc. *82*, 2640 (1961)], which has proved to be of great value as a method for the synthesis of steroids. Another regrettable omission is the lack of reference to the photolysis of alkyl hypohalides among the decomposition reactions on pp. 499–500.

4. The bicyclo[2,2,1]heptane and bicyclo[2,2,2]octane systems should have been depicted uniformly throughout the whole volume in the manner shown on p. 710, which corresponds to the internationally accepted convention and which simultaneously conveys a more precise image of the structure of the molecule.

5. In addition, the steric structure of molecules has been disregarded in most formulae. It may be that the stereochemistry is unknown or uncertain in individual cases, and this is probably why references to orginal literature are given. However, when the discussion in the text is concerned with stereoisomeric compounds or reaction products, the steric relationships should be presented more clearly in the formulae. Thus, for example, it would have been better to intimate that the β,δ-dimethylsorbic acid of m.p. 67.5 °C described on p. 822 has the Δ^2-*cis*-structure.

6. The preparation of terebinic acid (p. 637) involves a photosensitized addition of isopropanol onto fumaric acid with

[*] Thanks are due to Dr. *H. D. Scharf* for his generous support in this task.

benzophenone as sensitizer. The expression "chemically sensitized" used in the book does not convey much information to the reviewer. Moreover, the publications of *G. O. Schenk* [Angew. Chem. *69*, 177 (1957)] should have been cited, for he described this addition earlier. The same applies to the photodimerization of coumarins (p. 758), for again there is no reference to *G. O. Schenck*'s work [cf. Chem. Ber. *95*, 1409 (1962)], although he discovered the relationships between the substrate, sensitizer, and sterochemistry of the photodimerized coumarins.

7. *R. Kothe* (not *Kohte*) does not deal with dehydrogenation of diols in his paper cited in footnote 5 on p. 718, but with the production of dialkyl phthalides.

8. Why is it that "Krystalle" and "krystallisieren" have been spelled with "y" throughout the book? The procedures given on pp. 491 and 806 contain the old-fashioned method of expressing quantities in "Teilen" or "Tl" (parts); these procedures can perhaps be modernized in a later edition.

On the whole, however, the book represents a magnificent feat for which the authors, the editor, and the publisher can all be equally congratulated. It succeeds in coordinating results which are strewn throughout inorganic and organic literature and in organizing them according to both methods and materials into a lucid arrangement; it will thus form an extremely useful advisor for the organic chemist engaged in preparative work. Even for a chemist who has worked for a long time in one special field, *e.g.* lactone chemistry, this volume is an extraordinarily rich treasure trove. *F. Korte* [NB 294/152 IE]

Inorganic Polymer Chemistry. By *F. G. R. Gimblett*. Butterworths & Co., Ltd., London 1963. 1st Edit., x + 452 pp., numerous illustr. and tables, linen, £4.10.0 (about $12.50).

The field of polymeric inorganic compounds has undergone an unforeseen development within the past few years. It is therefore a great credit to the author that he has devoted himself to presenting the essential features of this field in a systematic treatment. His main aim has been to approach the principles governing the formation and structure of inorganic polymers particularly from the physico-chemical standpoint and thus to afford incentives for further developments in this field. The basis for his systematic arrangement is formed by the methods for obtaining the polymers: 1. condensation reactions and 2. addition reactions. The reviewer agrees that this is the best basis for dealing with the subject, for it permits a readily surveyable systematic treatment.

In the introduction, the nature of the bonding in inorganic polymers is discussed and compared with that of the bonds in organic polymers. This is followed by a discourse on condensation processes at high temperatures (with a relatively detailed treatment of polyphosphates and metaphosphates and of silicates), and then cationic aggregation processes in aqueous and non-aqueous solutions are described. Next comes a special chapter on "Coordination Polymerization", which deals with polymers whose formation is due more or less to the tendency of a cation to coordinate, *e.g.* in the complex incorporation of Be^{2+} into a bis-1,3-diketone. The next section deals with anionic aggregation processes in aqueous solution, such as the formation of iso- and heteropolyacids, and includes a short description of the condensation of dialkylsilanediols to give silicones. The relatively few cases of addition polymerizations (S, Se, Te, and phosphorusnitrile chlorides) are then discussed. A relatively large chapter is devoted to the structures of crystalline and glass-like polymers; this deals with borides of transition elements and with nitrides (*e.g.* BN), *etc.* The phenomenon of depolymerization is also described in detail. In conclusion, the latest developments in the chemistry of inorganic polymers are presented, and a very clever selection is made from the numerous publications by *Andrianov*, for example.

The book is very easy to read and conveys the general impression that the author is well acquainted with the material and has thought it all over carefully. Its topics are stimulating and can be heartily recommended especially to those who want to start work in the field of inorganic polymers.

O. Schmitz-DuMont [NB 297/155 IE]

Einkristalle. Wachstum, Herstellung und Anwendung (Single Crystals – Growth, Production, and Use). By *A. Smakula*. Volume 14 in the series: Technische Physik in Einzeldarstellungen, edited by *W. Meissner* and *M. Näbauer*. Springer, Berlin-Göttingen-Heidelberg 1962. 1st Edit., VIII, pp. 431, 240 illustr., 160 tab., linen, DM 76.– (about $19.00).

The author has set out to give a comprehensive review of the present status of the knowledge of crystal growth and of the methods for the growth of single crystals. This intention is most welcome, since as yet there have been only few books of this kind, and important work scattered throughout the literature can be found only with difficulty.

The first part, about one-third of the book (*Aufbau und Abbau der Kristalle*), deals with the properties of crystal structural elements, crystal structure, nuclei formation, crystal growth, crystal analysis, dislocations, and theories of crystal growth. The second part, about half of the text (*Methoden der Kristallherstellung*), deals with the preparation of crystals, *i.e.* crystal growth from solution, high temperatures and their measurement and control, crystal preparation from melts, and flame-fusion, vapor-phase recrystallization, and electrolytic methods, as well as with "whiskers". The short third part (*Anwendung der Einkristalle*) is devoted to the applications and manipulation of single crystals.

The book is written simply and intelligibly, maintaining the correct balance between theoretical and empirical considerations; owing to the variety of experimental possibilities here, this approach is especially suitable for treatment of the subject. The text is illustrated with numerous flow-sheets, sketches of apparatus, and diagrams; about a quarter of the illustrations are photographs – enough to assist comprehension of the text, but not so many that the result is a "picture book". One can overlook the one or two minor points of error, for example the designation of crucible floating zone purification as "flotation" (this designation should be reserved, as has hitherto been customary, for the action of foam on solids) or the omission of a discussion on the fundamental work on zone melting by *G. Schreiber* and *R. Schubert* [Z. physik. Chem. *206*, 102 (1956)]. A book of this scope on a specific topic must naturally develop into a reference book; as such it can be thoroughly recommended to the novice or the expert, and to the physicist, chemist, or engineer alike.

G. Matz [NB 220/89 IE]

Applications of Neutron Diffraction in Chemistry, by *G. E. Bacon*. Topic 11, Vol. 1 of: International Encyclopedia of Physical Chemistry and Chemical Physics. Published by Guggenheim/Mayer/Tompkins. Pergamon Press, Oxford-London-New York-Paris 1963. First edition. xi + 141 pp., 82 illustrations, some Tables, linen, £2.2.0.

Neutron diffraction has two advantages, besides a number of disadvantages, as a method for studying the spatial arrangement of atoms in solids. Because of the irregular variation of the neutron scattering amplitude with atomic weight, it is possible to fix the positions of light atoms even in the presence of many heavy ones and to distinguish between neighboring elements. Moreover, because of the interaction between the magnetic moments of neutrons and unpaired electrons, information can be obtained on the location, orientation and magnitude of the magnetic moments in ferro-, antiferro- and ferri-magnetic materials. It is not surprising, therefore, that neutron diffraction has led to highly important results in the field of structure chemistry, and this book is an account of them. As one would expect of Dr. Bacon, it is very competently written. The theoretical and experimental background is treated only very briefly, and the reader in

search of more detailed information in this direction should turn instead to the same author's "Neutron Diffraction" (2nd Edition, 1963, Oxford); the two books overlap to some extent. The newer book is shorter, but it could easily have been made shorter still, simply by cutting down the size of many of the eighty-two figures and condensing their somewhat lengthy and repetitive legends.

J. D. Dunitz [NB 251/109 IE]

Classical Thermodynamics of Non-Electrolyte Solutions. By *H. C. van Ness*. Pergamon Press, Oxford-London-New York-Paris 1964. 1st Edit., VIII + 166 pp., 38 figs., 2 tables, linen, £2.0.0 (about $ 5.50).

On the basis of the fundamental equations of thermodynamics, a discussion is given of the thermodynamic properties of liquids, the alterations of these properties on mixing, and the partial molar quantities. Systems of equations are developed which can be used to calculate thermodynamic data from measured quantities in order to apply the former to the solution of practical problems.

As an example of the broad scope of application of the systems of equations, vapor-liquid equilibria are dealt with, in accordance with their importance for distillation, but without going into the theory of distillation. The author restricts his discussion to simple systems at low pressures. After studying the monograph, the reader should be in a position to acquaint himself easily with the thermodynamics of multicomponent systems.

The presentation of the subject matter is terse and abstract, and the equations derived are only rarely illustrated in the text or in graphic presentations by practical examples. In consequence, the book will probably not be easy to read for the practical experimenter. However, anyone who enjoys grappling with the formal and logical skeleton of thermodynamics will be amply rewarded for perusal of this book.

U. Schindewolf [NB 305/164 IE]

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Cyclic Compounds as Configurational Models for Stereoregular Polymers

BY DR. M. FARINA, DR. M. PERALDO, AND PROF. DR. G. NATTA
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It is possible to draw analogies between linear polymers and cyclic compounds. Stereochemical considerations developed in this connection led to the recognition of new aspects of importance for the systematic classification of both classes of compounds; for example, asymmetric structures can be predicted which had hitherto never been suspected. – The concept of "diasteric centers" is introduced, and the definition of an "asymmetric center" is expressed in more general terms.

Determination of the crystal structure of many stereoregular polymers has led to an independent formulation of the principles for configurational and conformational analysis of polymers with respect to other types of organic compounds [1].

This approach is possible because linear polymers can be considered essentially as monodimensional molecules, *i.e.* the order necessary for a crystalline structure to develop is determined in one dimension by the succession rules existing within the macromolecule, In addition, the configurational sign (D or L) often loses its meaning; instead, the relationship between the configurations (no matter how defined) of atoms belonging to the same macromolecular chain becomes important.

In this paper, a method is outlined for considering polymeric structures from a configurational point of view. An attempt is made to point out analogies between macromolecules and the low molecular-weight molecules usually considered in classical organic stereochemistry. In particular, some analogies between the configurational properties of linear macromolecules and those of cyclic compounds are described.

1. Polymeric Chains, Their Lengths, and Cyclic Models

Studies of the configurational properties of polymers are remarkably simplified by considering polymeric chains of infinite length [2]; from several points of view, this extrapolation seems justified and useful. Various parameters in macromolecular chemistry, such as melting and transition points [3a] depend asymptotically on the molecular weight, *i.e.* above certain molecular weights their value is constant and practically equal to that of a polymer of infinite chain length. The configurational properties of polymers also exhibit this asymptotic dependence on molecular weight, as shown below.

The tertiary carbon atoms in an ideal isotactic polymer of infinite length derived from a vinyl monomer cannot be considered as asymmetric [2]. An isotactic vinyl polymer chain of finite length with identical end groups is usually considered as a *meso*-form, having two sequences of atoms with opposite configurations (DDD...DDLL...LLL). In reality, there is no sharp transition in the central region, since each asymmetric atom differs from the preceding one and becomes less asymmetric the nearer it is to the center of the molecule ($D_1D_2D_3 \ldots D_{n/2}L_{n/2} \ldots L_3L_2L_1$). The data reported in the literature concerning the influence exerted by the length of a substituent on the optical activity of an asymmetric atom show that such influence diminishes rapidly and that the molar optical activity soon tends to constant values (possibly zero).

This is illustrated in Figure 1, where Curve I represents schematically the situation occurring in compounds of the tartaric acid type (*meso*-forms with only two asymmetric atoms), Curve II represents that of a *meso*-compound having four or more similar asymmetric atoms, and Curve III refers to an isotactic vinyl polymer. Here the major portion of the macromolecule has no measurable asymmetry and can therefore be described by the model of infinite length (Curve IV).

The model of infinite length may be conveniently replaced by a cyclic model, if the concept of an unlimited chain is taken instead of that of an infinite chain.

A line closed on itself, in particular a circumference, has the property in common with an infinite straight line of being unlimited. The straight line is infinite and unlimited (in one dimension), while a circumference is a finite though unlimited figure. Analogous remarks apply to a segmented line

[1] *G. Natta* and *P. Corradini*, Suppl. Nuovo Cimento [10] *15*, 9 (1960); Chim. e Ind. *45*, 299 (1963).

[2] *G. Natta*, *P. Pino*, and *G. Mazzanti*, Gazz. chim. ital. *87*, 528 (1957).

[3a] *P. J. Flory*: Principles of Polymer Chemistry. Cornell University Press, Ithaca, N.Y., 1953, p. 571.

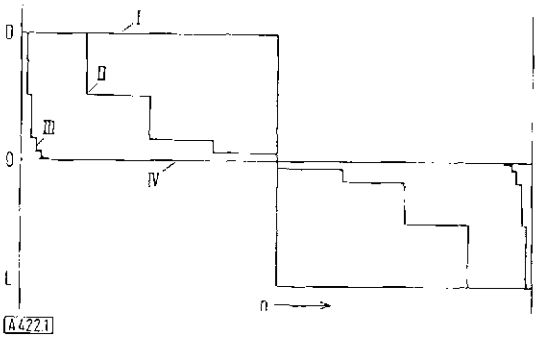

Fig. 1. Schematic representation of the asymmetry of each asymmetric atom in *meso*-tartaric acid (I), in a *meso*-compound with several homo-substituted atoms (II), in an isotactic polymer with equal terminal groups (III), and in an isotactic polymer of infinite length (IV).

Abscissa: number of carbon atoms.
Ordinate: asymmetric character

with an infinite number of segments and to a polygon. On this basis, it is possible, to use a cyclic model to describe and to make predictions about polymers.

The concept of a polymer as an unlimited structure without end groups has recently also been developed by other authors: "In a strict sence, only a macrocyclic compound is a real polymer" [4]. Only a cyclic polymer can consist exclusively of one type of structural unit; a linear polymer of finite length always contains end groups with a structure different from those in the chain. For linear polymers, the monomeric units are all the same only when the chains are of infinite length.

Analogies between the physical properties of cyclic compounds and those of linear polymers can be observed only when the cycles are large enough. For instance, it has long been known that macrocyclic hydrocarbons crystallize in long straight segments similar to linear hydrocarbons [5]. It can also be expected that cyclic and linear compounds, whose molecules have the same distance between subsequent folds of the chain in the crystals will have similar melting points.

It must be remembered that, although compounds consisting of small cycles differ in their physical properties from those consisting of large cycles, the configurational properties of both are the same. It thus follows that the configurational properties of linear polymers can be predicted very simply by considering cyclic structures comprising only a few structural units either equal or equivalent to those in the corresponding linear polymer.

It is interesting to note that the hypothesis of cyclic structures for polymers was long supported by a number of workers owing to the difficulty in distinguishing by chemical means between linear macromolecules and cyclic compounds – even of small size – with analogous structures [3b].

2. Types of Representation and Symmetry Elements

In order to facilitate the configurational analysis proposed, simple and consistent representations of the two series of compounds (cycles and chains) must be chosen.

We have therefore chosen a regular plane polygon for the cyclic compounds and Fischer projection formulae for the chains [6a]. Complete rotation of substituents around the bonds is admitted, so that they can be symbolized by a letter and treated in symmetry operations as spheres, unless they are asymmetric, when the mirror image of the generic substituent D is then L.

Passage from one series of compounds to the other, *i.e.* from cycles to chains and *vice versa*, involves transformation of the symmetry elements inherent in the type of representation selected and valid only from a configurational point of view. Table 1 reports the relationships existing between the symmetry elements of a cyclic model with n sides and of the corresponding polymeric chain represented according to the Fischer convention.

Table 1. Correlation among the symmetry elements of a linear polymer chain (represented according to the Fischer convention) and of its cyclic models.

Cyclic model with n sides	Fischer projection
m-fold rotational axis perpendicular to the ring	Repetition period equal to n/m
Two-fold axis in the plane of the ring	Two-fold axes normal to the projection, placed at a distance of n/2 from each other
Mirror plane in the plane of the ring [a]	Mirror plane containing the chain axis and normal to the projection [a]
Mirror plane normal to the ring (one-fold alternating axis)	Mirror planes normal to the chain axis, placed at a distance of n/2
Center of symmetry (two-fold alternating axis)	Glide plane containing the chain and perpendicular to the projection, with a period of n/2
Four-fold alternating axis	Glide plane containing the chain and perpendicular to the projection, with a period of n/4

[a] Absence of stereoisomerism in both series.

It can be observed that no independent symmetric element corresponding to the four-fold alternating axis exists in linear polymers: a cyclic model containing such an axis, can always be reduced to one half; in this case it has a center of symmetry.

The relationships indicated in Table 1 suggest that the conditions for predicting the optical activity in low molecular-weight compounds, *i.e.* the absence of alternating axes of the 1st, 2nd and 4th order [6b,7], must be modified in the case of linear macromolecules. Here, the existence of configurational enantiomorphous forms is in fact connected with the absence, in the Fischer projection, of mirror planes normal to the chain axis and of glide planes containing the chain and being perpendicular to the projection.

These conclusions complete and put into a systematic form some considerations recently made by *Arcus* [8].

[3b] See [3a], Chapter I.

[4] *W. Kern* and *R. C. Schulz* in *Houben-Weyl*: Die Methoden der organischen Chemie. Thieme, Stuttgart 1963, Vol. XIV/1, p.4.

[5] *A. Müller*, Helv. chim. Acta *16*, 155 (1933).

[6a] *G. W. Wheland*: Advanced Organic Chemistry. 3rd Edit., Wiley, New York 1960, p. 249.

[6b] See [6a], p. 211.

[7] *E. L. Eliel*: Stereochemistry of Carbon Compounds. McGraw-Hill, New York 1962, p. 7.

[8] *C. L. Arcus* in *P. B. D. de la Mare* and *W. Klyne*: Progress in Stereochemistry. Butterworths, London 1962, p. 264.

3. Models of Stereoregular Structures and "Diasteric" Centers

cis-Hexamethylcyclohexane, *cis*-1, 3, 5 - trimethylcyclohexane, and *cis*-1,4-dimethylcyclohexane are configurational models of isotactic polymers (Fig. 2); *trans*-hexamethylcyclohexane, *trans*-1,4-dimethylcyclohexane, and *trans*-tetramethylcyclobutane are models of syndiotactic polymers [*].

All the models contain at least a plane of symmetry, the *trans*-models also possess a center of symmetry or a four-fold alternating axis; correspondingly, all the polymers have symmetry planes normal to the chain, and the syndiotactic polymers also have glide planes parallel to the chain.

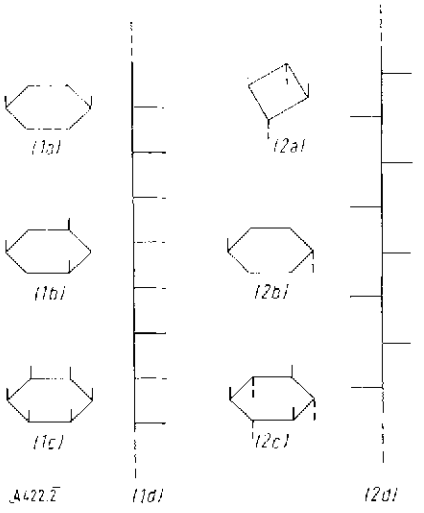

Fig. 2. Cyclic models and Fischer projection formulae of isotactic *(1)* and syndiotactic polymers *(2)*.

The tertiary carbon atoms of the models are not asymmetric: we therefore deduce that the tertiary atoms of the macromolecule are not asymmetric either. In both cases, however, these atoms are centers of diastereoisomerism in the sense that inversion of the disposition of the substituents at some of these centers leads to a different stereoisomer, which is not enantiomorphous with the original compound. This is the situation involved in the transition from *cis*- to *trans*-substituted cyclohexanes, or from isotactic to syndiotactic polymers.

These diastereoisomerism phenomena are not necessarily connected with the presence of asymmetric or pseudo-asymmetric atoms, as can be seen from the models already discussed. It is proposed that the general term "diasteric" (*i.e.* capable of diastereoisomerism) be used to describe an atom, independently of its asymmetry, when interchange of two substituents on this atom causes the molecule to be transformed into one of its diastereoisomers (non-enantiomorphous stereoisomers). It can be shown that if a diasteric carbon atom is neither asymmetric nor pseudo-asymmetric, it must necessarily be part of a cycle or of an infinite chain.

A case similar to that of the vinyl polymers is that of the di-isotactic and di-syndiotactic polymers obtained from 1,2-disubstitued ethylenes of the type CHA=CHB.

[*] For a correlation of the terms isotactic and *cis*, and syndiotactic and *trans*, see [1].

Figure 3 shows the cyclic models for all possible forms (*erythro*- and *threo*-di-isotactic, and di-syndiotactic polymers).

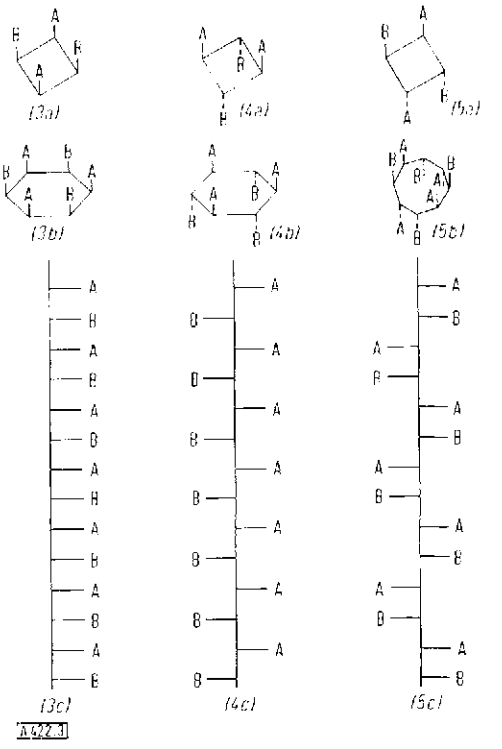

Fig. 3. Cyclic models and Fischer projection formulae of *erythro*-di-isotactic *(3)*, *threo*-di-isotactic *(4)*, and di-syndiotactic polymers *(5)*.

It must be observed that no planes of symmetry exist in the models of di-syndiotactic polymers, but only a center or a fourfold alternating axis of symmetry. In the corresponding polymer chain, in agreement with the correlations reported above, there is only a glide plane parallel to the chain axis.

Incidentally, it is noteworth that the octagonal model in Figure 3 represents the simplest cyclic compound with no asymmetric substituents which possesses an alternating axis of the fourth order as the only alternating configurational axis.

4. Optical Activity in Polymers

The symmetry of the structures just examined excludes the possibility of the existence of optical antipodes for all isotactic, syndiotactic, di-isotactic, and di-syndiotactic macromolecules. This fact is widely known [2, 8–10], but even recently some misunderstandings have arisen with regard to this question. Several classes of optically active polymers have been obtained to date: poly(propylene oxide) [11], poly-(3-methylpentene) and other polyolefins with asymmetric substituents [12], polysorbates and other substituted poly(pentadienoic

[9] *G. Natta, M. Farina*, and *M. Peraldo*, J. Polymer Sci. *43*, 289 (1960); Chim. e Ind. *42*, 255 (1960); Makromolekulare Chem. *38*, 13 (1960).

[10] *C. Schuerch*, J. Polymer Sci. *40*, 533 (1959).

[11] *C. C. Price* and *M. Osgan*, J. Amer. chem. Soc. *78*, 4787 (1956).

[12] *P. Pino, G. P. Lorenzi*, and *L. Lardicci*, J. Amer. chem. Soc. *82*, 4745 (1960).

esters) [13], polybenzofuran [14], polypentadiene [15], *etc.* Examination of the polymeric structures and cyclic models of all of these compounds reveals the absence of planes or centers of symmetry and alternating axes of the fourth order in the models, and of perpendicular planes and glide planes of symmetry parallel to the chain in the polymers.

Such optically active polymers are of two types: 1. polymers of the vinyl type with asymmetric substituents, and 2. compounds with asymmetric atoms in the main chain.

In the former type, the tertiary atoms in the chain are diasteric, but not asymmetric. Some polymers of the latter type are derived from monomers that contain asymmetric atoms, *e.g.* propylene oxide, others are obtained by asymmetric synthesis from monomers that do not contain centers of optical stereoisomerism, *e.g.* 1-monosubstituted or 1,4-disubstituted butadienes and cyclic olefins [13, 16].

Using cyclic models, it can be seen that neither cyclobutene nor 1,5-cyclooctadiene, which are models of the 1,4-polybutadiene chains, possess configurational asymmetry [*].

The recent isolation of the antipodes of *trans,trans*-1,5-cyclooctadiene by *Cope* [18] does not invalidate this observation because here the stability of the asymmetric conformations is due solely to steric hindrance to rotation around the C—C bonds.

Figure 4 shows some optically active substituted cyclobutenes and 1,5-disubstituted cyclooctadienes and the corresponding isotactic and di-isotactic polymeric forms. The active forms are of the *threo*-type if the substituents are equal, and of both the *erythro*- and *threo*-type if they are different.

Analogously, it is possible to predict the existence of enantiomorphous forms for di-isotactic polymers of cyclic olefins: of the *threo*-type *(10)* for cycloolefins with identical substituents, and of the *erythro*- *(12)* and *threo*-type *(11)* for the more general case of different substituents (cf. Fig. 5) [16]. Figure 5 also shows the corresponding polycyclic compounds: *trans-anti-trans (10b)* for cycles with identical substituents, and *trans-anti-trans* and *cis-syn-cis* for cycles with different substituents. It is difficult to find examples of these models as the polycyclic compounds represented in Figure 5 are not well known.

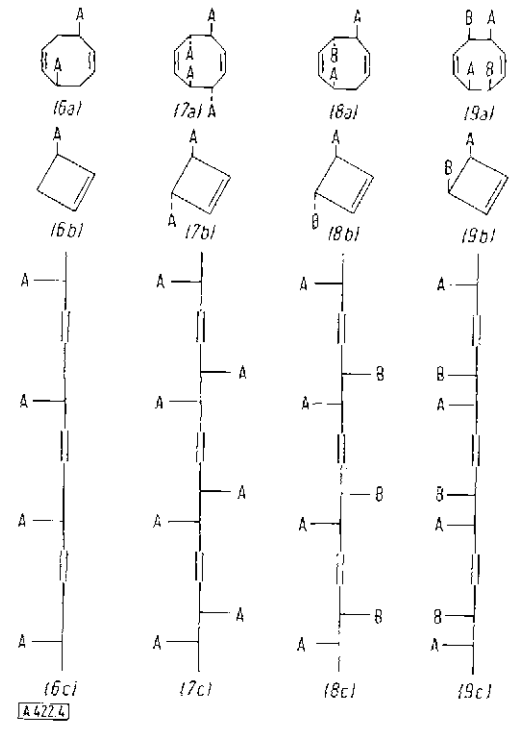

Fig. 4. Optically active polymers. Models and Fischer projection formulae of substituted 1,4-polybutadienes: isotactic 1-substituted polybutadiene *(6)*, *threo*-di-isotactic 1,4-disubstituted polybutadienes *(7)* and *(8)*, *erythro*-di-isotactic 1,4-disubstituted polybutadiene *(9)* (only one antipode is shown).

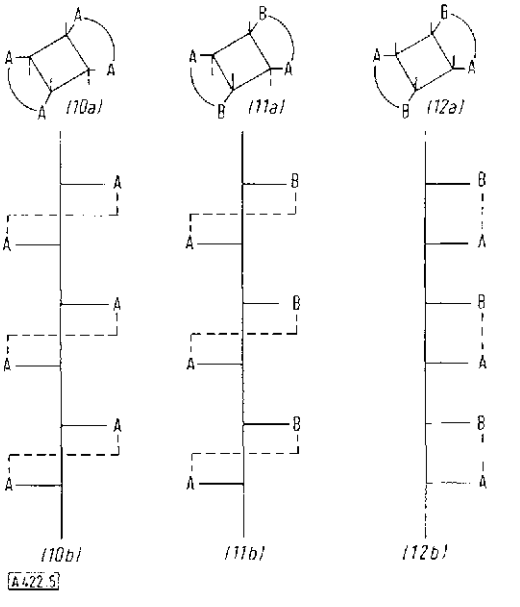

Fig. 5. Optically active polymers. Models and Fischer projection formulae of polymers of cyclic olefins: *threo*-di-isotactic polymers *(10)* and *(11)*, and *erythro*-di-isotactic polymers *(12)*.

From what has been stated so far it may seem impossible to obtain optically active polymers from α-olefins and from 1,2-disubstituted ethylenes which are not cyclic and which do not contain asymmetric groups. However, this is true only for simple repetitions, either isotactic or syndiotactic, but not if more complex structures are taken into account. Here the usefulness of the cyclic model is clearly seen. It is known that homocyclic compounds with 3, 4, or 5 atoms which are all equally substituted are optically inactive. Optically active isomers of this type exist only in the cyclohexane and

[13] *G. Natta, M. Farina, M. Peraldo*, and *M. Donati*, Chim. e Ind. *42*, 1363 (1960); *G. Natta, M. Farina*, and *M. Donati*, Makromolekulare Chem. *43*, 251 (1961).

[14] *G. Natta, M. Farina, M. Peraldo*, and *G. Bressan*, Chim. e Ind. *43*, 161 (1961); Makromolekulare Chem. *43*, 68 (1961).

[15] *G. Natta, L. Porri, A. Carbonaro*, and *G. Lugli*, Chim. e Ind. *43*, 529 (1961); *G. Natta, L. Porri*, and *S. Valenti*, Makromolekulare Chem. *67*, 225 (1963).

[16] *C. L. Arcus*, J. chem. Soc. (London) *1955*, 2801.

[*] Cyclobutene is not only a model of the polybutadiene chain but 1,4-polybutadiene can actually be obtained from it [17]. In this reaction and all other polymerizations involving ring opening, the symmetry properties of the monomer can be transferred to the polymeric chain using the rules already developed, provided that the configurational repetition period is equal to only one monomeric unit, and that there are no inversions of configuration during the polymerization.

[17] *G. Dall'Asta, G. Mazzanti, G. Natta*, and *L. Porri*, Makromolekulare Chem. *56*, 224 (1962).

[18] *A. C. Cope, C. F. Howell*, and *A. Knowles*, J. Amer. chem. Soc. *84*, 3190 (1962).

higher series, *e.g.* inositols [see Fig. 6, *(13a)*]; the corresponding polymeric chains are also asymmetric, *e.g.* *(13b)*. This type of structure can actually be obtained with six monomeric vinyl units, or with three units derived from monomers of the CHA=CHA type.

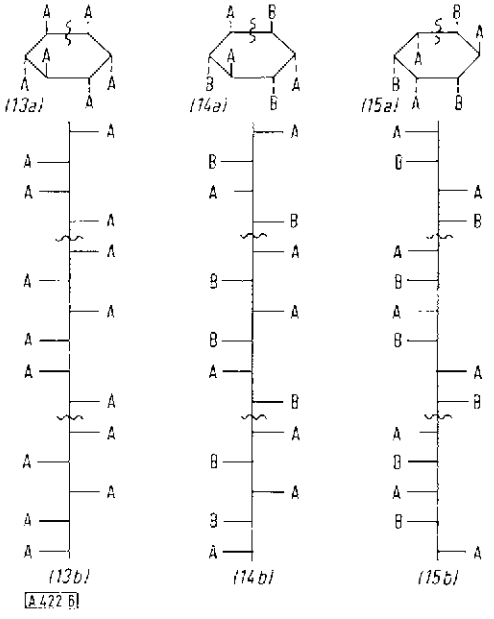

Fig. 6. Optically active polymers. Models and Fischer projection formulae of polymers derived from non-cyclic olefins.

It is also possible to foresee the existence of enantiomorphs for structures derived from monomers of the CHA=CHB type: the simplest have a configurational repetition period of three monomeric units and are represented in Figure 6. Structures *(14)* and *(15)* have an *erythro-/threo*-relationship. The *threo*-structure *(14b)* is analogous to the active structure obtained from monomers of the CHA=CHA type. It can be observed that the *erythro*-isomer *(15b)* has real asymmetry only when the *threo*-form is asymmetric and the substituents of the adjacent asymmetric atoms are different (Figs. 4, 5, and 6); otherwise, the *erythro*-form can be identified with a *meso*-form. In the optically active polymers of Fig. 6 all the tertiary carbon atoms are asymmetric, since the two chain portions bound to each atom are diastereoisomeric.

5. Polymeric Chains as Models of Cyclic Compounds

The formal analogy between polymeric substances and cyclic compounds has also contributed to the knowledge of certain classes of cyclic compounds.

Examination of the symmetry properties of the atoms in the chain of polybenzofuran shows that the definition of the asymmetric carbon atom commonly used is insufficient here [19], for each carbon atom of the polymeric chain is bonded to two substituents which are effectively identical if considered separately (Fig. 7). Such atoms seem to possess substitution of the C_{abdd} type. However, they differ substantially from the C_{abdd} atoms (*e.g.* a-CH_2-b) usually considered. In fact, in the structure under examination, the two substituents d are different

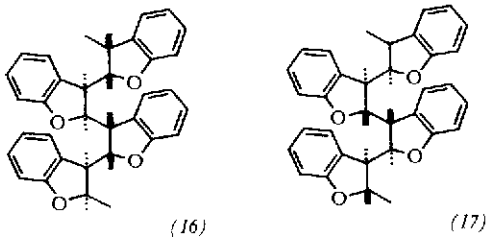

Fig. 7. Optically active polybenzofuran: *erythro*-di-isotactic *(16)* and *threo*-di-isotactic structures *(17)*.

in their relationships to the atom considered: one belongs to the same cycle (*endo*-), whercas the other belongs to a different cycle (*exo*-) [14]. This therefore leads to a more general definition of the asymmetric carbon atom: the four substituents must be different either in themselves or at least in their relationships to the atom considered (*e.g. exo*- or *endo*-) [19].

The above discussion can be applied to the analogous cyclic compounds shown in Figure 6. As already mentioned, the chemistry of homocyclic or heterocyclic saturated compounds of this type is not well developed.

We have therefore synthesized one of these models, the *trans-anti-trans-anti-trans* isomer of perhydrotriphenylene [20]. It is a crystalline compound melting at 128 °C, and its configurational and conformational structure is

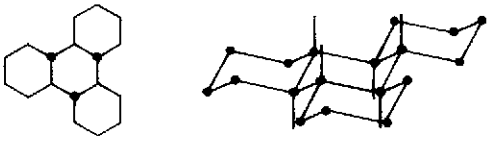

Fig. 8. Structural and conformational formulae of (*R*)-*trans-anti-trans-anti-trans*-perhydrotriphenylene.

given in Figure 8. In spite of its high symmetry (1 threefold axis and 3 two-fold axes), it does not possess alternating axes of any order, hence it exists in two enantiomorphous forms, one of which is shown in Figure 8. The symmetry properties of the tertiary atoms are analogous to those of the tertiray carbons in polybenzofuran, of which perhydrotriphenylene represents the best model available at present. By applying the rule "*endo* precedes *exo*" recently proposed [19,21] to extend the Cahn-Ingold-Prelog nomenclature [22] to this compound, one finds that the six asymmetric atoms of the isomer shown in Figure 8 have all an absolute *(R)*-configuration.

[19] *G. Natta* and *M. Farina*, Tetrahedron Letters *1963*, 703.

[20] *M. Farina*, Tetrahedron Letters *1963*, 2097.

[21] *M. Farina* and *G. Bressan*, Makromolekulare Chem. *61*, 79 (1963).

[22] *R. S. Cahn*, *C. K. Ingold*, and *V. Prelog*, Experientia *12*, 81 (1956).

6. Conclusions

The discussion of the analogies between cyclic and polymeric compounds reveals a substantial unity between classical organic and macromolecular stereochemistry. In our opinion, previous misunderstandings can easily be cleared up by adopting a cyclic model rather than by trying to extrapolate the configurational properties of macromolecular compounds from those of the low molecular-weight linear compounds.

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Structure and Crystallization Behavior of Glasses [*]

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Almost all optical and technical glasses contain micro-heterogeneities which can be seen using an electron microscope. These heterogeneous regions are shaped like small drops, and their size (20 to 500 Å) depends on the construction of the glass, on its temperature-history, on the field strength of the cations, and also on the adjacent gas atmosphere. – Preparation of valuable ultramicrocrystalline ceramics for industrial use from ordinary and photosensitive glasses involves controlled phase-separation processes and subsequent crystallization.

I. Classical Views on the Structure of Glasses

When a batch of frit is melted, the crystalline raw materials are converted into a viscous melt which solidifies to an amorphous glass on rapid supercooling. The energy absorbed in fusion is not entirely liberated on solidification. Consequently, all glasses are considerably richer in energy than the crystalline materials from which they are formed, so that the glass state is metastable. This energy reserve provides the driving force for many processes which can take place, controlled or uncontrolled, in the glass.

Various views on the fine structure of glasses have been developed during the past 40 years. *Tammann* [1] was the first to compare the structure of glass to that of liquids. Owing to the high viscosity of glass melts, the liquid structure is probably largely retained and fixed during rapid supercooling. *Goldschmidt* [2] concluded from his chemical studies of the crystalline state that the ability of a simple compound to solidify readily to a glass after fusion depends on the size ratios of the ions. An oxide or a simple compound should be capable of forming a glass only if the ratio of the radii of the cation and the anion ($r_C : r_A$) is between 0.2 and 0.4. This condition is fulfilled by the principal glass-forming compounds such as SiO_2, B_2O_3, and P_2O_5. The theory is convincingly verified by the fact that BeF_2, which also satisfies the above condition, solidifies to a glass. Furthermore, the laws governing the formation of a glass structure should be the same as those which apply in crystal chemistry.

A. Network Theory

Whereas previous attempts had been directed mainly towards the classification and explanation of the known properties of glasses by means of a theory of the structure of glasses, *Zachariasen*'s hypothesis (1932) [3], which was confirmed by the X-ray investigations of *Warren* in 1933 [4], brought about a revolutionary advance. For the first time it became possible, to a limited extent, to calculate the properties of glass from data concerning the constituent ions. The Zachariasen-Warren hypothesis is based on the principle that, for example, the $[SiO_4]$-tetrahedron is the smallest structural unit in an SiO_2-glass. It is thought, however, that these tetrahedra are not linked uniformly to give a three-dimensional network, such as that found by *Bragg* in crystalline silicates, but that they are rather linked in an irregular manner. The very large increase in the viscosity of glass melts on cooling is easily explained by the formation of an irregular infinite three-dimensional network from building units with small coordination numbers, *e.g.* C.N. = 4 in the $[SiO_4]$ tetrahedron of the SiO_2 glasses, or C.N. = 3 in the planar trigonal $[BO_3]$ group of B_2O_3 glass.

According to the network theory of *Zachariasen* [3] and *Warren* [4], the formation of low-order space lattices, *i.e.* the vitrification of the simple compounds SiO_2, B_2O_3, P_2O_5, GeO_2, As_2S_3, BeF_2, *etc.*, is governed by the following selection rules:

a) An oxide or other compound will tend to form a glass if it readily forms polyhedral groups as the smallest building units.

[*] For a more detailed treatment of this subject, see *W. Vogel*: Struktur und Kristallisationsverhalten der Gläser. Deutscher Verlag für Grundstoffindustrie, Leipzig. Expected date of publication: 1965.

[1] *G. Tammann*: Kristallisieren und Schmelzen. Barth, Leipzig 1903; Der Glaszustand. Voss, Leipzig 1933; Aggregatzustände. Voss, Leipzig, 1923, 2nd Edition.

[2] *V. M. Goldschmidt*, Skrifter norske Videnskaps.-Akad. Oslo, I. Math.-naturvidensk, Kl. *1926*, No. 8, p. 7.

[3] *W. J. Zachariasen*, J. Amer. chem. Soc. *54*, 3841 (1932).

[4] *B. E. Warren*, Z. Kristallogr., Mineralog. Petrogr. *86*, 349 (1933).

b) Not more than one corner may be shared by any two such polyhedra.

c) An anion, *e.g.* O^{2-}, S^{2-}, or F^-, must not be linked to more than two central atoms of polyhedra. Thus the anions form bridges between pairs of polyhedra in all simple glasses.

d) The number of corners of a polyhedron must be less than six.

e) At least three corners of a polyhedron must be linked to adjacent polyhedra *via* anion bridges.

If large cations are incorporated (*e.g.* by fusing SiO_2 together with Na_2O or CaO) into simple glasses which obey the selection rules, the bridges will be broken. The anion, introduced with the large cation, will then occupy the free corner of one of the two separated tetrahedra, while the large cation will be accommodated in the enlarged cavity resulting from rupture of the network. Rupture of the network and incorporation of the large cations should occur in a random manner. This leads to continuous changes in the properties of glasses.

Zachariasen further classified all the cations capable of participating in glass formation into three groups:

a) Network formers such as Si, B, P, Ge, As, and Be (as BeF_2) mostly having coordination numbers of 3 or 4.

b) Network modifiers such as Na, K, Ca, and Ba, generally having coordination numbers ≥ 6.

c) Intermediate oxides with cations such as Al, Mg, Zn, Pb, Be, Nb, and Ta, generally having coordination numbers from 4 to 6.

The intermediate oxides occupy an intermediate position between the network formers and the network modifiers. In a multi-component glass, these substances can either strengthen the glass structure by forming tetrahedra (with C.N. = 4), or, acting like network modifiers, further loosen the basic structure (with C.N. = 6 to 8), depending on the composition.

The Zachariasen-Warren principle readily accounts for most of the properties of glasses, and permits prediction of these properties within certain limits. It brought about the greatest advance to date in the investigation of glass structure. Nevertheless, even this concept fails to explain certain characteristics as, for example, the discontinuities in the curves relating glass properties to composition.

A further significant advance was made by *Dietzel* [5] (1942). Whereas *Goldschmidt* considered the size-ratios as being the principal property that affects glass formation, *Dietzel* also took into account the field strengths of the ions. This enabled him to explain phenomena which cannot be explained by the Zachariasen-Warren hypothesis alone.

As the melt of a binary silicate cools, the two cations compete for the oxygen ions, trying to surround themselves with the latter in the closest possible packing. If the field strengths of the two cations are equal, separation into two phases generally takes place. If, however, the field strengths of the cations differ, the oxygen ions will arrange in the closest packing, mainly around the cation with the higher field strength. The cation with the lower field strength then becomes linked, with a higher coordination number, to the resulting anion complex (*e.g.* $[SiO_4]^{4-}$). According to *Dietzel*, compound formation and crystallization occur at a difference in field strength above $\Delta F = 0.3\ Z/a^2$ [*] while phase-separation occurs when $\Delta F = 0\ Z/a^2$; glass formation readily occurs when $\Delta F > 1.33$.

The best glass-forming substances are SiO_2, B_2O_3, and P_2O_5. However, melts of any two of these (SiO_2/P_2O_5; B_2O_3/P_2O_5) generally solidify in the crystalline form, although the Zachariasen-Warren conditions for glass formation are satisfied. This deviation from *Zachariasen*'s concept is easily explained by *Dietzel*'s results. Since the field strength of B^{3+} in $[BO_3]$ is $1.63\ Z/a^2$, that of Si^{4+} in $[SiO_4]$ is $1.57\ Z/a^2$, and that of P^{5+} in $[PO_4]$ is $2.1\ Z/a^2$, the differences in field strength are greater than $\Delta F = 0.3\ Z/a^2$, and this explains the crystalline solidification of the SiO_2/P_2O_5 and B_2O_3/P_2O_5 melts.

Phase separation should occur in the SiO_2/B_2O_3 system, when $\Delta F = 0.06\ Z/a^2$. Instead glass-formation is observed. This fact does not represent a deviation from *Dietzel*'s results, since electron-microscopic investigations have in fact shown a microphase separation in B_2O_3–SiO_2 glasses [23, 24, 35, 36]. *Dietzel*'s field-strength relationships, which enable us to assess both the stability and the number of possible compounds in melt systems, represent a significant advance of the network theory.

Similar progress has been brought about by the theories of *Smekal* [6] (1949), and *Weyl* [7] (1958). According to *Smekal*, glasses are characterized by mixed bonding. Substances with purely ionic or purely homopolar bonding are low-melting, have a low hardness and crystallize easily. On the other hand, substances with mixed bonding such as quartz, are very hard, high-melting, very viscous in the melting range, and readily solidify to form glasses after fusion. Moreover, they all exhibit conchoidal fracture.

According to *Smekal*, heteropolar bonding is accompanied by about 50 % of homopolar bonding in rock crystal, about 44 % in B_2O_3, and about 60 % in Al_2O_3. In the beryllium fluoride model-glasses first prepared by *Goldschmidt*, on the other hand, the homopolar bonding component is only about 21 % [8, 9].

Weyl's shielding theory [7] considers in particular the residual valence forces resulting from polarization and deformation. These forces are responsible for the polymerization of the coordination groups, such as $[SiO_4]$, $[BO_3]$, $[PO_4]$, and $[BeF_4]$, into irregular networks.

B. The Crystallite Theory

The development of the network hypothesis was paralleled by that of *Lebedev*'s crystallite theory [10] which was supported by X-ray investigations by *Randall*, *Rooksby*, and *Cooper* [11], and by *Valenkov* and *Poray-Koshits* [12]. The crystallite theory was originally described as the antithesis of the network hypothesis. Whereas the latter is characterized by the random

[5] *A. Dietzel*, Z. Elektrochem. angew. physik. Chem. *48*, 9 (1942); Glastechn. Ber. *22*, 212 (1948/1949).

[*] Z = valence; a = distance between ions in oxides.

[6] *A. Smekal*, Glastechn. Ber. *22*, 278 (1949).

[7] *W. A. Weyl*, Silicates Ind. *23/24*, Part I–XII, 309, 374, 458, 518, 587, 662 (1958); 36, 88, 151, 208, 267, 321 (1959).

[8] *J. D. Mackenzie*: Modern Aspects of the Vitreous State. Butterworths, London 1960.

[9] *L. Pauling*: The Nature of the Chemical Bond. Cornell University Press, Ithaca-New York 1945.

[10] *A. A. Lebedev*: Works of the State Optical Institute, Leningrad (Russian) *2*, No. 10, p. 1 (1921).

[11] *I. T. Randall, H. P. Rooksby*, and *B. S. Cooper*, Z. kristallogr., Mineralog., Petrogr. *75*, 196 (1930).

[12] *N. N. Valenkov* and *E. A. Poray-Koshits*, Z. Kristallogr., Mineralog., Petrogr. *95*, 195 (1936).

distribution of large cations in a disordered basic glass network, the crystallite theory assumes considerable ordering of the cations, owing to the existence of crystallites in the glass. According to *Lebedev* [10], glasses may be regarded as aggregates of microcrystalline structures, *e.g.* of SiO_2 and silicates in the case of silicate glasses. Even pure quartz glass is assumed to be constituted in this way.

In particular, the crystallite hypothesis explains discontinuities in the curves of properties of glass systems where the network hypothesis offers no satisfactory interpretation. In this manner, for example, *Tudorovskaya* [13] has traced the discontinuous change in the refractive index of a sodium silicate glass with increasing temperature to α-β transitions of the SiO_2 crystallites.

From theoretical calculations based on X-ray diffraction patterns, *Valenkov* and *Poray-Koshits* [12] have established that the structure of a crystallite is most regular in the center, where it is practically the same as that of a crystal. The degree of order of the crystal lattice decreases towards the periphery of the crystallite. This results in the formation of a highly amorphous intermediate layer, which links all the crystallites together. The diameters of the crystallites were found to be 8 to 15 Å in most cases. These dimensions correspond to only a few unit cells, and so are very close to the limits beyond which the lattice concept is no longer valid.

Lebedev finally modified his original crystallite theory to the extent of taking the emphasis from the expression "crystallite". In his opinion, glass contains disordered as well as ordered regions in the form of definite chemical compounds. According to *Lebedev*, this concept of the glass state greatly diminishes the contradiction between the crystallite and the network theories.

II. The Development of New Structural Concepts

A. Micro-Heterogeneities in Glass

A number of authors determined the interionic distances in glass from X-ray diagrams which are generally very indistinct, and reached certain conclusions concerning the short- and the long-range order. *Hoffman* and *Statton* [14] (1955), as well as *Poray-Koshits* and *Andreyev* [15] (1959), measured the small-angle X-ray diffraction of several glasses, and established that glass is neither as homogeneous in structure as is required by the network theory, nor does ist possess such a high degree of order as the crystallite theory ascribes to it; on the contrary, it is characterized by "micro-heterogeneities". These findings agree with the results obtained previously by electron microscopy.

Thus *Slayter* [16] (1952) as well as *Prebus* and *Michener* [17] (1954) have shown, by electron microscopy, that silicate glasses contain structural inhomogeneities, the dimensions of which are by one order of magnitude greater (20 to 200 Å) than those required for the crystallites (8 to 15 Å) in the crystallite theory. *Šelyubsky* [18] (1954) and *Oberlies* [19] (1956) were the first to use the replica process in electron microscopy for the study of glass, and independently came to the same conclusion as *Slayter*, *Prebus*, and *Michener*.

In 1955, following the network theory, we began a series of systematic investigations on beryllium fluoride glasses. According to *Goldschmidt* [2], crystalline fluoroberyllates may be regarded as the crystallochemical models of crystalline silicates. A model structure is produced when two substances crystallize in the same lattice, and their ions have identical or similar radii but different charges. The model and the original then differ only in their lattice forces.

Owing to the difference in the charges of oxide and fluoride ions on the one hand, and silicon and beryllium ions on the other, the bonding forces in the BeF_2 model are only $^1/_4$ as large as those in the SiO_2 original. By virtue of the weaker bonding forces in beryllium fluoride glasses, processes of structure formation may be expected to take place in a more discernible manner.

In the course of a preliminary investigation of binary alkali beryllium fluoride glasses by physicochemical methods, opalescent turbidity was observed in composition ranges in which it was not expected. This phenomenon was first attributed to secondary or glass defects and disorders, but these could not be identified by optical microscopy or by X-ray crystallography. However, extensive electron-microscopic studies showed that the opalescent turbidity was caused by regions of phase separation in the form of droplets.

Since small drop-shaped regions with a diameter of 300 to 600 Å could be definitely detected even in model glasses which showed no Tyndall effect, it was assumed that the processes of phase separation are closely associated with the formation of the glass structure and are of general validity.

B. Factors Affecting the Dimensions of the Drop-Shaped Microphases

The presence of drop-shaped regions of phase separations was subsequently established in many different glasses, such as optical, technical, and laboratory-ware glasses, and became recognized as an essential structural feature [20–28]. These results were later confirmed by numerous electron-microscopic studies [29–40].

[13] *N. A. Tudorovskaya*: The Constitution of Glass (Russian). Acad. Sci. U.S.S.R. Press, Moscow-Leningrad 1955, pp. 190–197.

[14] *L. C. Hoffmann* and *W. O. Statton*, Nature (London) *176*, 561 (1955).

[15] *E. A. Poray-Koshits* and *N. S. Andreyev*, J. Soc. Glass Technol. *43*, 235 (1959).

[16] *G. Slayter*, Amer. ceram. Soc. Bull. *31*, 276 (1952).

[17] *A. E. Prebus* and *J. W. Michener*, Ind. Engng. Chem. *16*, 147 (1954).

[18] *W. J. Šelyubsky*, Glass and Ceramics (Russian) *11*, 19 (1954).

[19] *F. Oberlies*, Naturwissenschaften *43*, 224 (1956).

[20] *W. Vogel* and *K. Gerth*, Glastechn. Ber. *31*, 15 (1958).

[21] *W. Vogel* and *K. Gerth*, Silikattechnik *9*, 353 (1958).

[22] *W. Vogel* and *K. Gerth*, Silikattechnik *9*, 495 (1958).

[23] *W. Skatulla*, *W. Vogel*, and *H. Wessel*, Silikattechnik *9*, 51 (1958).

[24] *W. Vogel*, Silikattechnik *9*, 323 (1958).

[25] *W. Vogel*, C. R. Union Scientifique Continentale du Verre, Bruxelles *1958*, 741.

[26] *W. Vogel*, Silikattechnik *10*, 241 (1959).

Control of the microphase separation is important, *e.g.* in preventing defects during the production of glass and in the development of new types of glass. The recent manufacture of novel ceramic or semi-ceramic products from glass is based on controlled microphase separation. The following factors have so far been shown to influence the dimensions of the drop-shaped microphases in glass:

1. *The Concentration of the Principal Constituents of Glass* [20]

The phase separation taking place during cooling of a glass melt tends to form one microphase with a higher concentration of network formers, and another with a higher concentration of network modifiers, the phase with the greater surface tension forming droplets. A change in the concentration of the glass components will favor phase separation in one direction or the other. Figure 1 shows the dependence of the phase separation in the model system on concentration.

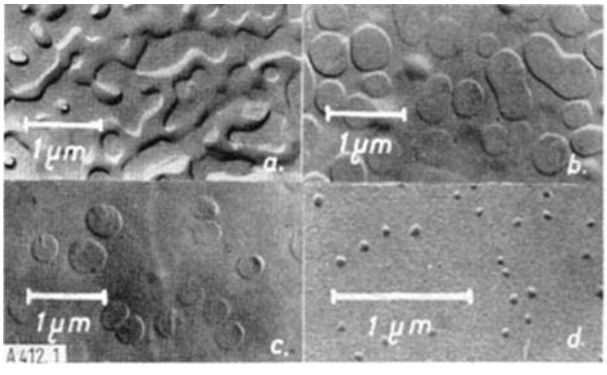

Fig. 1. The effect of concentration on phase separation in binary $LiF-BeF_2$ glasses containing (a) 15, (b) 25, (c) 35, and (d) 45 mole-% of LiF. The droplet size clearly decreases. Glass (d) does not show any Tyndall effect.

2. *Previous Thermal Treatment of the Glass* [23]

Glasses are not in a state of minimum energy, but are characterized by the fact that the order present in the melt is "frozen in". The ordering process can be reinitiated by subsequent thermal treatment. The phase separation in binary sodium borate glasses is shown in Figure 2. All processes of phase separation occurring in glasses depend on temperature; further heat-treatment results in the formation and aggregation of droplets.

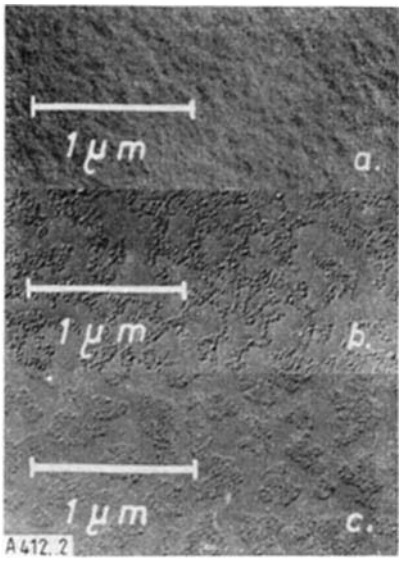

Fig. 2. The effect of temperature on phase separation in binary $Na_2O-B_2O_3$ glasses containing 16 mole-% of Na_2O. (a) Strongly quenched, (b) normally cooled, and (c) annealed at 500 °C for 2.5 hours after cooling. Formation and aggregation of droplets increase in those glasses which do not show the Tyndall effect.

3. *The Field Strength of the Cations* [20]

The field strength of the cations affects the tendency not only towards crystallization, but also towards phase separation in a glass melt. In binary alkali beryllium fluoride glasses containing *e.g.* 15 mole-% of NaF, KF, or RbF the droplet size rapidly decreases in this order.

4. *Trace Additives* [26, 28]

It has been found from experimental studies, and in particular from observations on the day-to-day operation of the melting plant of a glass works, that phenomena of phase separation are considerably altered by the presence of certain ions even in small quantities. Microphase formation may be either suppressed or increased by the deliberate introduction of trace additives. This fact is of great significance in the manufacture and development of glass. A striking practical example is shown in Figure 3, where traces of $[SO_4]^{2-}$ have caused the growth of the microphases in an originally clear optical glass to such an extent as to cause visible turbidity.

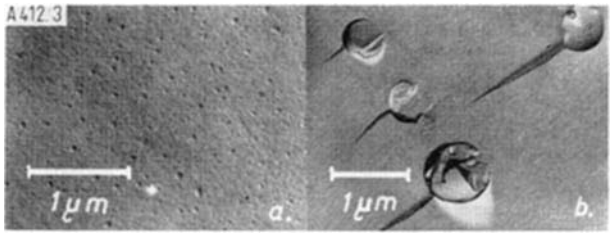

Fig. 3. The effect of trace impurities on phase separation. The microphases (a) in an optical titanium silicate glass containing fluoride are so greatly increased by traces of $[SO_4]^{2-}$ (0.01 % by weight) as to cause turbidity (b).

5. *The Surrounding Gas Atmosphere*

It has been found recently that the size of the droplets appears to be influenced by the surrounding gas atmosphere. The surface tensions of two glass phases of different compositions do not change to the same extent when the surround-

[27] *W. Vogel*: The Structure of Glass (Russian). Acad. Sci. U.S.S.R. Press, Moscow-Leningrad 1960, p. 24; Consultants Bureau, New York 1960, p. 17.

[28] *W. Vogel*, Silikattechnik *12*, 54 (1960).

[29] *F. A. Hummel*, Pittsburgh Ceramist *9*, 1 (1957).

[30] *F. A. Hummel*, *T. S. Tien*, and *K. H. Kim*, J. Amer. ceram. Soc. *42*, 81 (1959).

[31] *K. H. Kim* and *F. A. Hummel*, J. Amer. ceram. Soc. *42*, 286 (1959).

[32] *B. S. R. Sastry* and *F. A. Hummel*, J. Amer. ceram. Soc. *43*, 23 (1960).

[33] *F. A. Hummel*, *T. S. Tien*, and *K. H. Kim*, J. Amer. ceram. Soc. *43*, 192 (1960).

[34] *M. Watanabe*, *H. Nooke*, and *T. Aibo*, J. Amer. ceram. Soc. *42*, 593 (1959).

[35] *K. Kühne* and *W. Skotulla*, Silikattechnik *10*, 105 (1959).

[36] *K.T. Bondarev* and *V. A. Minakov*, Glass and Ceramics (Russian) *17*, 22 (1960).

[37] *J. Warshaw*, J. Amer. ceram. Soc. *43*, 4 (1960).

[38] *M. Navez* and *C. Sella*, C. R. hebd. Séances Acad. Sci. *251*, 4325 (1960).

[39] *M. Ohlberg*, *H. Golob*, and *C. M. Hollabaugh*, J. Amer. ceram. Soc. *45*, 1 (1962).

[40] *J. Zarzycki* and *R. Mezard*, Physics Chem. Glasses *3*, 163 (1962).

ing gas atmosphere is changed. This can result in appreciable changes in the difference between the surface tensions of the two microphases at the glass/gas interface and in acceleration of the phase separation in this region. Liquation of SiO_2-rich phases on the surfaces of the melts and the substantially greater difficulty in melting of silicate glasses with high lead contents in SO_2-rich atmospheres can evidently be attributed to processes of this kind.

C. Special Problems of the Micro-Heterogeneous Structure of Glass with Particular Reference to the Li_2O—SiO_2 System [41—45]

Figures 4a and 4b represent an example of the micro-heterogeneous structure of most glasses. They are electron micrographs of a completely clear binary lithium-silicate glass which exhibits no Tyndall effect,

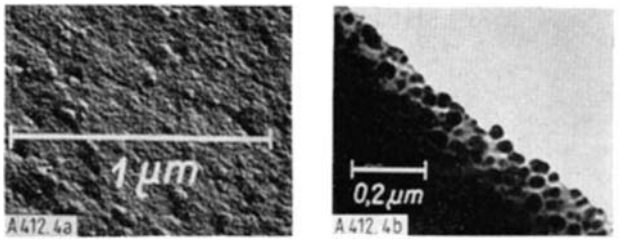

Fig. 4. Binary lithium silicate glass (28.6 mole-% of liquid Li_2O) which is completely free of Tyndall effect, showing drop-shaped microphases about 450 Å in diameter. (a): Electron micrograph obtained by the replica method, (b): direct exposure. The droplets are richer in Li_2O than their surroundings.

but Figure 4a was obtained by the replica process, and Figure 4b by direct exposure. The micro-heterogeneous structure of this glass can be clearly recognized in both cases. The detection of the drop-shaped regions of phase separation, the dependence of the droplet size on several factors, the very uniform sizes of the regions, and the crystallization behavior of the droplets (see Section III), led to the question: are the regions of phase separation due to purely random aggregations of ions, or does the phenomenon conceal some fundamental regularities, *e.g.* the formation of relatively uniform structural groups in the form of definite chemical compounds?

Analogies concerning the distribution of the network modifiers in glasses can be drawn from the distribution of the guest component in mixed crystals. *Laves* [45] has illustrated the problems of mixed crystal formation in terms of the

Fig. 5. Distribution of black and white squares according to *Laves* [45]: (a) statistical, (b) better than, and (c) worse than statistical.

[41] *W. Vogel* and *H. G. Byhan*, Z. Chem. *3*, 154 (1963).

[42] *W. Vogel, I. Hoyer*, and *H. G. Byhan*, Z. Chem. *3*, 197 (1963).

[43] *W. Vogel*, Z. Chem. *3*, 271 (1963).

[44] *W. Vogel*, Habilitations Thesis, Universität Jena, 1963.

[45] *F. Laves*, Naturwissenschaften *27*, 65 (1939).

possible distribution of 50 % black and 50 % white squares (see Figure 5). The distribution of the guest component in a mixed crystal is almost random, *i.e.* it lies between the state shown in Figure 5a and that in Figure 5c. The diagrammatic representation shows that even a random distribution permits a certain formation of aggregates and clusters.

It is suggested that the formation of clusters of ions during the cooling of a glass melt, which may be regarded as preliminary to the separation of the drop-shaped micro-heterogeneities, may quite possibly also lie within the scope of statistical considerations. In American hyalogical literature such aggregations are termed "cluster formations". In our opinion, however, these relationships can no longer be explained by statistical considerations in so far as an ion cluster begins to separate from the rest of the glass by formation of a phase boundary.

The results which we have obtained with glasses of the Li_2O—SiO_2 system may contribute to the elucidation of some unsolved problems of the structure of glass. The lithium silicate glasses, which were prepared under constant conditions, contain regions of phase separation whose dimensions greatly depend on the composition of the glass. Figure 6 may serve as an example for the series of glasses obtained.

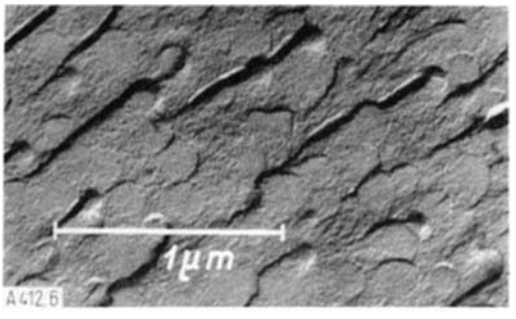

Fig. 6. Binary lithium silicate opal glass (20 mole-% of Li_2O and 80 mole-% of SiO_2). The drop-shaped phase-separation zones, the composition of which approximates that of lithium silicate, are embedded in a SiO_2 rich matrix glass.

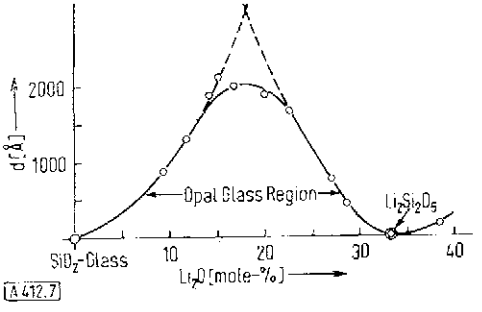

Fig. 7. Dependence of the diameter d of the droplets on the composition of the glass in the system Li_2O—SiO_2.

The entire course of phase separation is reproduced in Figure 7. While pure quartz glass has a homogeneous structure, a phase-separation maximum occurs between 0 and 33.3 mole-% of Li_2O. Glasses with compositions corresponding to the first possible compound ($Li_2Si_2O_5$, lithium disilicate) in the crystallization diagram are again homogeneous. A lithium content which exceeds the disilicate ratio (Li_2O > 33.3 mole-%) tends to cause

phase separation to increase again. However, the trend of the curve leads us to assume that the droplet phase is a silicate with a high Li_2O content. Since the droplet size falls to zero in the case of 33.3 mole-% of Li_2O, the glass of the droplets should tend towards the disilicate composition. The identification of the droplets as a phase with a high Li_2O content may be considered as certain.

At 1300 °C, a glass with the disilicate composition has a surface tension which is by 37.2 dyne/cm greater than that of pure SiO_2-glass. The disilicate glass must therefore take the form of droplets at this temperature [46–49].

Figure 4b also shows that regions of high Li_2O content, which are denser than the SiO_2-rich glass, stand out as dark regions in the electron microscope.

When small quantities of Li_2O (< 10 mole-%) are incorporated into quartz glass, it must be assumed that the lithium ions are randomly distributed in the $[SiO_4]$ lattice, in accordance with the network theory. When the Li_2O content is increased, however, clusters of lithium ions are formed and finally separate out as drop-shaped microphases. After the glass of the droplets has reached the disilicate composition (about 16 mole-% of Li_2O in the glass as a whole), Li_2O is preferentially incorporated into the surrounding glass phase until the latter attains the same composition as the droplet phase. This is accompanied by a decrease in the size of the droplets, until they finally disappear when the overall composition of the glass corresponds to that of the disilicate. At this point, therefore, we have again a glass with a homogeneous basic structure of evidently uniform disilicate building units, to which the network theory applies.

The same process which occurs between 0 and 33.3 mole-% of Li_2O begins to recur when the Li_2O content is increased beyond 33.3 mole-%. The continuous glass phase now consists only of disilicate, while the composition towards which the droplets tend, suddenly changes from disilicate to metasilicate.

Curves similar to those in Figure 7 have also been obtained during the investigation of other glass systems. It is therefore by no means possible to speak of a uniform structure of glass, even in the case of glasses within the same system. Both the network and the crystallite theories should be treated as limiting cases. Most glasses possess micro-heterogeneous structures. If the drop-shaped microphases had the cluster character which is statistically possible, the composition of the cluster would have to change continuously with, and in the same direction as the overall composition of the glass. According to Figure 7, however, this is not the case.

In the case of binary lithium silicate glasses with low Li_2O contents (up to 15 mole-%), the droplets which have not yet attained the disilicate composition can be dissolved out of the almost pure SiO_2 glass with dilute hydrofluoric acid (Figure 8). This is because SiO_2 glass is substantially less soluble in HF than glass containing Li_2O.

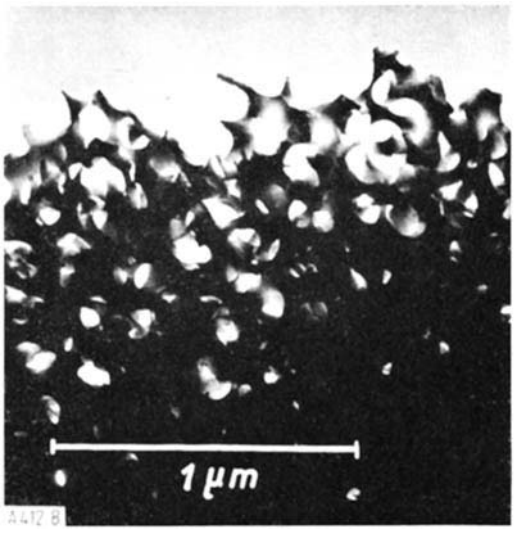

Fig. 8. Fragment of a binary lithium silicate glass (9.5 mole-% of Li_2O and 90.5 mole-% of SiO_2) after brief treatment with 2.5 % hydrofluoric acid. Direct electron micrograph. The Li_2O-rich droplet phase has been dissolved out leaving behind an almost pure SiO_2 glass phase.

At the phase-separation maximum (see Figure 7) stronger tensile forces at the spherical phase boundaries of the disilicate droplets lead to a secondary phase-separation and formation of very small metasilicate droplets within the macro-droplets. This process, which takes place even at relatively low temperatures, corresponds completely to the incongruent melting of the crystalline lithium disilicate

$$Li_2O \cdot 2\,SiO_2 \xrightarrow{1033\,^{\circ}C} \begin{cases} Li_2O \cdot SiO_2 \\ SiO_2 \end{cases}$$

Thus, in the secondary phase-separation in the macro-droplet glass-phase an SiO_2 glass phase is formed which is purer than the LiO_2-containing but SiO_2-rich surroundings of the large droplets.

Hydrofluoric acid dissolves the surroundings of these large droplets first, so that the droplets remain behind. At the same time the metasilicate is extracted from the peripbery of the large droplets. Figure 9 shows a photograph of a sample obtained by accident. The

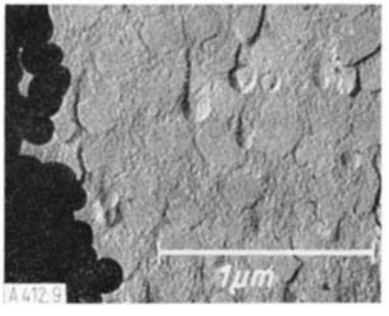

Fig. 9. Binary lithium silicate glass (20 mole-% of Li_2O and 80 mole-% of SiO_2) as in Figure 6. In the electron-microscopic preparation, the carbon replica was removed with hydrofluoric acid, and small glass splinters were etched at the same time. In contrast to the analogous etching process in Figure 8, the droplet zones (black) were isolated in this case. They were accidentally transferred to the replica film. Direct electron micrograph. The isolated droplet zones had the same dimensions as those appearing in the replica.

[46] *L. Shartsis* and *S. Spinner*, J. Res. nat. Bur. Standards *46*, 385 (1951).

[47] *L. Shartsis* and *W. Capps*, J. Amer. ceram. Soc. *35*, 169 (1952).

[48] *N. M. Parikh*, J. Amer. ceram. Soc. *41*, 18 (1958).

[49] *W. D. Kingery*, J. Amer. ceram. Soc. *42*, 6 (1959).

replica film here was loosened from the glass using dilute hydrofluoric acid. The droplets were thus isolated and collected on the replica film. Electrons directly passed through the sample during subsequent electron microscopy. The photograph can thus be regarded as the image and mirror-image of the droplets. Isolation of the droplets (see Figure 10) then allowed various investigations to be carried out on the separated microphases. These confirmed the views which have already been advanced concerning the structure of lithium silicate glasses.

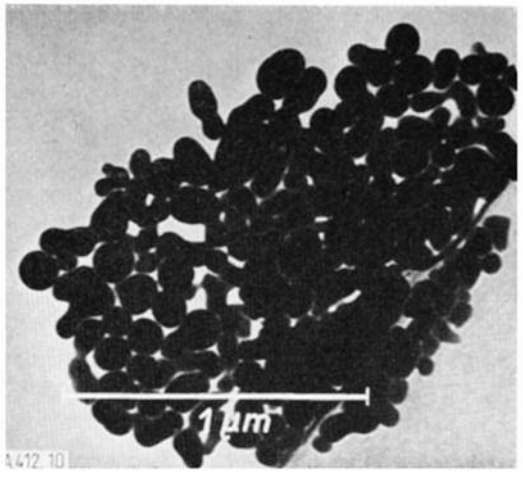

Fig. 10. Isolated droplets from a binary lithium silicate glass. Glass powder with a particle size of between 1 and 2 µm was treated with 2% hydrofluoric acid for 15 minutes and placed on a lacquer-film support. Direct electron micrograph.

Homogeneous glasses of disilicate composition are uniformly attacked by hydrofluoric acid, as is shown by the fact that the luster remains almost constant.

Secondary phase separation during the solidification of glass melts has only recently been detected [43,44] [*]. The significance of these processes for heterogeneous crystal-nucleus formation in connection with the production of novel semi-ceramic products from glass will be discussed in Section III.B. Theoretical considerations concerning the mechanism of cluster formation and phase separation [43,44] in glass will not be dealt with here.

Originally the network theory and the crystallite theory were opposing concepts. However, *Hartleif* [50] and *Dietzel* [5] were the first to discuss network modifiers as being distributed in clusters instead of being distributed statistically throughout the lattice of the parent glass. The original crystallite concept has also been modified, especially by *Lebedev*'s school in Leningrad, as indicated in particular by the work of *Markin* [51], *Yevstropev* [51], and *Poray-Koshits* [51].

Basically the new ideas on the micro-heterogeneities in connection with compound formation in glass were expressed as early as 1940 by *Botvinkin* [51,52]. The theoretical conclusions from other investigations

[*] These phenomena have also been observed in the case of glasses of alkaline earth silicates. *Toropov*, personal communication, Fourth Soviet Conference on Glass Structure (1964).

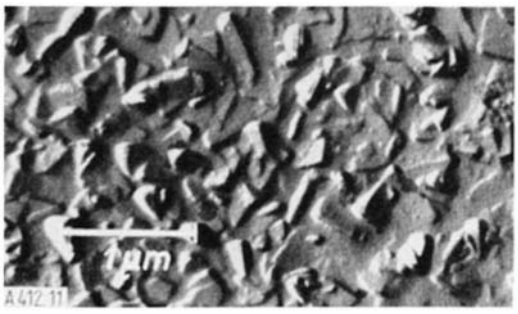

Fig. 11. Binary magnesium phosphate glass (58 mole-% of MgO and 42 mole-% of P_2O_5), which is free of Tyndall effect, with numerous crystallites of considerable dimensions. These evidently have roughly the same refractive index as the surrounding glass. This glass can serve as a model for *Lebedev*'s crystallite theory.

[53–61] point in the same direction, although the aggregates in glasses are denoted by terms such as "structones", "vitrones", "micelles", and "microphases". Disregarding border-line cases in which excellent agreement is found even with the original extreme interpretations of the network and crystallite theories (see especially Figure 11), experimental evidence for a long time did not permit acceptance of the new structural concepts. Decisive progress was essentially due to the use of electron microscopy.

III. Controlled Crystallization in Glass [44,62,63]

A. Crystallization as a Glass Defect and as a Basis for the Production of Novel Materials

The solidification of a melt to form a glass leads to a metastable state. The state with the lowest energy, *i.e.* the normal state, would result from crystallization.

The conditions which are necessary to inhibit crystallization in glass have been investigated particularly by *Tammann* [1] and his school. Crystallization represents the principal source of defects in the manufacture of glass. There are many examples, both in science and in technology, of defects, undesirable reactions, and other phenomena which lost their "horror" and acquired a new, unsuspected significance when their nature was understood, and man had learned to master them. A similar development is still in progress in the case of crystallization in glass, and this has led to the production from glass of valuable ultramicrocrystalline ceramic materials and of photosensitive

[50] *G. Hartleif*, Z. anorg. allg. Chem. *238*, 353 (1938).

[51] The Constitution of Glass (Russian). Acad. Sci. U.S.S.R. Press, Moscow-Leningrad 1955, pp. 26–29.

[52] *O. K. Botvinkin*, Westnik Akad. Nauk SSSR, Physik. Ser. *4*, 600 (1940).

[53] *E. Preston*, J. Soc. Glass Technol. *26*, 82 (1942).

[54] *H. O'Daniel*, Glastechn. Ber. *22*, 1 (1948).

[55] *M. L. Huggins*, J. Amer. ceram. Soc. *38*, 172 (1955).

[56] *W. Tilton*, J. Res. nat. Bur. Standards *65*, 117 (1961).

[57] *J. M. Stevels*, Philips techn. Rdsch. *22*, 337 (1961).

[58] *H. Salmang*, Glastechn. Ber. *35*, 6 (1962).

[59] *R. Yokota*, J. physic. Soc. Japan *5*, 354 (1960).

[60] *T. Moriya*, Bull. Tokyo Inst. Technol. Ser. B *1957*, 1.

[61] *M. Watanabe*, J. ceram. Assoc. Japan *68*, 273 (1961).

[62] *S. D. Stookey*, Glastechn. Ber. *32 K*, 1 (1959).

[63] *W. Vogel*: Symposium on Nucleation and Crystallisation in Glasses and Melts. Amer. ceram. Soc. *1962*, p. 11; Z. Chem. *2*, 261 (1962).

glasses [64]. The principal problem here is the production of minute dimensionally homogeneous crystals in the glass.

In order that crystallization may begin, crystal nuclei must be present. In this respect the transition range between the melt and the crystalline state, in which the nuclei are formed, is of special importance.

Kleber [65] and *Roy* [66] have described the conditions for nucleation. According to *Kleber*, the frequency of nucleation is chiefly determined by two factors:

a) by the actual work of nucleation, which may be defined as the energy required for the formation of a nucleus, if its building units are already present at the site of the nucleus, and

b) by the activation energy required to bring the building units of the nucleus to the site of its formation [65].

The work of nucleation is the difference between two energy terms. One term is the work consumed in the creation of a new nuclear surface by overcoming the surface tension of the surroundings. The second term is the energy liberated during the formation of the nucleus, when an amorphous region changes to the ordered state of a crystal lattice. This term is volume-dependent. If we assume that the building units of a nucleus are already present at the site of nucleation, *i.e.* that factor (b) is zero, the work of nucleation will be small and nucleation will proceed particularly readily when the stoichiometric composition of the amorphous region of nucleation corresponds to the composition of the nucleus. In this case, the difference between the two energy terms contributing to the work of nucleation is determined mainly by the energy liberated in the ordering process. The energy required to overcome the surface tension of the surroundings will be very small in this case and will be determined solely by the different degrees of order.

B. Homogeneous Nucleation

A nucleus will develop preferentially at a site where the composition of the glass corresponds to that of the nucleus. In glasses with homogeneous basic structures (according to *Zachariasen*) nucleation must follow statistical laws. This means that the first nuclei formed can develop into crystals of appreciable dimensions before the critical nucleus size is reached elsewhere, *i.e.* before other nuclei can start to grow. Thus the nuclei formed first enjoy relatively unhindered growth until the growth fronts of two crystals meet. The dimensions of the resulting crystals are rather large. Figure 12 shows a crystalline lithium silicate phase ($Li_2Si_2O_5$) formed in a binary lithium disilicate glass of homogeneous basic structure.

In a glass of micro-heterogeneous basic structure, the compositions of the microphases tend to correspond to those of definite compounds ("pre-crystalline state" [21,25,26]). On annealing, nucleation and crystallization will therefore begin preferentially in the microphases which are in a pre-crystalline state. Whether the microphase which is richer in network modifiers or that which is richer in the network former will take the form of droplets as the melt cools, depends on which has the higher surface tension. Normally the phase which is

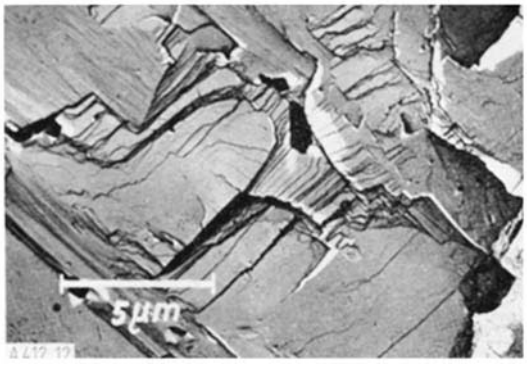

Fig. 12. Crystallization in a binary lithium silicate glass of disilicate composition (33.3 mole-% of Li_2O and 66.6 mole-% of SiO_2) and of homogeneous structure. A macroscopic $Li_2Si_2O_5$ crystal phase is formed

richer in network modifiers has a greater tendency to crystallize, since here the greatest proportion of network bridges are broken, so that the network is loosened and ions are most mobile. Theoretically, therefore, crystallization should sometimes occur preferentially in the droplet phase, and sometimes in the surrounding glass phase. Both cases have been detected. In Figure 13, nucleation and crystallization occurred in the droplet phase, and crystal growth terminated at the phase boundary, since the composition of the surrounding glass was dissimilar. In contrast, Figure 14 shows a beryllium fluoride glass in which crystallization occurred mainly in the surroundings of the droplets, so that the amorphous droplet-phase is finally embedded in a completely crystalline glass-phase.

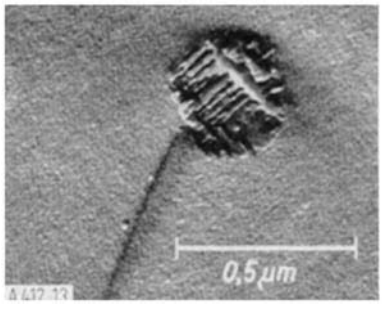

Fig. 13. Drop-shaped phase separation zones with a barbed fracture in a fluorosilicate glass. The drop-shaped glass phase is just beginning to crystallize.

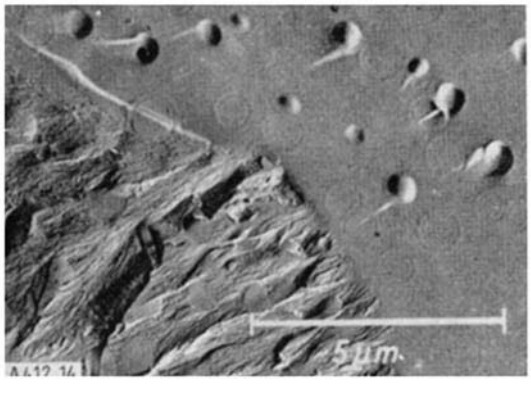

Fig. 14. Induced crystallization in a binary lithium beryllium fluoride opal glass (40 mole-% of LiF and 60 mole-% of BeF_2). The crystallization front is advancing into the two-phase glass and surrounds the vitreous, BeF_2-rich drop-shaped phase-separation zones.

[64] German Patent 962110 (1954), 1045056 (1957), 1090397 (1959), US.-Pat. 2515275 (1950), 2515937 (1950), Corning, Glassworks, Inventor: *S. D. Stooky*.

[65] *W. Kleber*, Silikattechnik *13*, 5 (1962).

Whereas the last case is of more theoretical interest, glasses in which the droplet phase has the greater tendency towards crystallization are of great practical importance. This type of crystallization is the basis of the new ultramicro-crystalline ceramic or semi-ceramic materials of the "Pyroceram" type [62–64]. In the "Pyroceram" process, the article is first formed from a clear glass which has a tendency towards phase separation; the phase separation to form droplets is developed further during the first annealing stage (at the nucleation temperature). Crystallization of the micro-phases is then brought about in the second annealing stage at a higher temperature, *i.e.* the glass is converted to an ultramicro-crystalline ceramic product.

Since all microphase separation-processes occurring in glass result in the formation of droplets with very uniform dimensions and compositions, a very large number of sites are thus created each having the same starting conditions for homogeneous nucleation and crystallization at the higher temperature. A further dimensional equalization results from the temporary interruption of crystal growth at the boundaries of the droplets (see Figure 13). The diffusion of the network modifier, which becomes more intense at high temperatures, enables the crystals formed in the droplet-shaped microphases to pass beyond the phase boundary, until growth is finally stopped by contact with other spherulites. Figure 15 shows an original "Pyroceram" glass in which this stage has been reached at a number

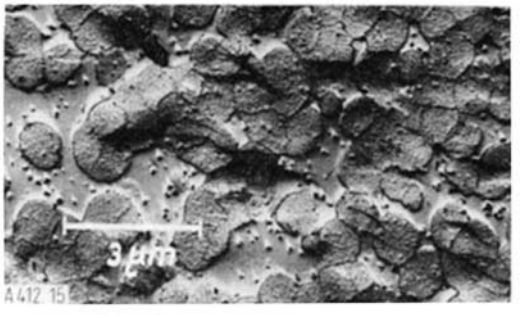

Fig. 15. "Pyroceram" glass annealed at 760 °C for 30 minutes. Crystallization has started in all the drop-shaped phase-separation zones and has already passed beyond the droplet boundary. Growth ceases when the spherical crystal-growth fronts come into contact with each other.

of points. The uniform dimensions of the crystallites are particularly noticeable. It should also be noted that the crystallization occurring after homogeneous nucleation in a glass with a homogeneous basic structure is fundamentally different from that occurring in a glass with a heterogeneous structure (compare Figure 12 to Figure 15).

C. Heterogeneous Nucleation

Whereas in homogeneous nucleation the composition of the primary nuclei does not differ from that of the main crystalline phase, in heterogeneous nucleation the crystallization of the glass is induced by foreign nuclei.

In photosensitive glasses arbitrarily chosen sections can be converted to sharply limited crystalline zones by ultraviolet irradiation followed by heating, while the surrounding parts, which have not been irradiated, are completely unaffected. In this way it is possible to produce permanent scales and designs in glass, or using a subsequent etching process, to produce miniature precision ceramic components for the electronics industry.

In general, glasses can be made photosensitive by the addition of small quantities of Cu^+, Ag^+, or Au^+ ions (ca. 0.001 mole-%), and of Ce^{3+} ions (ca. 0.01 mole-%). The mechanism of the reduction of silver by ultraviolet irradiation is assumed to be as follows:

$$Ce^{3+} \xrightarrow{h\nu} Ce^{4+} + e^-$$

$$Ag^+ + e^- \longrightarrow Ag^0$$

In the absence of Ce^{3+} ions, glasses containing Ag^+ ions are not sensitive toward ultraviolet irradiation. They are, however, sensitive toward X-rays, which have a higher energy. In this case, annealing of the glass following irradiation leads to the formation of silver nuclei and initiation of crystallization of the surrounding glass phase.

As in homogeneous nucleation, the formation of the primary silver nuclei depends on the fine structure of the parent glass. In a homogeneous silicate parent-glass, the silver ions are statistically distributed. However, this makes it difficult for the silver nuclei to reach the critical dimensions at an infinite number of sites in the glass. The fact that the critical size of the silver nuclei is attained only at relatively few sites results in the formation of rather large glass crystals. It is obvious therefore that only relatively coarse images can be obtained in glasses with homogeneous basic structures.

In micro-heterogeneous silicate glasses, the Ag^+ ions accumulate, together with other network modifiers, in the droplet phase. This results in a higher photosensitivity. The silver nuclei formed in the droplets by irradiation initiate the ordering process in the droplet phase, which by itself has a greater tendency towards crystallization. In micro-heterogeneous glasses, it is therefore possible to obtain lines down to 0.01 mm thick.

In connection with heterogeneous nucleation, brief mention must again be made of the production of new ceramic materials of the "Pyroceram" type. The formation of these materials has so far been attributed to homogeneous nucleation. However, titanium dioxide, which is only required in relatively low concentrations in the parent glass, separates out as minute droplets in the macro-droplet phase in a secondary phase-separation [44, 67]. According to their degree of order, these secondary TiO_2-rich ultramicro-droplets must already be regarded as nuclei. The same phenomenon was observed in the case of lithium silicate glasses by X-ray studies. It seems therefore correct to attribute the formation of "Pyroceram" to heterogeneous nucleation. The TiO_2 nuclei formed in the secondary phase-separation act in the same way as the Cu, Ag, or Au nuclei formed by ultraviolet irradiation in photosensitive glasses.

[66] *R. Roy*, J. Amer. ceram. Soc. *43*, 670 (1960); Symposium on Nucleation and Crystallization in Glasses and Melts. Amer. ceram. Soc. *1962*, 39.

[67] *W. Vogel*, Z. Chem. *3*, 313 (1963).

D. Epitaxy as the Process Initiating Controlled Crystallization [44,63]

The initiation of the crystallization of a glass phase by foreign nuclei suggests an epitaxial interaction, *i.e.* the oriented deposition of material on foreign nuclei with similar lattice dimensions. This assumption is the more probable, since the nature of the crystals formed in a glass by heterogeneous nucleation may be specific for the nucleus-forming substance [62]. An experiment which confirms these assumptions will now be described.

In the case of photosensitive glasses, the surfaces of Cu, Ag, or Au nuclei have an orienting effect on the structural elements of the glass which are deposited on them. Metals (*e.g.* Pt or Ir), carbon, or SiO are frequently evaporated onto the samples in the preparation of electron-microscopic replicas. If Cu, Ag, or Au are evaporated onto photosensitive glass in which controlled crystallization is induced by nuclei of the same metal, the deposition of the metal on the glass crystals should also be oriented. In Figure 16, silver was evaporated onto a sodium beryllium fluoride glass whose basic structure was very similar to that of the glass in the lower part of Figure 14, and in which crystallization had been induced by silver nuclei. As can be seen from Figure 16, the crystalline silver particles are deposited on the micro-crystalline $NaBeF_3$ phase in the form of a string of pearls.

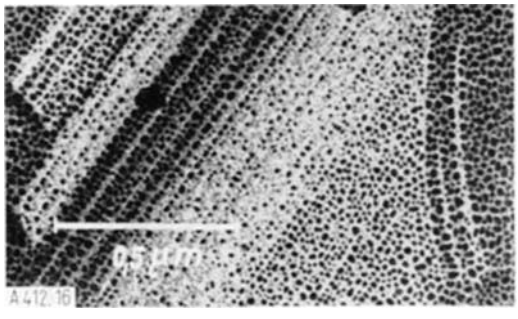

Fig. 16. The $NaBeF_3$ crystalline phase in a glass of the type shown in the lower part of Figure 14, having silver evaporated onto it, showing oriented deposition of the silver particles in the form of a string of pearls.

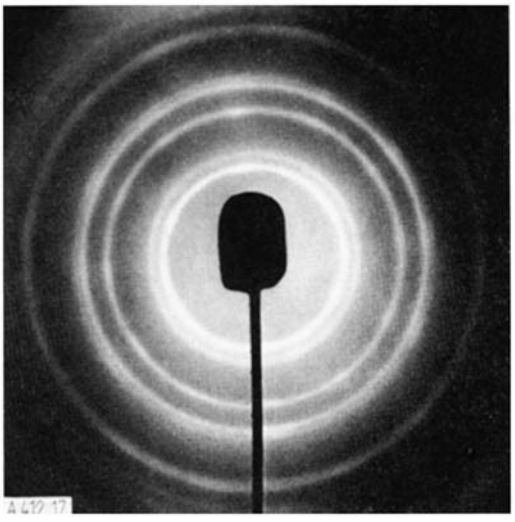

Fig. 17. Electron-diffraction diagram (direct radiation technique) of the carbon replica-film prepared after evaporation of silver (see Figure 16). The resolution of the diffraction rings into single reflections indicates the two-dimensional orientation of the silver particles on the $NaBeF_3$ crystal.

Figure 17 is an electron-diffraction photograph (direct) of the deposited silver particles. The incipient resolution of the diffraction rings into individual reflections is clearly recognizable. The two-dimensional orientation detected in this way rules out the possibility of a stepwise induction exerted on depositing silver particles, and shows that epitaxy must play a decisive part in heterogeneous nucleation in glass.

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Strained Polycyclic Systems Consisting of Three- and Four-Membered Rings

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Polycyclic compounds consisting of small rings have been known for several years. Their chemical and physical properties, which are of both theoretical and practical interest, are discussed, and methods of preparation of a few examples are illustrated. The carbon skeletons of tetrahedrane, Dewar benzene, prismane, and cubane are discussed in greater detail, since the preparation of these compounds has now been achieved, or has at least been made possible.

I. Introduction

A few years ago it was still possible to discuss the entire chemistry of three- and four-membered ring compounds in a single review [1]. Since then this field has become so large that an exhaustive treatment would require an extensive monograph.

In recent years a theoretically and preparatively interesting group of compounds has become accessible, consisting of polycyclic compounds containing only three- and/or four-membered rings. These highly strained systems form the subject of the present review. (Accord-

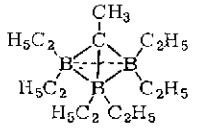
[1] *E. Vogel*, Angew. Chem. *72*, 4 (1960); Fortschr. chem. Forsch. *3*, 430 (1955).

ing to their reactions, bicyclic compounds containing condensed three-/five- and four-/five-membered rings are not included in this group.) Some notable representatives of the compounds under discussion are tetrahedrane *(1)*, tne dimer of acetylene which has not yet itself been prepared although the structure has been almost built up, prismane *(10)*, and "Dewar benzene" *(11)*, which are trimers of acetylenc, and cubane *(12)*, a tetramer of acetylene.

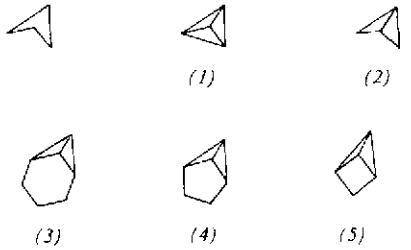
II. Classification and Properties of Strained Polycyclic Compounds [*]

A. Bicyclobutane

The most highly fused system comprising only small rings is the tetrahedron *(1)* [2]. The only structure of this type which could be hitherto synthesized contains three boron atoms (as carborane, spherical bond system) [2a].



The tetrahedron consisting of four carbon atoms is a cyclobutadiene isomer [3], but may be thought of as being formed from two molecules of acetylene [5] or by interlinking of opposite corners of a four-membered ring [4]. However, its relationship to acetylene is not purely formal, as has been shown by the most remark-



(1) *(2)* *(3)* *(4)* *(5)*

able properties of compounds with the structures *(2)* to *(5)* which are already known: the tertiary protons at the bridgehead positions, like the protons of acetylene, are acidic in character.

To explain this, it is necessary to examine the character of tne bonds in the three-membered carbon ring, which was considered as early as 1949 in a theoretical publication by *Coulson* and *Moffit* [6]. The angles between the lines joining the carbon atoms are 60 °, while those between the orbitals cannot be distorted from the tetrahedral angle (109 °) to such small values. The smallest theoretically possible angle between orbitals of carbon is 90 °, *i.e.* the angle between pure p-orbitals. Consequently, the center of gravity of the bonding electron cloud does not lie on the line joining the carbon atoms, and the resulting bonds are "bent bonds".

The most important properties of the three-membered carbon ring result from its tendency to attain the greatest possible overlap of the orbitals with resultant stabilization of the system. This is achieved:

1. by shortening of the C–C distance from the normal value of 1.540 Å to 1.524 Å,

2. by reduction of the tetrahedral valence angle (to 105 ° according to calculations by *Coulson* and *Moffit)*; this is made possible by partial change in the state of hybridization: the ring bonds assume higher p-character, and the exocyclic bonds consequently acquire higher s-character,

3. by delocalization of electrons [6] as a result of the higher p-character of the ring bonds, leading to stabilization of the entire bond system and to a kind of ring current in the plane of the three carbon atoms.

The fact that the C–C internuclear distance in the three-membered ring is reduced has been known for some time [4]. The increased p-character of the ring bonds explains why three-membered rings react with reagents which attack double bonds. It also explains the conjugative effect of three-membered rings coupled to double bond systems [7] The increased s-character of the exocyclic bonds has now been confirmed for many examples (Table 1). Recent NMR investigations by *Roberts* [7a] prove the cyclic delocalization of electrons.

The degree of hybridization of a C–H bond, a factor of interest in connection with the acidic character of the protons on the bridgehead carbon atoms in bicyclobutanes, can be measured using nuclear magnetic resonance [7b]. Natural carbon contains 1.1 % ^{13}C which has a nuclear spin $J = {}^1/_2$. The coupling of ^{13}C nuclei, present at the natural concentration in organic compounds, with the protons bonded to them can be measured by high-resolution NMR spectrography. The coupling constant (125–250 cps) depends on the disposition of the electrons in the bond, *i.e.* on the bond order. Using the coupling constants measured for a given compound, the s- and p-components of the C–H bond in question can be read off directly from a calibration curve [7b, 7c, 10]. A few values are listed in Table 1.

Since the maximum residence probability of an s-electron lies closer to the nucleus than that of a p-

[*] The formulae drawn in this section do not necessarily represent the unsubstituted compounds which in many cases have not yet been prepared, but are intended to illustrate the properties and types of compounds known.

[2] *W. N. Lipscomb*, Tetrahedron Letters *1959*, No. 18, 20.

[2a] *R. Köster* and *G. Benedikt*, Angew. Chem. *76*, 650 (1964); Angew. Chem. internat. Edit. *3*, 515 (1964); *R. Köster* and *G. W. Rotermund*, Tetrahedron Letters *1964*, 1667.

[3] *R. Criegee*, Angew. Chem. *74*, 703 (1962); Angew. Chem. internat. Edit. *1*, 519 (1962).

[4] *J. M. Conia* and *J. L. Ripoll*, Bull. Soc. chim. France *1963*, 768; *A. Wilson* and *D. Goldhamer*, J. chem. Educat. *40*, 504 (1963).

[5] *W. Weltner jr.*, J. Amer. chem. Soc. *75*, 4224 (1953).

[6] *C. A. Coulson* and *W. E. Moffit*, Philos. Mag. *40*, 1 (1949); *A. D. Walsh*, Trans. Faraday Soc. *45*, 179 (1949); *D. Peters*, Tetrahedron *19*, 1539 (1963).

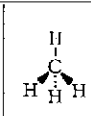
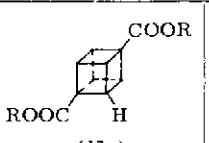
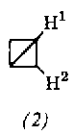
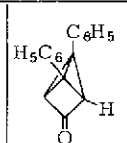
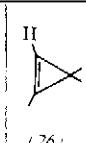
[7] *M. T. Rogers* and *J. D. Roberts*, J. Amer. chem. Soc. *68*, 843 (1946); *A. L. Goodman* and *R. H. Eastman*, ibid. *86*, 908 (1964).

[7a] *D. J. Patel*, *M. E. H. Howden*, and *J. D. Roberts*, J. Amer. chem. Soc. *85*, 3218 (1963).

[7b] *J. D. Roberts*, Angew. Chem. *75*, 20 (1963); Angew. Chem. internat. Edit. *2*, 53 (1963).

[7c] *N. Muller* and *D. E. Pritchard*, J. chem. Physics *31*, 768, 1471 (1959).

Table 1. Coupling constants and s-character of C–H bonds.

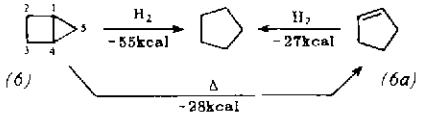
	 (sp³)			 (12a)	 (2)	 (5b)	(3)	 (26)	C≡C–H (sp)
J^{13} C–H [cps]	125 [7b]	134	161	160	1:170 2:159 [27]	190	200	220	250 [7b]
s-Character of the C–H bond [%]	25	27 [8]	32 [8]	32 [24a]		38 [31b]	40 [10]	44 [11]	50

electron, the acidity of protons increases with increasing s-character of the C–H bond. In fact, bicyclobutanes of structures *(3)* and *(4)* react [10,31] just like other substances with highly mobile hydrogen atoms. Thus, the protons on the bridgehead carbon atoms of *(3)* are exchanged for deuterium with $(H_3C)_3C{-}OD$ in the presence of $(H_3C)_3C{-}OK$ [10]. This means that the pK_a value of *(3)* is smaller than that of $(H_3C)_3C{-}OH$ ($pK_a \approx 19$).

The C–H valence-band in the infrared spectrum is shifted to short wavelengths because hybridization of the bond in such systems is altered [17a].

B. Systems Consisting of Condensed Three- and Four-Membered Rings

Unsubstituted bicyclopentane *(6)* was first prepared by *Criegee* and *Rimmelin* [12–13b]. *Criegee*'s research group also recently obtained a methylated derivative of



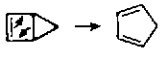
tricyclo[3,1,0,0^{2,4}]hexane *(7)* [9]. The "strain" in such systems is manifest in their reaction with double-bond reagents such as Br_2, H_2, and $Pb(OAc)_4$, which proceeds much more readily than with cyclopropane. The strain may be measured using the heat of hydrogenation.

(7a)

(7b)

Thus, hydrogenation of *(6)* to cyclopentane resulted in liberation of 55 kcal per mole of H_2, the highest heat of hydrogenation measured until that time [13b].

Therefore the heat of combustion of *(6)* must be very high too (the heat of combustion of the reaction $H_2 + {}^1/_2\,O_2 \rightarrow H_2O$ is −58 kcal/mole of H_2), with the result that the use of *(6)* as a rocket fuel has been considered in the U.S.A. By comparison the heat of hydrogenation of cyclopentene is −27 kcal/mole; the bicyclic compound is therefore spoken of as having an extra strain energy of (−55 + 27) = −28 kcal/mole, which also represents the energy for the isomerization *(6)* → *(6a)*.


(8) *(8a)*

Derivatives of the unsaturated compound *(8)* have not yet been prepared, but are postulated as intermediates in several reactions from which cyclopentadienes have been isolated [3,14]. Their high instability is due not only to the increased strain resulting from the double bond in the four-membered ring and the gain in resonance energy of a conjugated system on transition to *(8a)*, but also to the possibility of valence-bond isomerization [15], a concept which can be explained by comparing *(6)* with *(8)*. Both compounds isomerize to give five-membered rings; whereas *(6)* must be heated above 300 °C (activation energy: 45 kcal/mole [14a]), *(8)* isomerizes so readily that the five-membered ring is already formed at −78 °C. To transform *(6)* into cyclopentene, a proton must migrate, while in the case of *(8)* only a cyclic electron-displacement is required with no great change in the position of any atom. This cyclic electron-displacement is the characteristic feature of valence-bond isomerizations which are encountered with all the following compounds.

If the free corners of the two three-membered rings of *(7b)* are linked by a methylene group, quadricyclene *(9)* is obtained, a highly symmetrical compound consisting of two five-, one four-, and two three-membered rings, which was prepared independently by *Dauben*, *Hammond*, and *Prinzbach* [16]. It exhibits the

(9)

(9a)

[8] *C. S. Foote*, Tetrahedron Letters *1963*, 579.

[9] *H. H. Stechl*, Angew. Chem. *75*, 1176 (1963); Angew. Chem. internat. Edit. *2*, 743 (1963); Chem. Ber. *97*, (1964), in the press.

[10] *G. L. Closs* and *L. E. Closs*, J. Amer. chem. Soc. *85*, 2022 (1963).

[11] *G. L. Closs*, Proc. chem. Soc. (London) *1962*, 152.

[12] *R. Criegee* and *A. Rimmelin*, Chem. Ber. *90*, 414 (1957).

[13a] *A. Ludwig*, Ph. D. Thesis, Technische Hochschule Karlsruhe, 1958.

[13b] The heat of hydrogenation was measured by *R. B. Turner*, cf. J. Amer. chem. Soc. *79*, 4116 (1957).

[14] For example, *L. Skattøl*, Chem. and Ind. *1962*, 2146; *P. M. Maitlis* and *M. L. Games*, J. Amer. chem. Soc. *85*, 1887 (1963).

[14a] *S. G. Cohen* et al., J. Amer. chem. Soc. *86*, 679 (1964).

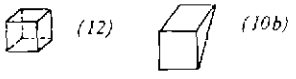
[15] *E. Vogel*, Angew. Chem. *74*, 829 (1962); Angew. Chem. internat. Edit. *2*, 1 (1963).

[16] *W. G. Dauben* and *R. L. Cargill*, Tetrahedron *15*, 197 (1961); *G. S. Hammond*, *N. J. Turro*, and *A. Fischer*, J. Amer. chem. Soc. *83*, 4674 (1961); *H. Prinzbach* and *J. Hartenstein*, Angew. Chem. *74*, 506 (1962).

typical properties of strained three-membered ring compounds, *viz.* reaction with acids, bromine, and hydrogen, as well as ready thermal isomerization to its valence-bond isomer norbornadiene *(9a)*, from which *(9)* was prepared by irradiation

Like tetrahedrane *(1)* and cubane *(12)*, a hydrocarbon prismane *(10)* containing six tertiary carbon atoms is a very interesting compound.

(10) *(11)*



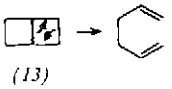
(12) *(10b)*

Since *(10)* is an isomer of "Dewar benzene" and of benzene, it is not surprising that in the first experiment in which prismane was probably an intermediate [17], only the corresponding benzene derivative could be isolated [17a].

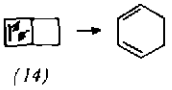
A compound closely related to prismane is the tricyclic carbohydrate *(10b)* [17b] which contains "only" one C–C linkage less than prismane.

C. The Bicyclo[2,2,0]hexane Skeleton

The simplest compound containing only four-membered rings is bicyclo[2,2,0]hexane *(13)*, which isomerizes at 200 °C (activation energy: 36 kcal/mole [14a]) to 1,5-hexadiene, a reaction corresponding to the pyrolysis of cyclobutane into two molecules of ethylene [18, 19]. Introduction of a double bond into *(13)* leads



(13)



(14)

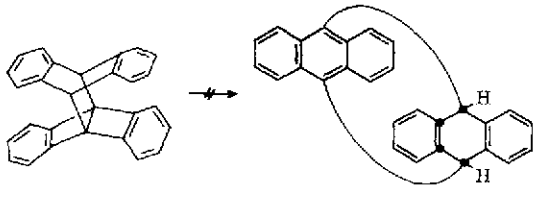
to the bicyclohexenes *(14)*, which readily undergo valence-bond isomerizations to cyclohexadienes. The first compound with a bicyclo[2,2,0]hexane structural element was isolated more than 20 years ago by *Windaus* [20], and its true structure was discussed; however it was only in 1959 that this structure was proved by *Dauben* and *Fonken* [20]. With two double bonds in *(13)* the so-called Dewar benzene, bicyclo[3,3,0]hexadiene *(11)*, is obtained. This compound does not have the benzene structure *(15)* suggested by *Dewar* (which is planar and is included in the description of benzene by the valence-bond theory) but is the non-planar molecule

(15)

formed by two cyclobutene rings with a 1,4-σ-bond. Bicyclohexadienes naturally isomerize readily to benzene derivatives, with release of the strain and liberation of the resonance energy which, being 36 kcal/mole, is so great that it is surprising that a molecule such as *(11)* can be prepared at all. Three means of stabilization of such molecules may be quoted.

1. Bracket Effect

Eschenmoser and *Vogel* [21] found with norcaradiene that an unstable structure can be stabilized if, for example, a "five-membered ring bracket" is inserted to link the two atoms between which the labile bond is situated. Meanwhile this principle was also applied to the bicyclohexane derivative *(16)*. This "Dewar benzene" derivative [22c] is so stable that it can be recovered 63 % unchanged even after 1.2 h at 360 °C, while the unsubstituted "Dewar benzene" is extremely labile [$\tau_{1/2}$ (20 °C) = 2 days] [22a].



(16) *(16a)*

The six-membered "clamp" holds the bicyclic system together. A cyclophane-type linkage of the 9,10-sp^2-hybridized valences of anthracene through the four carbon atoms indicated in *(16a)* is impossible. This agrees with the fact that the only products which are isolated on pyrolysis of *(16)* are anthracene and bianthryl.

2. Steric Hindrance

Labile structures can also be stabilized by bulky groups which would hinder each other to a greater extent in the structurally more stable isomeric molecule or which would have to move past one another in the course of isomerization of the less stable species. This effect

[17] *R. Breslow* and *P. Gal*, unpublished results; *R. Breslow* in *P. de Mayo:* Molecular Rearrangements, Part I. Interscience, New York-London 1963, pp. 243–245.

[17a] Isolation of a prismane derivative has recently been reported by *H. G. Viehe* et al., Angew. Chem. *76*, 922 (1964); Angew. Chem. internat. Edit. *3*, 755 (1964).

[17b] *D. M. Lemal* and *K. S. Shim*, J. Amer. chem. Soc. *86*, 1550 (1964).

[18] *Sh. Cremer* and *R. Srinivasan*, Tetrahedron Letters *1960*, No. 21, 24; *R. Srinivasan*, J. Amer. chem. Soc. *83*, 4923 (1961).

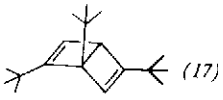
[19] *R. Srinivasan* and *S. M. E. Kellner*, J. Amer. chem. Soc. *81*, 5891 (1959).

[20] *A. Windaus, K. Dimroth*, and *W. Breywisch*, Liebigs Ann. Chem. *543*, 240 (1940); *W. G. Dauben* and *G. J. Fonken*, J. Amer. chem. Soc. *81*, 4060 (1959).

[21] *A. Eschenmoser* et al., Helv. chim. Acta *44*, 540 (1961); *46*, 2892 (1963); *E. Vogel, Th. Wiedemann, H. Kiefer*, and *W. F. Harrison*, Tetrahedron Letters *1963*, 673.

[22a] *E. E. v. Tamelen* and *S. P. Pappas*, J. Amer. chem. Soc. *85*, 3297 (1963).

played a part in the preparation of the first derivative of "Dewar benzene" by *van Tamelen* [22b].

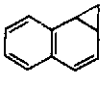


(17)

The bicyclic compound *(17)* is formed on irradiation of 1,2,4-tri-t-butylbenzene; in contrast to unsubstituted "Dewar benzene" [22a], *(17)* is perfectly stable at room temperature. The photocatalysed rearrangement is largely due to the strain produced by the three t-butyl groups in the benzene derivative. Assuming that the two sp^3-hybridized bridgehead carbon atoms in *(17)* exhibit their normal valence angles, the planes containing the two bulky groups in the bicyclic compound lie at an angle of about 55 °C to each other [4,50]. The mutual repulsion of the t-butyl groups prevents reversion of the isomerization at normal temperatures.

3. Benzene Resonance

If a benzene ring is fused to a molecule that isomerizes easily, in such a way that the ring adopts a quinonoid structure through valence-bond isomerization, *i.e.* that on cyclic electron shift the resonance energy of benzene is lost, then this molecule is rendered stable. An example is the norcaradiene system: the unsubstituted cycloheptatriene appears as a seven-membered ring, the amount of valence-bond isomeric norcaradiene present being too low to be detectable by NMR spectroscopy [7b]; on the other hand, the valence-bond isomeric benzocycloheptatriene cannot be detected in benzonorcaradiene *(17a)* [23,23a] [cf. also *(57)*].



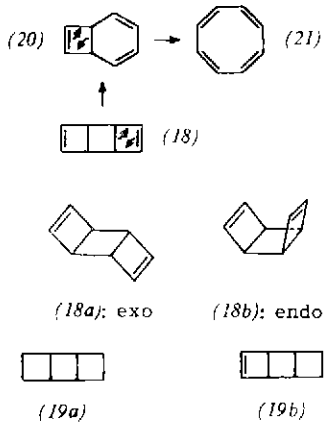
(17a)

D. The Tricyclo[4,2,0,$0^{2,5}$]octane Skeleton

Tricyclic compounds consisting of three *ortho*-condensed four-membered rings are nearly all derived from dimeric cyclobutadienes *(18)*.

Little is yet known about the saturated system *(19a)* and the mono-unsaturated system *(19b)*.

Isomerization of the dimeric cyclobutadienes *(18)* to cyclooctatetraenes proceeds *via* the bicyclo[4,2,0]octatrienes *(20)* [40,48,49,51][*], which are valence-bond isomers of cyclooctatetraene *(21)* and derivatives of which were first prepared in this manner [40,47,49]. The



tricyclic compounds can exist in the *endo*- (*syn*) or *exo*- (*anti*-) forms; representatives of both configurations have been obtained during numerous attempts to prepare cyclobutadienes.

E. Cubane

It can be seen that the *endo*-form *(18b)* is very similar to the structure of cubane *(12)* which could result from cycloaddition of the mutually opposed double bonds of the tricyclic compound. It has been calculated [5] that this cube of eight carbon atoms should be less stable by 80 kcal per mole than its isomer cyclooctatetraene. Experiments with tetraphenylcyclobutadiene readily led to a compound which was described as having the octaphenylcubane structure [24]; it was recently shown, however, to be octaphenylcyclooctatetraene [24a]. *Eaton* and *Cole* have prepared unsubstituted cubane [24b,54].

All five possible cyclobutadiene dimer structures C_8H_8 appear to have been isolated: cubane *(12)*, *exo*- and *endo*-tricyclooctadiene *(18a)* and *(18b)*, bicyclooctatriene *(20)*, and cyclooctatetraene *(21)*.

III. Synthesis of the Strained Ring Systems

The methods used for the preparation of the strained systems can be divided up into a few groups. The principles of the reactions, some of which are novel [25], are briefly discussed in the following Sections.

A. Reaction Types

α) Transannular elimination: In this reaction a new transverse C–C bond is formed in an existing ring by thermal or photolytic elimination of N_2 or CO, by elimination of HX with strong bases, or by elimination of X_2 with alkali metals.

[22b] *E. E. v. Tamelen* and *S. P. Pappas*, J. Amer. chem. Soc. *84*, 3789 (1962).

[22c] *D. E. Applequist* and *R. Searle*, J. Amer. chem. Soc. *86*, 1389 (1964).

[22d] *R. Criegee* and *F. Zanker*, Angew. Chem. *76*, 716 (1964); Angew. Chem. internat. Edit. *3*, 695 (1964).

[23] *W. v. E. Doering* and *M. J. Goldstein*, Tetrahedron *5*, 53 (1959).

[23a] *E. Vogel, D. Wendisch*, and *W. R. Roth*, Angew. Chem. *76*, 432 (1964); Angew. Chem. internat. Edit. *3*, 443 (1964).

[*] See, however, [50].

[24] *H. H. Freedman* and *D. R. Petersen*, J. Amer. chem. Soc. *84*, 2837 (1962).

[24a] *H. P. Throndsen, P. J. Wheatley*, and *H. Zeiss*, Proc. chem. Soc. (London) *1964*, 357; *G. S. Pawley, W. N. Lipscomb*, and *H. H. Freedman*, J. Amer. chem. Soc. *86*, 4725 (1964).

[24b] *P. E. Eaton* and *Th. W. Cole jr.*, J. Amer. chem. Soc. *86*, 962 (1964).

[25] *J. J. Bloomfield, R. G. Todd*, and *L. T. Takahashi*, J. org. Chemistry *28*, 1474 (1963).

β) Intramolecular carbene reaction: Here use is made of the high reactivity of carbenes which, in the absence of other coreactants, can undergo intramolecular C–H insertion or C=C addition reactions to form highly strained systems.

γ) Intramolecular photolytic reaction: Olefinic systems isomerize on absorption of light (often in the presence of a sensitizer). The isomers no longer absorb in the spectral region of the light used for irradiation.

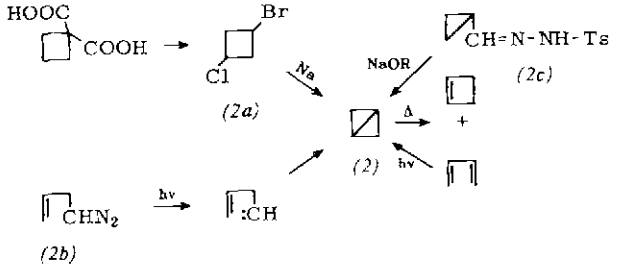
δ) Cycloaddition of highly reactive olefins: Highly activated olefins (fluoro-olefins and polycyano-olefins) undergo 1,2-additions onto double bonds even when the resulting molecules are strained. The olefins can also be activated photochemically; they then yield, in contrast to (γ), intermolecular addition compounds.

ε) Reactions of cyclobutadienes: This method is only a special case of reaction (δ) with cyclobutadiene as the reactive olefin. During attempts to prepare cyclobutadienes under the mildest possible conditions, secondary or side reactions [3] led to the formation of strained four-membered rings which are stable under the experimental conditions.

B. Examples

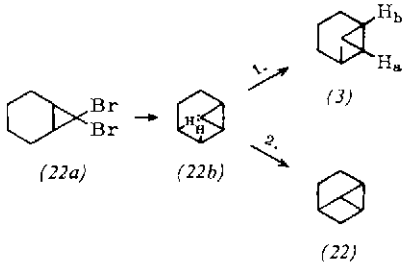
1. Bicyclobutanes

The first compound with a bicyclobutane structure was prepared in 1959 by *Wiberg* [26], who subsequently also succeeded in obtaining unsubstituted bicyclobutane *(2)* on a preparative scale from 1-bromo-3-chlorocyclobutane *(2a) via* reaction type (α) [27].



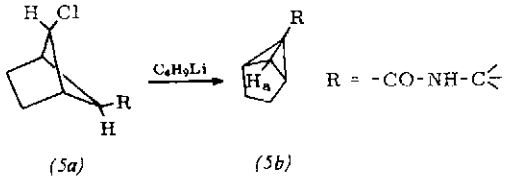
Compound *(2)* is also formed from diazobutene *(2b)* [28] *via* an intramolecular carbene addition reaction and from the tosylhydrazone *(2c) via* an intramolecular carbene insertion reaction [28a] [reaction type (β)]. Pyrolysis of *(2)* yields cyclobutene and butadiene. Under certain conditions bicyclobutane can be obtained on irradiating butadiene [28b]. This reaction is of practical importance in that, despite low yields (5 to 6 %), the bicyclic compound is produced in one step from commercially available starting material. Polymerization of *(2)* occurs readily, according to *Wiberg*, the C–C dissociation energy being so low that this compound possesses pseudo-olefinic character [26].

Carbene insertion into the C–H bond led *Moore* to the trimethylene-bridged bicyclobutane *(3)* mentioned above [29]. Elimination of bromine from the dibromide *(22a)*, which is readily available from cyclohexene and dibromocarbene, leads to the formation of a carbene *(22b)* which reacts further in two ways: insertion into the C–H bond in the α-position yields the bicyclobutane derivate *(3)* (NMR spectrum for H_a: $\tau = 8.33$; for H_b: $\tau = 8.55$ ppm); alternative insertion into the C–H bond in the β-position yields the bicyclopentane derivative *(22)* [29, 30].



As in all bicyclobutane derivatives, hydrogenation of *(3)* results in cleavage of both three-membered rings; here methylcyclohexane is formed.

By transannular elimination of HCl from the bicyclohexane derivative *(4a)*, *Meinwald* [31] prepared the bicyclobutane derivative *(4b)*, which is bridged by only two methylene groups [reaction type (α)].



The proton H_a bonded to the bicyclobutane bridgehead carbon atom is "acidic": it can be readily replaced by metal atoms, and a wide variety of groups can then be introduced by reaction with CO_2 or organic halides.

Ketocarbenes, formed by heating or photolysing diazoketone derivatives of cyclopropenes *(4c)* and *(5a)*, can react by intramolecular addition across the double bond [*cf. (2b)* → *(2)*]; compound *(4d)* [31a] is formed in 53 % yield, and when heated at 180 °C yields 3,4,5-triphenylphenol. The hydrogenation product of the tricyclic compound *(5b)* [31b] is *cis*-3,4-diphenylcyclopentanone; *(5b)* resembles the tetrahedron *(1)* more closely than any other known tricyclic compound.

[26] *K. B. Wiberg* and *R. P. Ciula*, J. Amer. chem. Soc. *81*, 5261 (1959).

[27] *K. B. Wiberg* and *G. M. Lampman*, Tetrahedron Letters *1963*, 2173.

[28] *D. L. Lemal*, *F. Menger*, and *G. W. Clark*, J. Amer. chem. Soc. *85*, 2529 (1963).

[28a] *H. M. Frey* and *I. D. R. Stevens*, Proc. chem. Soc. (London) *1964*, 144.

[28b] *R. Srinivasan*, J. Amer. chem. Soc. *85*, 4045 (1963).

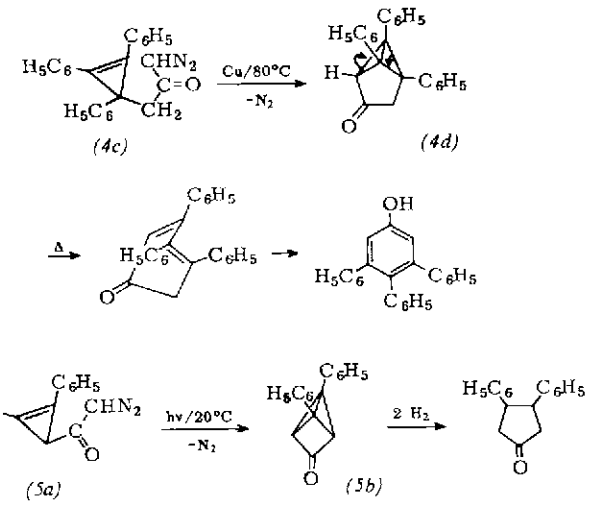
[29] *W. R. Moore*, *H. R. Ward*, and *R. F. Merrit*, J. Amer. chem. Soc. *83*, 2019 (1961).

[30] *H. C. Brown* and *H. M. Bell*, J. Amer. chem. Soc. *85*, 2324 (1963), where further references are given.

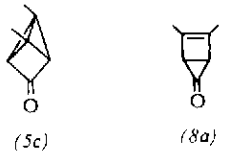
[31] *J. Meinwald*, *C. Swithenbank*, and *A. Lewis*, J. Amer. chem. Soc. *85*, 1880 (1963).

[31a] *A. Small*, J. Amer. chem. Soc. *86*, 2091 (1964).

[31b] *S. Masamune*, J. Amer. chem. Soc. *86*, 735 (1964).



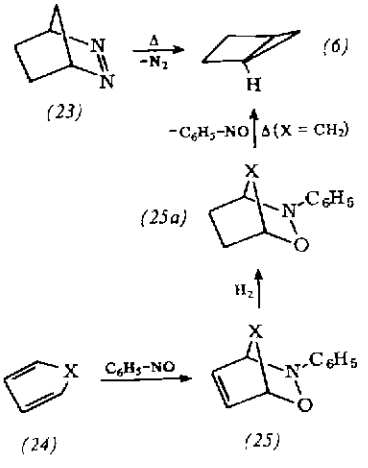
Doering and *Pomerantz* [31c] isolated *(5c)* with methyl substituents instead of phenyl substituents in 1 % yield by the same method (NMR spectrum of *(5c)*: two maxima with an intensity ratio of 3:1 at τ = 7.95 and 8.17 ppm). Hydrogenation yields *cis*- and *trans*-dimethylcyclopentanone.



According to the authors structure *(8a)* is not inconsistent with the spectral data for compounds *(5b)* and *(5c)*. From experimental observations on valence-bond isomerization of cyclobutenes ([38, 38a]; see also Section II.B), a cyclobutene of type *(8a)* containing a fused three-membered ring should isomerize readily to the dimer of cyclopentadienone *via* its monomer.

2. Systems with Bicyclopentane Groupings

Hydrocarbon *(6)* was prepared in 1957 from the bicyclic compound *(23)* by pyrolytic elimination of nitrogen [12]. However, a recent publication [32] reports its synthesis by a similar, more generally applicable



[31c] *W. v. E. Doering* and *M. Pomerantz*, Tetrahedron Letters *1964*, 961.

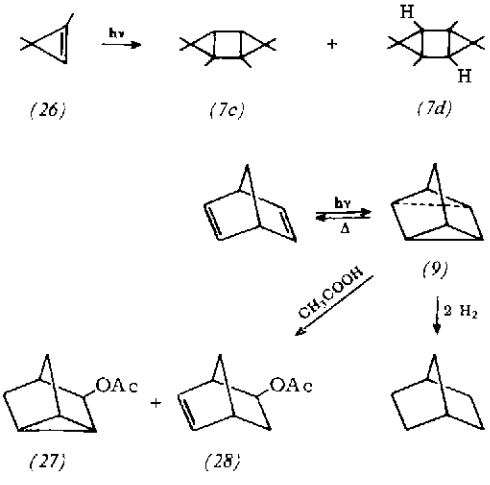
[32] *C. E. Griffin, N. F. Hepfinger*, and *B. L. Shapiro*, J. Amer. chem. Soc. *85*, 2683 (1963).

reaction [type (α)]. This involves the use of a cyclic diene *(24)* [*e.g.* X = $(CH_2)_n$; n = 1–4], which is converted into the Diels-Alder adduct *(25)* with nitrosobenzene; the double bond is then hydrogenated to give *(25a)*, and the nitrosobenzene is thermally eliminated. This yields *(6)* when X = CH_2.

Tricyclic compounds containing the bicyclopentane skeleton, *e.g. (22)*, can also be prepared starting from the norbornane system [30].

Tricyclohexane derivatives of type *(7)*, *e.g. (7c)* and *(7d)* (NMR spectrum for tertiary H: τ = 9.0 ppm), are formed in a novel reaction, namely photosensitized cyclodimerization of cyclopropene *(26)* [9, 33].

Quadricyclane *(9)* has a methylene-bridged tricyclohexane structure and has been known now for some years; its chemistry has therefore been investigated more thoroughly [16]. Its reactions result in the cleavage of one or both strained bonds. The reaction of *(9)* with acetic acid leads to the formation of the acetoxy



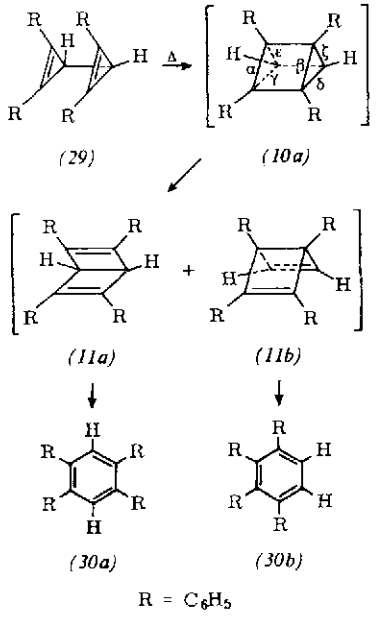
compounds *(27)* and *(28)*; catalytic hydrogenation yields norbornane, and heating to 200 °C gives the valence-bond isomer norbornadiene. Polycyclic compounds such as *(9)* which are built up of three- and four-membered rings are generally extremely sensitive to acids.

Evidence pointing to the existence of prismane, which is also tetracyclic, has recently been obtained for the first time [17, cf. 17a]. The two tetraphenylbenzenes *(30a)* and *(30b)* were isolated from *(29)* following a reaction similar to the dimerization of cyclopropene *(26)*.

The simplest explanation for this is the intermediate formation of tetraphenylprismane *(10a)* which, according to *Breslow*, may be imagined to react further through the isomeric "Dewar benzenes" *(11a)* and *(11b)* to form the tetraphenylbenzenes *(30a)* and *(30b)*, depending on whether bonds α and β or γ and δ (ε and ζ) in *(10a)* are broken.

Tricyclo[2.2.0.$0^{2,6}$]hexane *(10b)*, mentioned already, was obtained by *Lemal* and *Shim* [17b] in 30 % yield

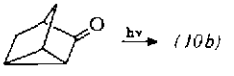
[33] The lines here and in the remainder of the paper indicate methyl groups.



(29) (10a) (11a) (11b) (30a) (30b)

R = C_6H_5

from the tricyclanone *(10c)* *via* mercury-sensitized liberation of carbon monoxide in a flow apparatus.

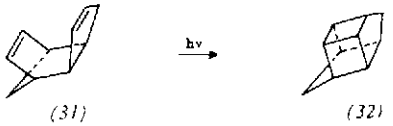


(10c)

3. The Bicyclo[2,2,0]hexane Skeleton

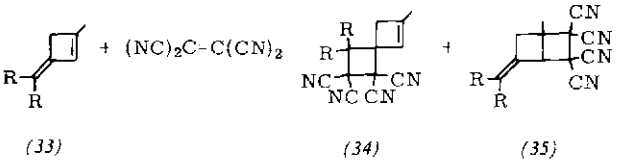
a) Bicyclohexanes

The parent hydrocarbon *(13)* was first prepared in small yields (< 5 %) by *Cremer* and *Srinivasan* in Hg-sensitized photoreactions in the gaseous phase [18]. It can now be prepared according to *Griffin* in 60 % yield from cheap starting materials [cyclohexadiene *(24)* with X = $(CH_2)_2$ and nitrosobenzene, cf. the formation of *(6)* from *(24)*]. The saturated bicyclohexane skeleton is formed, built into cage-like compounds [34], on exposure of dimeric cyclopentadienes to light. Thus, in the photosensitized cycloaddition [reaction type (γ)] of unsubstituted *(31)*, *Schenck* and *Steinmetz* [35] obtained the pentacyclic compound *(32)*. Compound *(32)* is stable at temperatures above 400 °C, in contrast to simple bicyclobutane derivatives, which isomerize at temperatures as low as 200 °C [14a, 18]; the compound differs from cubane in the insertion of a methylene group into two of the bonds. The key compound *(69)* for cubanedicarboxylic acid *(12a)* [24a] arises from the dimeric bromocyclopentadienone *(68)* *via* the same reaction.



(31) (32)

Cycloaddition of a highly reactive olefin onto a double bond [36] with formation of a bicyclohexane compound is exemplified by the reaction of tetracyanoethylene with methylenecyclobutenes *(33)* [reaction type (δ)].



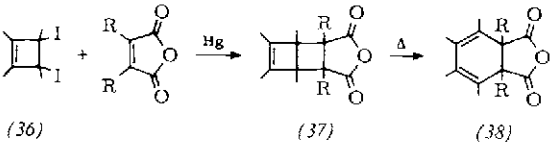
(33) (34) (35)

When R = H, the reaction leads simply to formation of the less strained spirane *(34)*; however, with greater steric hindrance of the exocyclic double bond (R = CH_3), the principal product is the bicyclic compound *(35)*.

Fluoro-olefins also add onto double bonds in the same manner at elevated temperatures to form polycyclic compounds with four-membered rings (cf. [37]). X-Ray studies showed that the supposedly perfluorinated tricyclo[4,2,0,$0^{2,5}$]octane is indeed the [3,3,0,$0^{2,6}$]-isomer having only one four-membered ring [37a].

b) Bicyclohexenes

Reaction type (ε) found its first application with the bicyclohexenes. According to *Criegee*, the only adducts of a "cyclobutadiene" with olefins so far isolated are the compounds *(37)* [3, 38] which are obtained by dehalogenation of the diiodide *(36)* with Hg in the presence of maleic anhydrides (attempts to trap other cyclobutadienes led directly to the isomeric cyclohexadienes [39]).



(36) (37) (38)

R = H, CH_3, Cl, Br, I

Chemical changes in the anhydride grouping [*] result in the formation of bicyclohexene derivatives *(37)* [38], which undergo valence-bond isomerization to yield cyclohexadiene derivatives [e.g. *(38)*] at about 200 °C (stabilizing influence of the methyl groups [40]). The dibromide *(37)* (R = Br) is the starting material in the preparation of "Dewar benzene" *(11d)* [22d].

A very thermolabile bicyclohexene *(39a)* [38a] is formed in 50 % yield by illuminating butyne in the presence of an ester of cyclobutenedicarboxylic acid [reaction type (δ)]. Under the additional influence of both carboxyl groups, isomerization to cyclohexadiene can be achieved

[34] *O. L. Chapman* et al., J. Amer. chem. Soc. *85*, 2031 (1963).

[35] *G. O. Schenck* and *R. Steinmetz*, Chem. Ber. *96*, 520 (1963).

[36] *J. K. Williams*, J. Amer. chem. Soc. *81*, 4013 (1959).

[37] *M. Prober* and *W. T. Miller jr.*, J. Amer. chem. Soc. *71*, 598 (1949); *A. H. Fainberg* and *W. T. Miller jr.*, ibid. *79*, 4170 (1957).

[37a] *I. J. Karle* et al., J. Amer. chem. Soc. *86*, 2523 (1964).

[38] *R. Criegee* et al., unpublished results.

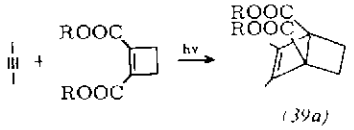
[38a] *D. Seebach*, Chem. Ber. *97*, (1964), in the press.

[39] *H. H. Freedman*, J. Amer. chem. Soc. *83*, 2195 (1961).

[*] For example, formation of hexamethylbicyclohexene from *(37)* (R = H) or 1,2,3,4,5,6-hexamethyl-8-oxatricyclo[4,3.0,$0^{2,5}$]-non-3-ene from *(37)* (R = CH_3).

[40] *R. Criegee*, *W. D. Wirth*, *W. Engel*, and *H. Brune*, Chem. Ber. *96*, 2230 (1963).

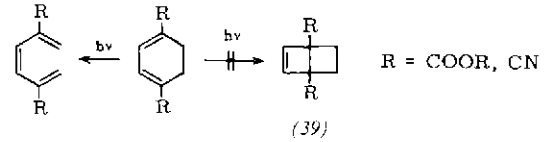
even at 80 °C ($\tau_{1/2}$ = 4.2 h; activation energy = 30.6 kcal/mole).



(39a)

Conversely, bicyclohexenes can be formed from cyclohexadienes by the action of light [reaction type (γ)]. Besides the examples mentioned in the interesting studies on sterols [20] and terpenes [41a], in which cyclization is facilitated by the sterically fixed proximity of the double bonds in the polycyclic skeleton, this photoisomerization has also been achieved with simple cyclohexadienes [22a, 41d].

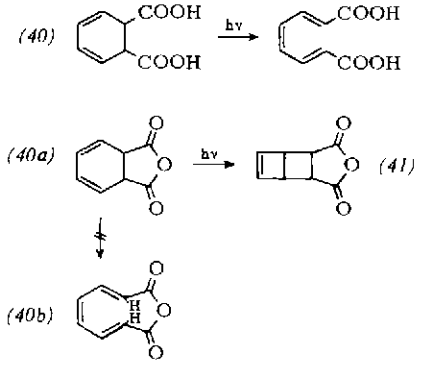
According to *Barton* [41], the "normal" photoreaction of the cyclohexadienes is ring-opening to yield extremely reactive hexa-1,3,5-trienes.



(39)

Meanwhile doubt has been thrown [41c] on the structure of the bicyclohexenes *(39)* described by *Prinzbach* [41b].

Another method of isomerizing cyclohexadienes has been demonstrated by *van Tamelen* [41d, 22a]. Whereas the six-membered ring of the dicarboxylic acid *(40)* is opened by the action of light, dihydrophthalic anhydride *(40a)* undergoes ring closure to form bicyclohexane *(41)* [22a]. A kind of bracket effect was proposed as the explanation for this: the monocyclic anhydride *(40b)* is not formed owing to steric hindrance of the hydrogen atoms indicated in the formula (cf. Section II.C.1).



The anhydride *(41)* is the starting material for a surprisingly simple preparation of the unsubstituted "Dewar benzene" *(11)*.

[41] *D. H. R. Barton*, Helv. chim. Acta *42*, 2604 (1959).

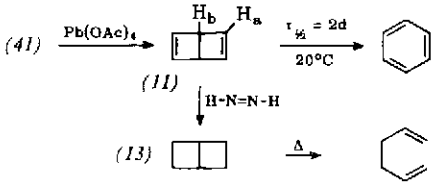
[41a] *W. H. Shuller* et al., J. org. Chemistry *27*, 1178 (1962); *W. G. Dauben* and *R. M. Coates*, J. Amer. Chem. Soc. *86*, 2490 (1964).

[41b] *H. Prinzbach* and *J. H. Hartenstein*, Angew. Chem. *74*, 651 (1962); Angew. Chem. internat. Edit. *1*, 507 (1962); Angew. Chem. *75*, 639 (1963); Angew. Chem. internat. Edit. *2*, 477 (1963).

[41c] *H. Prinzbach*, personal communication.

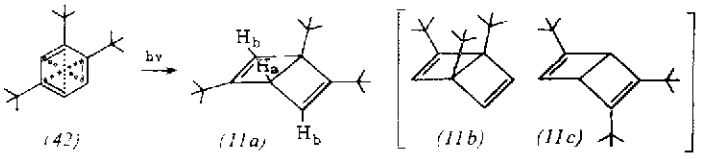
[41d] *G. J. Fonken* and *W. Moran*, Chem. and Ind. *1963*, 1841; *G. J. Fonken* and *K. Mehrotra*, ibid. *1964*, 1025.

Van Tamelen and *Pappas* have shown [22a], that a solution of "Dewar benzene" *(11)* [NMR spectrum for H_a: τ = 3.45; H_b: τ = 6.16 ppm] can be obtained in about 20 % yield by reaction of *(41)* with $Pb(OAc)_4$ in pyridine.



In addition to its spectra, the chemical reactions of *(11)* provide clear evidence for its structure: hydrogenation with diimide [*] yields bicyclo[2,2,0]hexane *(13)*, which is converted into 1,5-hexadiene by heating (both substances were identical with authentic samples [18]). "Dewar benzene" isomerizes to benzene at room temperature with a half-life of 2 days.

A much more stable "Dewar benzene" derivative (see Section II.C.2) had been prepared a year previously (1962). On irradiation of 1,2,4-tri-t-butylbenzene *(42)*, 1,4-ring closure could theoretically lead to formation of the three products *(11a)*–*(11c)* [reaction type (γ)]. Of these, only *(11a)* [NMR spectrum for H_a: τ = 6.80; H_b: τ = 3.90 ppm] no longer contains two t-butyl groups in a single plane together with the carbon atoms connecting them. The two groups on the bridgehead atoms in *(11b)* lie in a single plane, those on the double bond do in *(11c)*. Thus, the formation of *(11b)* and *(11c)* would involve no reduction in steric hindrance compared to *(42)* [**]. Compound *(11a)* was in



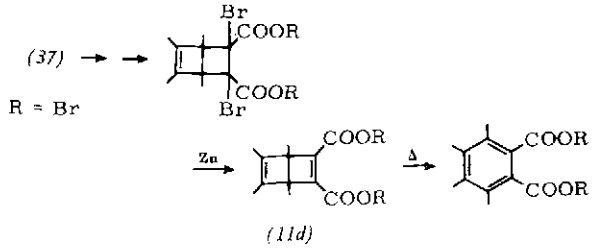
fact isolated as the first bicyclohexadiene. It can be vacuum distilled (10^{-7} mm) and is so stable that heating for 15 min at 200 °C is necessary to effect reversal of the isomerization.

Thus, although the unsubstituted compound *(11)* is very unstable and has not yet been isolated, while its derivative *(11a)* has been prepared in only very small amounts, *Criegee* and *Zanker* [22d] succeeded in synthesizing the "Dewar benzene" derivative *(11d)* on a preparative scale and in good yields from the dibromide *(37)* (R = Br) *via* the dicarboxylic acid ester.

[*] Diimide hydrogenates only non-polar double bonds [42].

[**] 1,2,3-Tri-t-butyl-4,5,6-trifluorobicyclohexadiene was recently isolated by *H. G. Viehe* et al., Angew. Chem. *76*, 922 (1964); Angew. Chem. internat. Edit. *3*, 755 (1964).

[42] Most recent publications with references to all earlier papers: *S. Hünig*, *H. R. Müller*, and *W. Thier*, Angew. Chem. *75*, 298 (1963); Angew. Chem. internat. Edit. *2*, 214 (1963); *E. J. Corey* and *W. L. Mock*, J. Amer. chem. Soc. *84*, 685 (1962); *E. E. van Tamelen* and *R. J. Timmons*, ibid. *84*, 1067 (1962).



(11d)

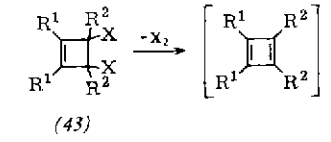
At room temperature compound *(11d)* is stable, but at 90 °C it isomerizes to the ester of tetramethylphthalic acid ($\tau_{1/2}$ = 4.7 h), in which the stabilizing influence of methyl substitution on an unstable valence-isomer can again be seen [3,40].

4. The Tricyclooctane Skeleton

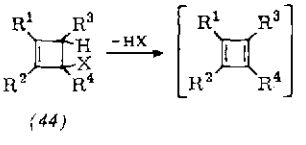
So far there is scarcely a reaction known [43,44] in which a tricyclooctane skeleton with three *ortho*-fused four-membered rings is formed, other than dimerization of cyclobutadienes [reaction type (ε)]. Only a brief description of the tricyclooctadienes, their formation, and their properties will therefore be given. Moreover, reviews have already been published on some parts of this field, such as the dimers of tetramethylcyclobutadiene and of benzocyclobutadiene (*cf. Criegee* [3] and *Cava* [45]). Besides these two workers, *Freedman* and *Nenitzescu* have also investigated the chemistry of the cyclobutadienes.

a) Generation of Cyclobutadienes

The reaction most frequently used for the generation of cyclobutadienes is the elimination of halogen from dihalogenocyclobutenes *(43)*. The elimination of hydrogen halides is less frequently used [47,48,50], owing to the greater difficulty involved in obtaining monohalogenocyclobutenes *(44)*.



(43)

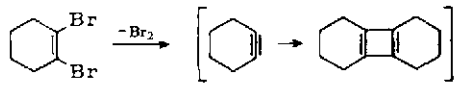


(44)

$R^1 = R^2 = H$; X = Cl [46]
$R^1 = R^2 = CH_3$; X = Cl, I [3]
$R^1 = R^2 = C_6H_5$; X = Br [39]
R^1 = ; R^2 = H; X = Br, I [47-49]

$R^1 = R^2 = R^3 = C_6H_5$; X = F [50]
$R^1 = R^2$ = ; $R^3 = R^4$ = H; X = Br [47,48]
$R^1 = R^2$ = ; $R^3 = R^4$ = X = Br [47,48]
$R^1 = R^4 = H$; $R^2 = R^3 = C_6H_5$; X = N< [50a]

Wittig and *Mayer* [51] obtained a cyclobutadiene derivative *(47)* by an entirely different reaction during the preparation of cyclohexyne *(46)* from 1,2-dibromo-1-cyclohexene *(45)*.

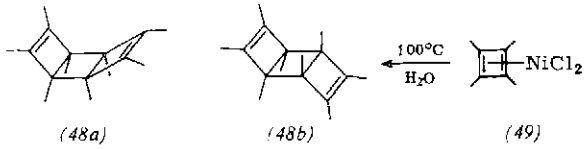


(45) (46) (47)

b) Secondary Products

The dimer of cyclohexyne *(47)* itself dimerizes like other cyclobutadienes to give the corresponding tricyclooctadiene [cf. *(18)*]; a tricyclooctadiene derivative is invariably the first secondary product formed from all cyclobutadienes.

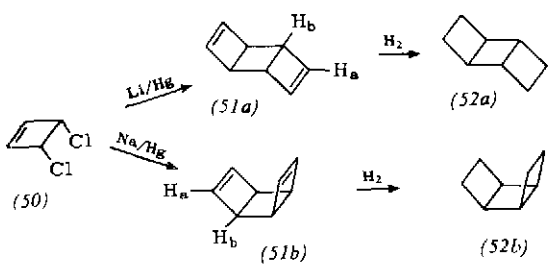
The *syn*- and *anti*-isomers of a tricyclooctadiene derivative were prepared and their structures proved and assigned for the first time by *Criegee* et al. [3]: the permethylated *syn*-tricyclic compound *(48a)* is formed by elimination of chlorine from the corresponding dichloride *(43)*, while the *anti*-tricyclic compound *(48b)* results from decomposition of the cyclobutadiene-nickel complex *(49)*.



(48a) (48b) (49)

Subsequently, unsubstituted analogues *(51a)* [NMR spectrum for H_a: τ = 3.52; H_b: τ = 7.06 ppm] and *(51b)* [NMR spectrum for H_a: τ = 4.05; H_b: τ = 6.92 ppm], catalytic hydrogenation of which leads to the saturated tricyclic hydrocarbons *(52a)* and *(52b)*, were also prepared by *Nenitzescu* [46].

Compound *(51a)* is formed from the dichloride *(50)* with Li/Hg, and *(51b)* with Na/Hg. A surprising specificity similar to that observed in the formation of *(48)* and



(50) (51a) (51b) (52a) (52b)

[43] *E. Vogel, O. Roos,* and *K. H. Disch,* Liebigs Ann. Chem. *653*, 55 (1962).

[44] *F. R. Jensen* and *W. E. Coleman,* Tetrahedron Letters *1959*, No. 20, 7; *M. P. Cava* and *K. Muth,* ibid. *1961*, 140; J. org. Chemistry *27*, 1561 (1962); *28*, 1861 (1963).

[45] *M. P. Cava,* Bull. Soc. chim. France *1959*, 1744.

[46] *C. D. Nenitzescu* et al., Chem. Ber. *97*, 382 (1964).

[47] *M. P. Cava* et al., J. Amer. chem. Soc. *78*, 500 (1956); *79*, 1701 (1957); *80*, 2255 (1958); *81*, 5409 (1959); *79*, 1706 (1957).

[48] *M. P. Cava* et al., Tetrahedron Letters *1961*, 140.

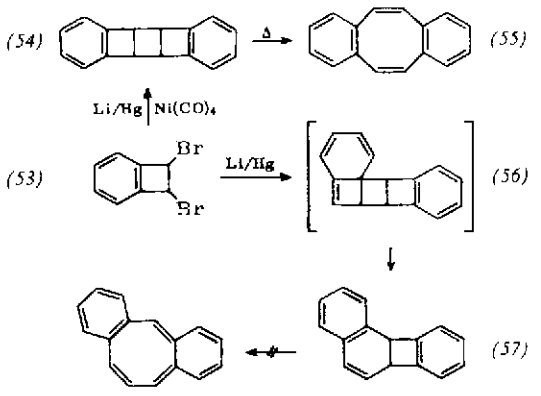
[49] *C. D. Nenitzescu* et al., Chem. and Ind. *1959*, 257; *1962*, 555; Chem. Ber. *93*, 1789 (1960); Tetrahedron *19*, 309 (1963).

[50] *J. D. Roberts* et al., J. Amer. chem. Soc. *82*, 3106 (1960); *86*, 449 (1964); *Ch. Fritchie jr.* and *E. W. Hughes,* ibid. *84*, 2257(1962).

[50a] *E. H. White* and *H. C. Dunathan,* J. Amer. chem. Soc. *86*, 453 (1964).

[51] *G. Wittig* and *U. Mayer,* Chem. Ber. *96*, 342 (1963).

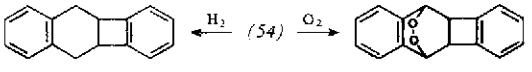
(51) is found in the dimerization of benzocyclobutadiene. Whereas benzocyclobutadienes generally



undergo angular dimerization leading to compounds of structure *(57)* [47,48], the reaction of the dibromide *(53)* with Li/Hg in the presence of $Ni(CO)_4$ yields a linear dimer *(54)* [49]. This specificity suggests that free cyclobutadiene compounds do not exist as intermediates in all cases [3].

Later however, experiments by *Skell* and *Petersen* [51a] indicated that free tetramethylcyclobutadiene exists in the gas phase for some period of time; the formation of the *syn*-tricyclic compound *(48a)* could be proved, Thus is seems no longer necessary to describe cyclobutadiene as being only a hypothetical compound.

In *(54)*, resonance is retained in both benzene rings; hence the compound can be isolated as such and is converted into the valence-bond isomer *(55)* only on heating. On the other hand, one of the benzene rings is present in an *ortho*-quinonoid form in the primary product *(56)* of the angular dimerization; consequently, *(56)* cannot be obtained as such, and instead the more stable product *(57)* is isolated. Compound *(57)* was the first derivative of bicyclo[4,2,0]octatriene to be isolated (see also [40]); it cannot isomerize to the eight-membered ring *(58)*, since this would again result in the formation of an *ortho*-quinonoid ring [see also Section II.C.3].

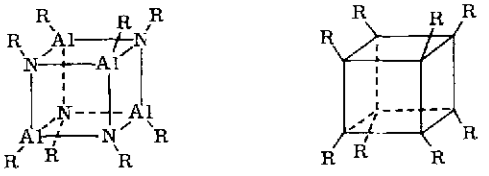


(59) *(60)*

The strain in the system consisting of three condensed four-membered rings is manifest in the reactions of *(54)* with hydrogen to yield bicyclo-octadiene *(59)* and with oxygen to yield the *endo*-peroxide *(60)* [49].

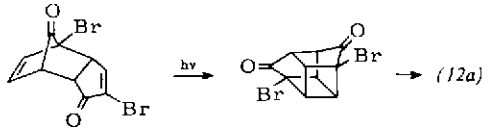
5. Cubane

Following the success of reactions leading to quadricyclene *(9)*, prismane *(10a)*, and the pentacyclic compound *(32)*, it also seemed possible to prepare the cubane skeleton from an *endo*-tricyclooctadiene such as *(48a)*. However, this tricyclic compound could not be converted into cubane either by exposure to light or at a pressure of several thousand atmospheres [38]. The first compound whose structure was known with certainty (from X-ray analysis) to be based on the cubane structure was the octaphenyl-Al-N cube *(61)* [52].



According to *Freedman* [24,39,53], the dimer of tetraphenylcyclobutadiene (m.p. 430 °C) seemed to have an octaphenylcubane structure *(62)*. However, it turned out to be octaphenylcyclooctatetraene [24a].

As already mentioned, *Eaton* and *Cole* have synthesized the cubane skeleton [24b,54]. The pentacyclic compound *(64)* is converted to cubanedicarboxylic acid *(12a)* using boiling 50 % aqueous KOH, the overall yield of *(12a)* obtained from the dimer of bromocyclopentadienone *(63)* being 30 %.



(63) *(64)*

The reaction is assumed to be a Favorskii rearrangement following the mechanism of the semi-benzilic acid rearrangement. The data hitherto available (see, for example, Table 1) favor the proposed structure *(12a)*. Further examination of *(12a)* and of the parent hydrocarbon C_8H_8 [54] should yield interesting results.

I am sincerely grateful to Professor R. Criegee for his interest in this review.

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Translated by Express Translation Service, London

[51a] *P. S. Skell* and *R. J. Petersen*, J. Amer. chem. Soc. *86*, 2530 (1964).

[52] *J. I. Jones* and *W. S. McDonald*, Proc. chem. Soc. (London) *1962*, 366, 382; Angew. Chem. *75*, 1030 (1963).

[53] *H. H. Freedman*, J. Amer. chem. Soc. *83*, 2194 (1961); J. org. Chemistry *27*, 2298 (1962); *H. H. Freedman* and *A. M. Frantz jr.*, J. Amer. chem. Soc. *84*, 4165 (1962); *H. H. Freedman* and *G. S. Gohlke*, Proc. chem. Soc. (London) *1963*, 249.

[54] *P. Eaton* and *T. Cole*, J. Amer. chem. Soc. *86*, 3157 (1964). The structure was proved by X-ray analysis: *E. B. Fleischer*, J. Amer. chem. Soc. *86*, 3889 (1964).

Reactions of Metal Acetylacetonates

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Certain metal acetylacetonates undergo reactions characteristic of aromatic systems. Outstanding among these are electrophilic substitutions and the formation of a stable diazonium fluoroborate. Unsymmetrically substituted chelates have been prepared by stepwise substitution of trifunctional complexes. Chemical and physical properties of such mixed-ring complexes provide evidence for intramolecular interannular electronic effects transmitted through the metal ion.

I. Introduction

Although the physical properties of metal acetylacetonates have been studied extensively over many years, until recently very little attention was given to the chemical reactivity of this heterocyclic ring system. In 1925 *Reihlen* et al. reported bromination of chromium(III) acetylacetonate and assigned the correct structure to the bromination product [1]. As we were beginning our own work in 1958, *Djordjevis, Lewis*, and *Nyholm* described nitration of copper(II) acetylacetonate with N_2O_4 [2]. Since then metal acetylacetonate chemistry has developed extensively [3]. This account reviews our work in this field.

In order to minimize degradation of these acid-labile chelates, our studies have been largely restricted to relatively inert tris-acetylacetonates of chromium(III), cobalt(III), and rhodium(III) *(1)*. These metals confer individual differences on their chelates so that certain reactions or physical properties are more conveniently studied in one case than another. The rhodium(III) chelate is by far the most stable to acids, bases, or thermal treatment. On the other hand the chromium(III) and cobalt(III) chelate rings are much more reactive towards electrophiles than is the rhodium(III) complex. Almost all reducing agents quickly degrade the cobalt(III) complexes by producing labile cobalt(II) species. $NaBH_4$ or B_2H_6 quickly reduce rhodium(III) in these chelates to rhodium metal; however, catalytic and other chemical reducing agents do not reduce complexed rhodium(III). By contrast chromium(III) acetylacetonate is inert to all but the most powerful reducing agents. The d^6-cobalt(III) and rodium(III) complexes are diamagnetic and amenable to proton magnetic resonance analysis. The d^3-chromium(III) complexes are strongly paramagnetic so that NMR spectra cannot be determined.

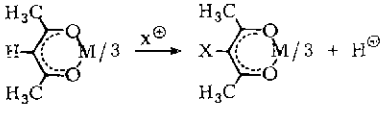
[1] *H. Reihlen, R. Illig*, and *R. Wittig*, Chem. Ber. *58B*, 12 (1925).

[2] *L. Djoidjeric, J. Lewis*, and *R. S. Nyholm*, Chem. and Ind. *1959*, 122.

[3] *J. P. Collman*, Adv. Chem. *37*, 78 (1963).

II. Electrophilic Substitution of the Chelate Rings

The central hydrogen atom on these chelate rings *(1)* can be replaced by several groups under apparently electrophilic conditions *(2)*. Because of the acid lability of these complexes, selective reagents must be employed to minimize degradation of the chelate rings. Halogenation [4, 5], thiocyanogenation [6, 7], arylsulfenylation [7], chlorosulfenylation [6, 7], nitration [8], acylation [7], formylation [8], chloromethylation and dimethylaminomethylation [9] have been realized.



(1) *(2)*

X = I, Br, Cl, SCN, SAr, SCl, NO_2, CH_2Cl, $CH_2N(CH_3)_2$, COR, CHO

Because of the trifunctional character of these tris-acetylacetonates an additional factor must be considered.

Mono-, di-, and tri-substituted chelates are formed if the concentration of electrophilic reagent is limited. Furthermore, the entering substituent may deactivate the remaining unsubstituted rings in a molecule so that higher degrees of substitution become progressively more difficult.

Halogenation of these acetylacetonates is best effected by the use of *N*-halogenosuccinimides (NCS, NBS, NIS) in hot chloroform [4, 5]. Excess reagent affords high

[4] *R. W. Kluiber*, J. Amer. chem. Soc. *82*, 4839 (1960).

[5] *J. P. Collman, R. A. Moss, H. Maltz*, and *C. C. Heindel*, J. Amer. chem. Soc. *83*, 531 (1961).

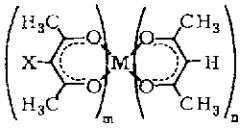
[6] *R. W. Kluiber*, J. Amer. chem. Soc. *83*, 3030 (1961).

[7] *J. P. Collman, R. L. Marshall, W. L. Young (III)*, and *C. T. Sears Jr.*, J. org. Chemistry *28*, 1449 (1963).

[8] *J. P. Collman, R. L. Marshall, W. L. Young (III)*, and *S. D. Goldby*, Inorg. Chem. *1*, 704 (1962).

[9] *R. H. Barker, J. P. Collman*, and *R. L. Marshall*, J. org. Chemistry *29*, 3216 (1964).

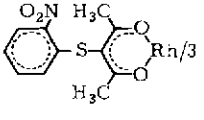
yields of trihalogenated chelates isolated as very stable 1:1-chloroform solvates. Chlorine, bromine, and iodine monochloride also halogenate these complexes; however, yields are lower because of acid degradation by released HX [5]. The rate of reaction decreases in the order NBS > NCS > NIS, and cobalt ≈ chromium > rhodium. Limited amounts of halogenating agents lead to mixtures of incompletely substituted chelates *(3)* which can be separated by chromatography [10]. Further elaboration of these chelates leads to a wide variety of mixed-ring complexes.

(1) $\xrightarrow{(H_2CCO)_2NX}$ 

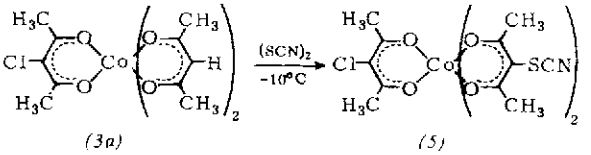
(3)

X = I, Br, Cl m = 1, n = 2
M = Rh, Co, Cr m = 2, n = 1
m = 3, n = 0

Sulfur can be introduced into the chelate ring by a number of electrophilic reagents [6,7]. Arylsulfenyl chlorides, sulfur dichloride, and thiocyanogen all react rapidly under mild conditions to form tri-substituted acetylacetonates. The arylsulfide chelates, *e.g. (4)*, form amazingly stable crystalline 1:1-benzene solvates. Mixtures of partially substituted thiocyanato chelates have proven intractable in our hands. Unsymmetrically substituted complexes containing sulfur *(5)* are better prepared from partially halogenated acetylacetonates *(3a)* [11].



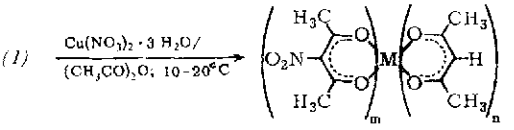
(4)



(3a) *(5)*

Nitration of metal acetylacetonates cannot be carried out with the usual mixtures of nitric and sulfuric acids since the complexes are rapidly decomposed by strong acid. High yields of nitrated chelates have been obtained using solutions of copper(II) nitrate trihydrate in acetic anhydride [8,12]. If sufficient reagent is employed, trinitrated chelates are formed. On the other hand, lesser amounts of copper(II) nitrate lead to mixtures of partially nitrated acetylacetonate complexes *(6)* which can be separated by chromatography [13].

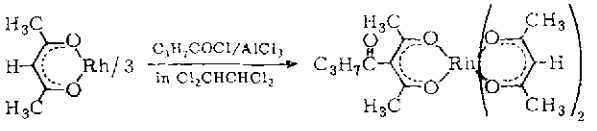
Friedel-Crafts acylation of these acetylacetonates can be accomplished under carfully controlled conditions [7]. Because of intramolecular deactivation by acyl substituents, each substitution becomes progressively slower, and mixtures result.

(1) $\xrightarrow[(CH_3CO)_2O;\ 10-20^\circ C]{Cu(NO_3)_2\cdot 3\,H_2O/}$ 

(6)

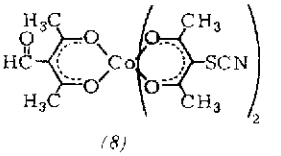
M = Rh, Cr, Co m = 1, n = 2
m = 2, n = 1
m = 3, n = 0

Chromium acetylacetonate yields mono-, di-, and triacetylated chelates when acetic anhydride and BF_3-OEt_2 is the reagent. Under these conditions cobalt acetylacetonate also gives mixtures, but very little triacetylated chelate is formed. The rhodium complex does not react, but acetyl chloride and aluminum chloride effect mono- and diacetylation of this complex (conditions which degrade the cobalt and chromium chelates). Thus a reactivity series chromium>cobalt>rhodium is established. Larger acyl groups can be introduced into rhodium acetylacetonate but these reactions are slower and lead largely to mono-substituted products *(7)*. Ketene or acyl chloride/pyridine mixtures fail to react with any of these chelates, but reaction does occur with the free ligands.



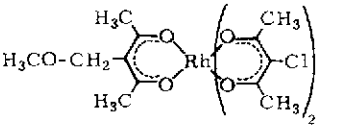
(7)

Formylation of these metal acetylacetonates was carried out using the Vilsmeir reaction [8]. Treatment of the chelates with $POCl_3$ in dimethylformamide afforded mixtures of mono- and di-formyl chelates. Trisubstitution is possible with cobalt acetylacetonate under forcing conditions. Further elaboration of the remaining unsubstituted rings has led to a series of unsymmetrically substituted chelate-aldehydes, *e.g. (8)* [10,11].

(1) M = Co $\xrightarrow[3.\ (SCN)_2]{1.\ POCl_3/DMF\ \ 2.\ NaOAc/H_2O}$ 

(8)

Chloromethylation of metal acetylacetonates is possible, but the reaction is complex [9]. Treatment of unsubstituted tris-acetylacetonates with chloromethyl methyl ether and BF_3-$O(C_2H_5)_2$ yields cross-linked methylene-bridged chelate-polymers. A similar result is obtained



(9)

[10] *J. P. Collman, R. L. Marshall,* and *W. L. Young (III)*, Chem. and Ind. *1962*, 1380.

[11] *J. P. Collman* and *W. L. Young (III)*, unpublished results.

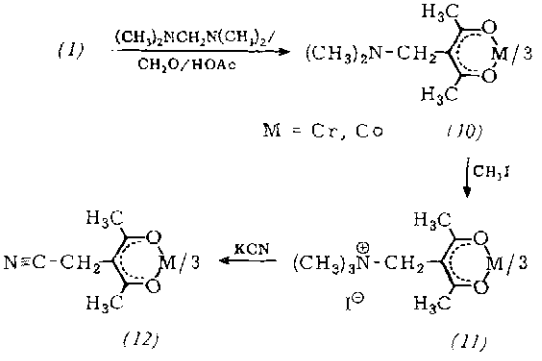
[12] *J. P. Collman* and *W. L. Young (III)*, Inorg. Synthesis 7 (1965), in the press.

[13] *J. P. Collman* and *M. Yamada*, J. org. Chemistry *28*, 3017 (1963).

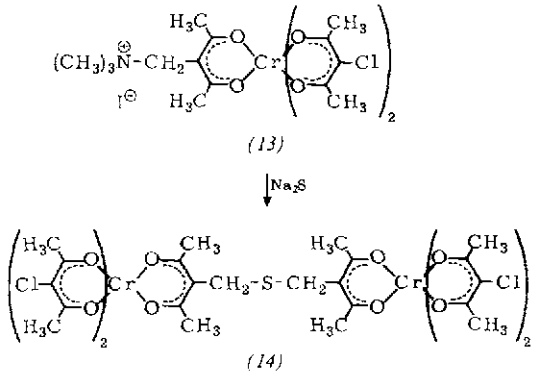
using acetic acid and paraformaldehyde [14]. Starting from dichlororhodium acetylacetonate an intermediate chloromethyl derivative is formed and can be trapped but not isolated. Alcoholysis affords the expected unsymmetrical ether *(9)*.

A modified Mannich reaction introduces dimethylaminomethyl groups into the acetylacetonate ring [9]. Tris-dimethylaminomethyl chelates *(10)* are unusually difficult to purify because of their high solublity in many solvents and because of their hygroscopic nature.

Quaternization of the uncoordinated tertiary amines *(10)* was effected by reaction with methyl iodide; however, the reaction is incomplete and yields intractable mixtures. Further treatment of the impure quaternary ammonium iodides *(11)* with potassium cyanide affords cyanomethylene complexes *(12)* which can be purified by chromatography.

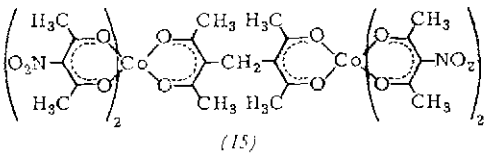


The problems arising on dealing with the polyfunctional reactive chelates *(10)*, *(11)*, and *(12)* can be simplified by using a dichlorinated acetylacetonate complex (one unsubstituted ring). However, some of the chlorine atoms were displaced by the Mannich reagent [9]. Again the amine was quaternized and the quaternary salt *(13)* was then treated with a series of nucleophiles, *e.g.* to yield a sulfur-bridged chelate *(14)*.



Attempted Friedel-Crafts alkylation of these metal acetylacetonates has been unsuccessful [14]. However, paraformaldehyde in glacial acetic acid attacks these chelates to produce methylene-bridged complexes. The dinitrocobalt acetylacetonate complex reacts to form the dimer *(15)*. The mononitro chromium- and cobalt chelates yield soluble polymers but the average molecular weights are not high [14].

[14] *J. P. Collman* and *R. H. Barker*, unpublished results.

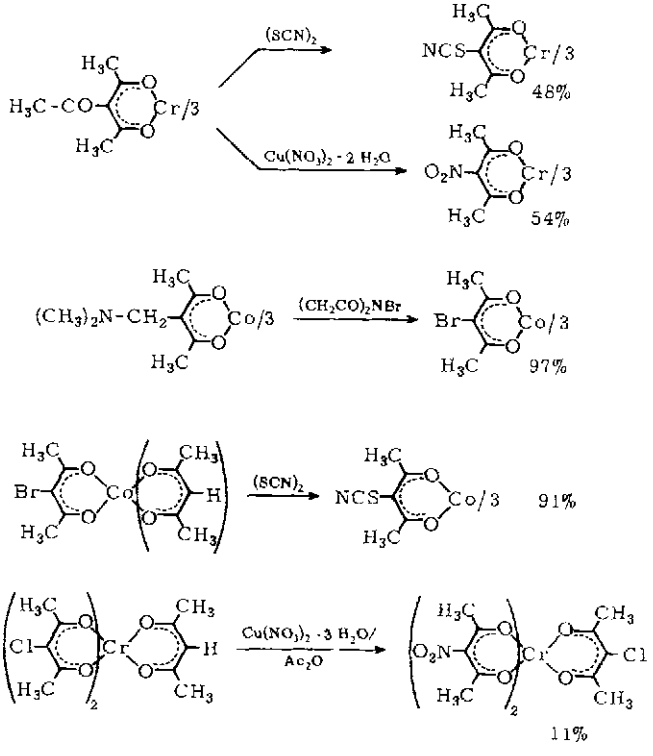


One aspect of the mechanism of these substitution reactions has been examined more closely: The unsymmetric tris-acetylacetonates were partially resolved by chromatography on a column (5 m long) of lactose hydrate, and the partially resolved complexes were then substituted with various electrophilic reagents [15]. Since the products were all optically active, it was presumed that substitution is not accompanied by ring opening.

An interesting sidelight on this work was the discovery of the racemization of cobalt acetylacetonate dnring crystallization [15,16]. This strange phenomenon, apparently the result of a preferential formation of racemic crystals, is being investigated at present.

III. Cleavage of Substituents from Acetylacetonate Rings under Electrophilic Conditions

We have observed a number of instances in which groups other than hydrogen are displaced from the chelate ring under apparently electrophilic conditions. A detailed investigation of this reaction revealed a pronounced selectivity of leaving groups, of electrophilic reagents, and of the metal in the chelate ring [11]. Typical examples of this type of reaction are outlined in Scheme 1.



Scheme 1. Typical examples of electrophilic displacement reactions with acetylacetonate chelates.

[15] *J. P. Collman, R. P. Blair, R. L. Marshall*, and *A. L. Slade*, Inorg. Chem. *2*, 576 (1963).

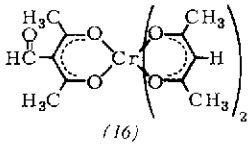
[16] *J. P. Collman, R. P. Blair, A. L. Slade*, and *R. L. Marshall*, Chem. and Ind. *1962*, 141.

The selectivity of substituents as leaving groups seems to parallel their stability as carbonium or halonium ions: $(CH_3)_2NCH_2 > CH_3CO > HCO > R$, and $I > Br > Cl$.

IV. Reactions of Functional Groups on Chelate Rings

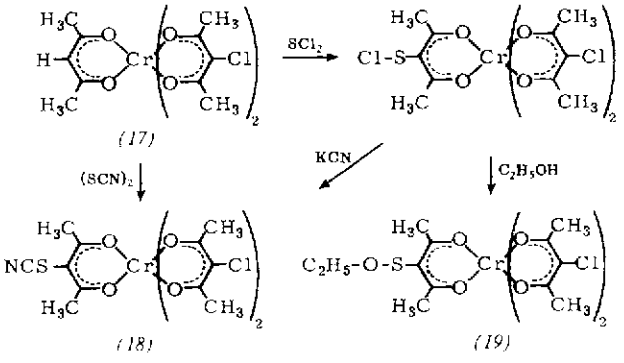
Substituent groups on these metal acetylacetonates sometimes exhibit unusual chemical properties. The high electron-density at the central carbon atom of the chelate ring and the steric shielding of this position by the flanking methyl groups are thought to be responsible for these abnormal properties.

Halogen atoms on chelate rings are unusually resistant to nucleophilic displacements [5]. They can, however, be displaced by electrophiles as described in Section III. All attempts to prepare Grignard or lithium reagents from halogenated chelates have failed. The starting materials were usually recovered unchanged. As illustrated below, the chelate rings are stable to Grignard reagents. An aldehyde group on the chelate ring is surprisingly inert. All attempts to prepare oxime, hydrazone and semicarbazone derivatives failed. The most amazing illustration of this low reactivity is the failure of the chromium-aldehyde chelate *(16)* to react with the methyl Grignard-reagent [17]. The starting material was recovered unchanged. The carbonyl groups in acetyl and ethoxycarbonyl-substituted chelates are similarly inert.



(16)

Sulfide groups on acetylacetonate rings are not oxidized by 30 % hydrogen peroxide [7]. Sulfenyl chloride groups behave quite normally, reacting with cyanide ion to form thiocyanate derivatives, *e.g. (18)* [6, 7], and with alcohols to form sulfenate esters *(19)* [7]. Reactive groups such as this are best studied using monofunctional chelates such as *(17)*.

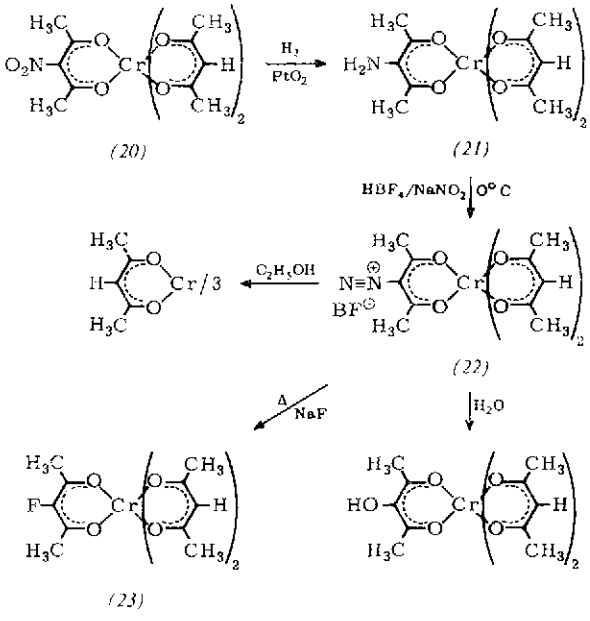


(17) *(18)* *(19)*

[17] *J. P. Collman* and *C. T. Sears Jr.*, unpublished results.

Derivatives with a 3-hydroxymethyl group have not been isolated. This group probably undergoes solvolysis to a carbonium ion with great ease as indicated by the formation of chelate polymers by reaction of metal acetylacetonates and formaldehyde under acidic conditions.

Nitrated acetylacetonates are resistant to chemical reduction of the nitro group. Catalytic hydrogenation of mononitro chromium acetylacetonate *(20)* affords the amino chelate *(21)* in 65 % yield. The amino chelate is easily autoxidized and should be handled under nitrogen. The amino group behaves like a typical aromatic amine in that it is reversibly protonated (pK_a 5.24 in 1:1 alcohol-water) and can be acetylated. The *N*-acetyl derivative resists hydrolysis. The amino chelate *(21)* is readily converted into a stable diazonium fluoroborate *(22)* which is very reactive. It undergoes reduction with ethanol, coupling with β-naphthol, and solvolysis in water or methanol [13]. The diazonium fluoroborate undergoes a Schiemann reaction with difficulty upon heating with dry, powdered sodium fluoride.



(20) *(21)* *(22)* *(23)*

V. Chemistry of Chelates Related to the Acetylacetonates

Acetylacetonates of other metals can also be substituted by some of the electrophilic reagents mentioned above. However, these complexes are usually more easily degraded by acids. Tris-acetylacetonates of aluminum(III), europium(III) and iron(III) have been brominated and, in the first case, nitrated [18]. Bis-acetylacetonates of copper(II) and palladium(II) [19] have been brominated. *Bailar* has studied reactions of bis-(2,4-pentanediono)-beryllium(II) in some detail [20, 21].

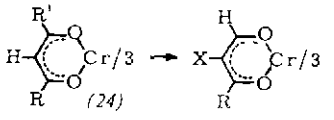
[18] *J. P. Collman* and *M. P. Cooke*, unpublished results.

[19] *J. P. Collman* and *C. Twine*, unpublished results.

[20] *R. M. Klein* and *J. C. Bailar Jr.*, Inorg. Chem. *2*, 1187 (1963).

[21] *R. M. Kelin* and *J. C. Bailar Jr.*, Inorg. Chem. *2*, 1190 (1963).

The malonaldehyde complex, tris-(1,3-propandialato)-chromium(III) *(25)* can be considered as the parent of the 1,3-dicarbonyl chelate systems [22]. So far only the chromium complex of this ligand has been prepared. Cobalt(III) and rhodium(III) cations are reduced by malonaldehyde salts. The malonaldehyde chelate has been brominated, thiocyanogenated, and nitrated. Attempted formylation or acetylation degrades this complex. Of the related formylacetone chromium chelate *(25b)* *cis*- and *trans*-isomers have been prepared. The formylacetone complex also undergoes electrophilic substitutions, but *(25)* and *(25b)* react more slowly and are less stable towards acidic reagents than chromium acetylacetonate. There is no tendency for the aldehydic protons to undergo substitution. It is probable that the methyl groups in acetylacetonate rings sterically retard but electronically enhance substitution reactions and simultaneously shield the oxygen donor-atoms from attack by the electrophiles.

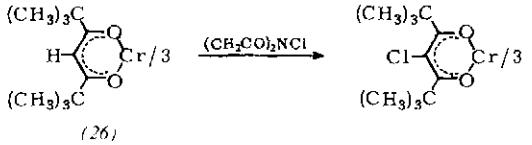


(24)

(25a): R = R' = H X = Br, SCN, NO_2

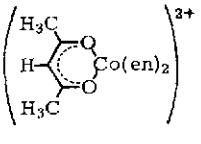
(25b): R = CH_3; R' = H R = H, CH_3(cis + trans)

The effect of massive steric hindrance on chelate reactions is illustrated by the chromium chelate of dipivaloylmethane *(26)*. This chelate undergoes reactions only very slowly under forcing conditions [17]. Chlorination and nitration have been observed. Chelates of dibenzoylmethane can be halogenated but the reactions are slower than with the acetylacetonates [5].



(26)

Electronegatively substituted complexes such as chromium chelates of trifluoro- and hexafluoro-acetylacetone are inert to electrophilic substitution, *e.g.* with *N*-bromosuccinimide [17]. The remarkably volatile hexfluoro complexes can be passed through vapor-phase chromatography columns. Another electron-deficient acetylacetonate ring, the bisethylenediamine-(2,4-pentanediono)cobalt(III) cation *(27)*, resists electrophilic substitutions such as bromination but is slowly deuterated

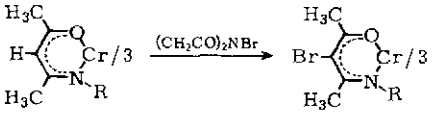


(27)

[22] *J. P. Collman* and *E. T. Kittleman*, J. Amer. chem. Soc. *83*, 3529 (1961).

on the central carbon atom of the chelate ring in strongly acidic D_2O solution [23].

In a few instances complexes have been prepared in which one of the oxygen atoms in the acetylacetonate rings is replaced by another hetero-atom. Chromium complexes of α,β-unsaturated β-amino ketones *(28)* have been prepared and halogenated [24]. More recently, chelates of monothioacetylacetone have been prepared, but little is known about their reactions [25,26]. In contrast to the acetylacetonate, the nickel thiochelate *(29)* is monomeric and diamagnetic. Chelates of tropolone *(30)* undergo electrophilic substitution of the tropolone ring but complex mixtures result [27].



(28)

(29) *(30)*

VI. Physical Properties of Metal Acetylacetonates

1. Chromatography

The tris-acetylacetonates are moderately soluble in organic solvents and thus amenable to purification by chromatography. Thin-layer chromatography is particulary useful in establishing the homogeneity of such substances. Mixtures of unsymmetrically substituted chelates so far can be separated by such techniques only. Mixtures of rhodium complexes are much more difficult to separate than the analogous cobalt or chromium chelates, and in some instances the former are intractable. Melting points are useful in characterizing substituted acetylacetonates but comparative thin-layer chromatography using known standards is more reliable.

2. Infrared Spectra

Infrared spectra are useful in characterizing acetylacetonate complexes. Unsubstituted acetylacetonates exhibit strong bands at 1570 and 1520 cm^{-1}. Substituted acetylacetonates show only weak absorption at 1520 cm^{-1} and the band at 1570 cm^{-1} is shifted to ca. 1550

[23] *J. P. Collman* and *D. A. Buckingham*, unpublished results.

[24] *J. P. Collman* and *E. T. Kittleman*, Inorg. Chem. *1*, 499 (1962).

[25] *J. P. Collman* and *P. Slagen*, unpublished results.

[26] *S. H. H. Chaston* and *S. E. Livingstone*, Proc. chem. Soc. (London) *1964*, 111.

[27] *J. P. Collman* and *M. Yamada*, unpublished results.

cm^{-1}. Thus substitution of the acetylacctonate ring causes the strong doublet in the 1500–1600 cm^{-1} region to apparently merge into one peak [28]. The disappearance of a weak C··H in-plane bending vibration at 1190 cm^{-1} also provides a measure of ring substitution. Infrared vibrations of the different chelate rings in unsymmetrically substituted acetylacetonates are nearly independent of one another. Spectra of analogous complexes of the three metals Rh, Cr, and Co are nearly identical.

Characteristic group-frequencies of substituents on these chelates are useful in determining the type of substitution product. However, certain of these group frequencies are unusual. For example, the uncoordinated aldehyde group in formyl chelates shows a carbonyl stretching frequency at 1670 cm^{-1}.

3. Electronic Spectra

The ultraviolet spectra of these chelates are often complex in that one to four bands or shoulders are found. The principal absorption bands in the ultraviolet region occur at about 256 mμ for cobalt, at about 317 mμ for rhodium, and at 331 mμ for chromium acetylacetonate. These bands probably arise from $\pi \rightarrow \pi^*$-transitions of the ligand [29].

Comparison of ultraviolet spectra of substituted acetylacetonates can be used to indicate the extent of steric inhibition of resonance of the substituents with the chelate ring [22]. Halogen, sulfur, and formyl are the only substituents which produce bathochromic shifts of the intense absorption bands, but in the spectra of formylacetone and malonaldehyde chelates, nitro groups also cause bathochromic shifts. The ultraviolet data for substituted chromium chelates shown in Table 1 indicate

Table 1. Ultraviolet absorption maxima and extinction coefficients of chromium chelates of type *(24)* in chloroform.

R	R'	X	First λ_{max} [mμ]	ε_{max}
CH_3	CH_3	H	335	15800
CH_3	CH_3	Br	358	13070
CH_3	CH_3	NO_2	330	12260
CH_3	H	H	259	9950
CH_3	H	Br	277	8700
CH_3	H	NO_2	282	27250
H	H	H	265	8580
H	H	Br	283	7670
H	H	NO_2	282	31000

that the two methyl groups in acetylacetonates prevent coplanarity of acetyl and nitro groups with the chelate ring and thus sterically inhibit resonance with the ring. When one or both of these methyl groups are replaced by hydrogen, as is the case with the formylacetone and malonaldehyde complexes, the nitro group becomes conjugated with the ring. This argument becomes important when intramolecular electronic effects are examined.

[28] *R. P. Dryden* and *A. Winston*, J. physical. Chem. *62*, 635 (1958).

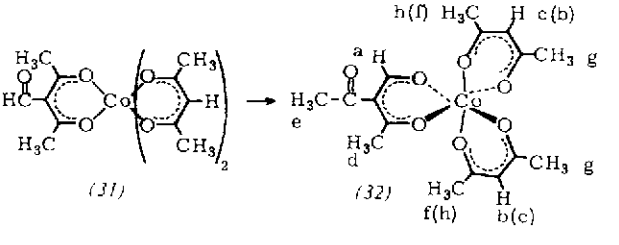
[29] *J. P. Fackler Jr.*, *F. A. Cotton*, and *D. W. Barnum*, Inorg. Chem. *2*, 97 (1963).

4. Nuclear Magnetic Resonance Spectra

Proton magnetic resonance spectra of rhodium and cobalt chelates are very useful for structure determination. These spectra are simplified by the absence of coupling. The unsubstituted acetylacetonates exhibit two proton signals in the ratio of 1:6. Trisubstitution results in disappearance of the lower-field peak and in a shift of the methyl signal to lower fields. The chemical shift of the methyl signals in trisubstituted acetylacetonates depends on the substituent, the metal, and the solvent [11].

Because of the peculiar and rigid geometry of tris-acetylacetonates, the NMR spectra of unsymmetrically substituted chelates exhibit an unexpected chemical shift [10]. The methyl groups on the uniquely substituted ring β of the disubstituted tris-acetylacetonate *(5)* are equivalent and give one sharp signal. However the two methyl groups on each of the two equally substituted rings α are not equivalent and give rise to two sharp signals. Examination of a model of *(5)* reveals that each methyl group on the β-ring is over the symmetry axis of one of the α-rings. On the other hand, chelates in which all three rings are differently substituted exhibit six methyl signals [11]. Over forty examples of this phenomenon have been observed in our laboratory [11].

A striking illustration of the use of NMR spectra for the determination of chelate structures is provided by the coordination isomer *(32)* of cobalt monoformyl acetylacetonate *(31)*. This isomer was formed by intermolecular ligand interchange on heating the formyl chelate in boiling toluene [30]. Models of this complex show 9 different kinds of protons. The NMR spectrum of *(32)* exhibits 8 peaks assignable to hydrogens a (2.08 τ), b (4.37 τ), c (4.40 τ), d (7.32 τ), e (7.65 τ), f (7.77 τ), g (7.79 τ), and h (7.80 τ), in the intensity ratios 1:1:1:3:3:3:6:3. Peak g corresponds to two slightly different methyl groups the signals of which are not resolved. There is no spincoupling. The chemical shifts were unequivocally assigned using model compounds.



(31) *(32)*

VII. Intramolecular Interannular Electronic Effects

1. Chemical Evidence

In a previous section several qualitative observations were reported which could be accounted for by intramolecular interannular electronic deactivation by sub-

[30] *J. P. Collman* and *J. Y. Sun*, unpublished results.

stituent groups. For example, formylation of each of the three chelate rings in the same molecule becomes successively more difficult (using the same concentrations of formylating reagent per number of unreacted rings) [11]. Similar effects were observed during acetylation.

Another example is the failure of the dinitro chromium chelate to undergo a Mannich reaction whereas the dichloro chromium chelate reacts readily under the same conditions. On competitive bromination of equivalent amounts of dichloro and dinitro chromium acetylacetonates, the dichloro chelate is exclusively brominated, but both complexes react if sufficient *N*-bromosuccinimide is present. These competitive brominations were followed by thin-layer chromatography using the pure starting materials and reaction products as internal standards.

2. Physical Evidence

A study of the NMR spectra of partially substituted cobalt and rhodium acetylacetonates showed that the chemical shift of the signal for the central hydrogen atom on the unsubstituted chelate ring depends on the substituents on the other rings. By using the unsubstituted cobalt or rhodium acetylacetonate as an internal standard and repeatedly measuring the separation between the chelate-ring hydrogen-signals on an expanded scale, this difference in chemical shift between unsubstituted and partially substituted chelates was measured with great precision. These shifts were then correlated by the Hammett equation (cf. Fig. 1 for the Co(III)-complexes) [11]. However, correlations were possible only when the NMR shifts were plotted versus σ_{para} constants for groups capable of resonance interaction (chloro, bromo, formyl) and versus σ_I constants for groups not capable of resonance (acetyl and nitro). As illustrated in Figure 1, the data are additive, even for complexes containing two different substituents. These correlations are considered to be "satisfactory to excellent" fits by the correlation coefficient criterion defined by *Jaffe* [31].

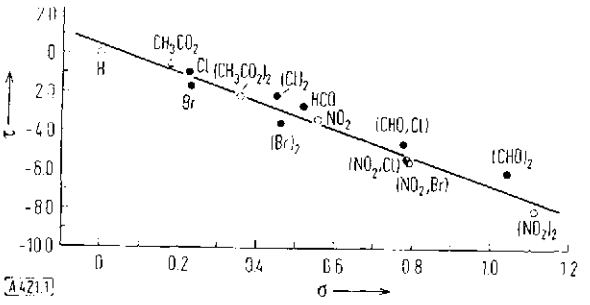


Figure 1. Correlation of proton-NMR shifts and σ constants for partially substituted cobalt(III) acetylacetonates in benzene [cobalt(III) acetylacetonate as internal standard].

○ = σ_I values
● = σ_p values
◐ = summation of $\sigma_I + \sigma_p$ values
Ordinate: Chemical shift τ [c.p.s.] at 60 Mc.
Abscissa: σ-Values

Succesful application of Hammett linear free-energy functions to partially substituted metal acetylacetonates implies that significant interannular intramolecular electronic effects are transmitted through the central metal ion. The slope of the regression line for partially substituted rhodium acetylacetonates is *ca.* 10 % less than that of the line for the corresponding cobalt series. This implies that intramolecular interannular electronic effects are transmitted to a lesser extent through the rhodium ion. This result is opposite to that expected from atomic polarization.

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German version: Angew. Chem. 77, 154 (1965)

[31] *H. H. Jaffe*, Chem. Reviews 53, 191 (1953).

Recent Results of Configurational Research [*]

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The problems involved in configurational research differ from those of many of the currently important fields of general chemistry. Consequently, many chemists are less familiar with recent developements in this field than, for example, with those of the generally important modern ideas on valence and reaction mechanisms. A survey of new methods and recent results of configurational studies is attempted in this review, some unpublished experimental findings by the author being included. However, no attempt has been made to present an exhaustive review, nor to give a detailed treatment of individual problems which may interest the specialist.

I. Absolute Configuration

The foundations of configurational stereochemistry rest on three great achievements of the last century: the discovery of the optical activity of organic compounds by *Jean Baptiste Biot* (1815), the discovery of optical isomerism by *Louis Pasteur* (1860), and the hypothesis of the tetrahedral arrangement of the substituents on saturated carbon atoms by *Jacobus Henricus van't Hoff* (1874).

The most important development in recent years in configurational chemistry, and at the same time one of the most important ever in this field, was the discovery by *Bijvoet*, *Peerdeman*, and *van Bommel* in 1951 of a physical method for determining absolute configurations [1]. This method is based on X-ray structural analysis with rays of anomalous phase difference, and led first to the elucidation of the absolute configuration of tartaric acid [2] and thereby to the establishment of the absolute configurations of all compounds which had been related to tartaric acid. Somewhat later it led to the elucidation of the configuration of isoleucine [3], and hence to a knowledge of the absolute configurations of all the other naturally occurring α-amino acids.

Long before *Bijvoet* made his discovery, theorists had tried to relate the rotation of plane-polarized light to absolute configuration and to predict the absolute configuration of an optically active compound from the direction of its rotation [4]. Similarly, detailed theories had been developed for the mechanisms of substitution at asymmetric carbon atoms, the practical value of which culminated in the empirical rule that Walden inversion always occurs when a bimolecular mechanism can be detected by kinetic measurements in the case of nucleophilic substitution (S_N2 rule) [5]. The main significance of the determination of absolute configuration (*Bijvoet*'s method is the only one yet known) lies in the fact that it is the basis and a criterion for the verification and development of any theory of optical activity [6], and of the Walden inversion [5].

Knowledge of absolute configurations is still only of hypothetical importance for the as yet unsolved problem of the origin of optical activity in living organisms. So far, only hypothetical answers to this question exist, and these fall into two categories. On the one hand, it is contended that the optically active substances in nature could have arisen by chance, although chemists have never succeeded in preparing an optically active substance from an inactive substance by a chemical reaction without the aid of a directing agent. On the other hand it is thought that a directional influence was present at the original production of the first optically active substance. A noteworthy attempt to show that the original production of optically active substances may have been due to the recently discovered non-validity of the law of parity for elementary particles has been abandoned for the present [7].

Important reference compounds whose absolute configurations have been elucidated with the aid of X-rays of anomalous phase-difference are, in addition to tartaric acid and isoleucine, bulbocapnine [8] (an atropisomeric biphenyl derivative), dihydro-β-erythroidine [9] (which has an asymmetric spiro-carbon atom), the tri-isopropylenediaminecobalt(III) ion [10], strychnine [11], and α-naphthylphenylmethylsilane [8] (a compound with an asymmetric silicon atom).

[*] From a plenary lecture delivered at the general meeting of the Gesellschaft Deutscher Chemiker in Heidelberg (Germany), September 13th, 1963.

Presentations of the entire field: *K. Freudenberg:* Stereochemie. Deuticke, Leipzig-Vienna 1933; *W. Klyne:* Progress in Stereochemistry. Wiley, New York 1954, Vol. 1, p. 177ff.; *E. L. Eliel:* Stereochemistry of Carbon Compounds. McGraw-Hill, New York 1962.

[1] Review: *J. M. Bijvoet*, Endeavour *14*, 71 (1955).

[2] *J. M. Bijvoet, A. F. Peerdeman*, and *A. J. van Bommel*, Nature (London) *168*, 271 (1951).

[3] *J. Trommel* and *J. M. Bijvoet*, Acta crystallogr. *7*, 703 (1954).

[4] *W. Kuhn*, Z. physik. Chem. B *31*, 23 (1936); Z. Elektrochem., Ber. Bunsenges. physik. Chem. *56*, 506 (1952); *W. J. Kauzmann, J. E. Walter*, and *H. Eyring*, Chem. Reviews *26*, 339 (1940); *W. W. Wood, W. Fickett*, and *J. G. Kirkwood*, J. chem. Physics *20*, 561 (1952).

[5] For a detailed discussion, see *C. K. Ingold:* Structure and Mechanism in Organic Chemistry. Bell, London 1953, pp. 372ff.

[6] For the present state, see *D. J. Caldwell* and *H. Eyring*, Rev. mod. Physics *35*, 577 (1963).

[7] *T. L. V. Ulbricht* and *F. Vesta*, Tetrahedron *18*, 629 (1962).

[8] *T. Aschida, R. Pepinsky*, and *Y. Okawa* in International Union of Crystallographers. VI. Gen. Assembly, Congress and Symposia, Rome, (September 9–18th, 1963), Abstr. of Communications, see Acta crystallogr. *16*, A 48 (1963).

[9] *A. W. Hanson*, Proc. chem. Soc. (London) *1963*, 52.

[10] *Y. Saito, H. Iwasaki*, and *H. Ota*, Bull. chem. Soc. Japan *36*, 1543 (1963).

[11] *A. F. Peerdeman*, Acta crystallogr. *9*, 824 (1956).

The compounds investigated by *Bijvoet* included sodium chlorate and sodium bromate which, like quartz, are optically active only in the crystalline state. Here the activity is not due to the shape of the molecule, but to the asymmetric arrangement of the structural units in the crystal lattice. The two salts are isomorphous. They form a continuous series of mixed crystals. The arrangement of the ions in the lattice is in principle identical, the only difference being that the dimensions of the elementary cell of the bromate lattice are slightly greater than those of the chlorate lattice.

It is therefore extremely surprising to find that the sign of the optical rotation of the bromate crystals [12] is opposite to that of the chlorate crystals [13] of the same configuration. No reliable explanation for this phenomenon has yet been given. *Bijvoet* himself put forward a tentative explanation, but despite careful checking, has so far found no experimental evidence to support it.

Since the two salts have almost identical lattices and form a continuous series of mixed crystals, it was to be expected that seeding of a saturated or slightly supersaturated solution of sodium chlorate with sodium bromate crystals would lead to the growth of sodium chlorate crystals with the same configuration as the seed crystals, and vice versa. In fact, numerous seeding experiments showed, without exception, that sodium bromate crystals always stimulate the growth of sodium chlorate crystals, with a sign of rotation opposite to that of the seed crystals. Similarly, sodium chlorate crystals only cause the growth of bromate crystals with the opposite sign of rotation. Despite initial difficulties, it also became possible to study the rotation of mixed crystals of sodium chlorate and sodium bromate. The results again confirmed that sodium chlorate and bromate of the same configuration rotate polarized light in opposite directions [14].

II. Nomenclature

At a time when only relative configurations could be determined, it was sufficient to use a few reference compounds to characterize configurations. Hydroxy compounds were related to optically active glyceraldehyde, and amino acids to optically active serine; one of the two possible steric formulae of these reference substances was assigned by convention to one of the enantiomorphs, and the prefixes D or L were appended to the names to indicate structural similarity of the compounds in question to D-(+)-glyceraldehyde or L-(−)-serine. Configurational relationships in steroid chemistry were denoted by the symbols α and β [15].

A new method of denoting configurations proposed by *Cahn*, *Ingold*, and *Prelog* [16] does not require a reference compound but expresses directly the absolute configuration of the active form in question. The two stereoisomeric forms are denoted by letters *R* and *S* according to the following principles: Sequence rules are used to establish an order of precedence for each of the four different substituents on the carbon atom. The asymmetric carbon atom is then oriented so that the substituent with the lowest precedence is turned away from the observer, and the other three lie on a circle perpendicular to the line of vision. If the order of precedence of the three ligands decreases in a clockwise direction, the asymmetric carbon atom is given the designation "*R*" (Lat. rectus = right), while if the class decreases in an anticlockwise direction, the designation "*S*" (Lat. sinister = left) is given.

The nomenclature of *Cahn*, *Ingold*, and *Prelog* also applies to atropisomerism and to the optical isomerism of allenes and spiro-compounds. One of the great advantages of this method of designating configurations is that it is absolutely unambiguous; consequently, there should be no future danger of confusion or disagreement as to notation.

III. Correlative Determinations of Configuration

In order that *Bijvoet*'s method may be applied, the asymmetric compound should contain an atom the eigen-frequency of which is similar to that of the X-rays used. This is not the case, for example, with hydrocarbons or alcohols. However, it is sufficient that the X-ray method has given and will continue to give the absolute configurations of reference compounds, A large number of asymmetric compounds can be related to these standards by the methods of "relative configurational analysis", thus yielding "absolute" configurations by an indirect route. A survey of recent methods and results in relative configurational analysis is given in the following Sections.

1. The Quasi-Racemate Method

This method originated in an investigation by *Timmermanns* in 1929 [17] and was developed mainly by *Fredga* [18]. It involves determination of the configuration of

[12] *G. Beurskens-Kerssen, J. Kroon, H. J. Endeman, J. van Laar,* and *J. M. Bijvoet,* in *G. N. Ramachandran:* Crystallography and Crystal Perfection, Proc. Sympos. Madras (January 14–18th, 1963). Academic Press, London-New York 1963, p. 225ff.

[13] *G. N. Ramachandran* and *K. S. Chandrasekaran,* Acta crystallogr. *10*, 671 (1957).

[14] Unpublished work by the author. Seeding methods of this type had already been attempted unsuccessfully over a century ago by *H. Marbach* who discovered the optical activity of the chlorate and bromate. The direction of rotation of bromate crystals, whose growth had been induced by chlorate, could not be determined owing to "lamellar polarization"; in the case of chlorate seeded with bromate, *Marbach* claimed that the directions of rotation of the "nucleus and the crust", *i.e.* of the seed crystal and of the crystals grown on it, were sometimes similar and sometimes opposite [Poggendorfs Ann. Physik Chemie, 4th Series, *H. Marbach*, *9*, 459 (1856)].

[15] See *L. F. Fieser* and *M. Fieser*: Steroids. Reinhold, New York 1959; Proposals for use of the (R)/(S)-nomenclature, see *G. R. Pettit,* Experientia *19*, 124 (1962).

[16] The first postulate of this new mode of designating configurations was published shortly before the determination of the absolute configuration of tartaric acid, and was based on D-(+)-glyceraldehyde as standard: *R. S. Cahn* and *C. K. Ingold,* J. chem. Soc. (London) 1951, 612. The second published version was based on absolute configurations: *R. S. Cahn, C. K. Ingold,* and *V. Prelog,* Experientia *12*, 81 (1956). Most recent publications: *R. S. Cahn,* J. chem. Educat. *41*, 116 (1964); *R. S. Cahn, C. K. Ingold,* and *V. Prelog,* Angew. Chem. and Angew. Chem. internat. Edit., in the press.

[17] *J. Timmermans,* Recueil Trav. chim. Pays-Bas *48*, 890 (1929).

[18] Summary: *A. Fredga,* Tetrahedron *8*, 126 (1960).

an optically active compound, *e.g.* (−)-bromosuccinic acid, by comparison with another active compound of similar molecular structure, *e.g.* (+)-chlorosuccinic acid, the configuration of which is known or is taken as a standard. A melting point *vs.* composition diagram of mixtures of the standard and the test sample is plotted. If the sample has the same configuration as the standard, the phase diagram is that of a solid solution; if the configurations are opposite, the compounds form a "quasi-racemate". Like a true racemate [*e.g.* a 50:50 mixture of (+)- and (−)-chlorosuccinic acids], a quasi-racemate [*e.g.* (+)-chlorosuccinic acid and (−)-bromosuccinic acid] is reflected in the phase diagram by a special branch of the curve with a maximum at 50 mole-%. Even when an optically active substance forms a solid solution with one of the enantiomorphs of the standard and an ordinary eutectic instead of a quasi-racemate with the other, an assignement can still be made [19]. The compound under investigation has the same configuration as its partner in the solid solution.

The results achieved by this method include the correlation of methyl-, chloro-, mercapto-, and hydroxysuccinic acids [18]. Very recent results regard the configurations of an asymmetric silicon compound [20] and an asymmetric germanium compound [21].

Conclusions based on the quasi-racemate method are extremely reliable; no case is known so far in which a result has subsequently heen shown to be wrong. However, the method is subject to certain restrictions. The substances must be crystalline and a reference substance of known configuration with a molecular structure similar to that of the test substance must be available. Occasionally, although rarely, the optically active substance forms quasi-racemates with both enantiomorphs of the reference compound [21a]; no conclusion can then be drawn.

2. Asymmetric Synthesis

The term "asymmetric syntheses" is used here [22] to denote syntheses in which a non-asymmetric starting material, *e.g.* an α-ketocarboxylic acid, is temporarily linked to an optically active compound of known configuration, *e.g.* is esterified with an optically active secondary alcohol. The keto ester is reduced or condensed with a Grignard reagent to yield a hydroxy ester, thus creating a second optically active carbon atom in the molecule. One of the two diastereoisomeric compounds to be expected is formed in excess, and hence subsequent saponification does not lead to a racemic but to a partially optically active β-hydroxycarboxylic acid. The configuration favored at the second asymmetric center depends on the configuration of the carbinol carbon atom of the original alcohol, and can be predicted by *Prelog*'s method [23] from the space requirements of the three substituents on this carbon atom. Conversely, if the configuration of the preferentially formed β-hydroxycarboxylic acid is known, the configuration of the active alcohol can be found [24]. This method led to the establishment of the configurations of, for example, atrolactic acid [25] and various triterpene alcohols [24] (α-amyrin, eupbol, dihydrolanosterol).

3. The Cotton Effect (Rotatory Dispersion and Circular Dichroism)

Within the past eight years, optical rotatory dispersion in the ultraviolet has rapidly become an important aid to configurational research. The principle is not new, as can be seen from the fundamental work of *Werner Kuhn* [26]. However, it has only become widely used since ultraviolet polarimeters became available. Credit for this is due to the pioneering work on steroids by *Djerassi* and his co-workers, which stimulated industrial production of the first ultraviolet polarimeter in the U.S.A.

The theory and results of the method can be only briefly indicated here [27,28]. Many optically active organic compounds, including saturated hydrocarbons, alcohols, fatty acids, and amino acids, show a monotonic increase in optical rotation, which obeys the simple Drude equation, on passing from longwave to shortwave light regions (down to ca. 260 mμ) [29].

However, if an asymmetric molecule contains a chromophore in the direct vicinity of the asymmetric center, a phenomenon known as the Cotton effect can be observed in the dispersion curve: the specific rotation passes through a maximum on the steep side of the absorption band, this is followed by a sudden drop, and finally reversal of the sign of rotation occurs. A change in sign with decreasing wavelength from (+) to (−) is termed a positive Cotton effect; if the change is from (−) to (+), the Cotton effect is termed negative.

It has been found that structurally similar compounds of the same configuration give Cotton effects of the same sign. This is the vital point in this "analogy" method for configurational analyses, which has proved useful especially in the investigation of steroid ketones and halogenated cyclic ketones.

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[19] *T. Raznikiewicz*, Acta chem. scand. *16*, 1097 (1962).

[20] *L. H. Sommer*, Angew. Chem. *74*, 176 (1962); Angew. Chem. internat. Edit. *1*, 143 (1962).

[21] *A. G. Brook* and *G. J. D. Paddle*, J. Amer. chem. Soc. *85*, 1869 (1963).

[21a] *M. Matell*, Dissertation, Universität Uppsala (Sweden) 1953, S. 21. Quoted after *K. Petterson*, Ark. Kemi *10*, 283 (1956) Ref. 9.

[22] For a treatise on asymmetric syntheses in general, see *J. J. Klabunowski*: Asymmetrische Synthese. Deutscher Verlag für Wissenschaften, Berlin 1963.

[23] *V. Prelog*, Bull. Soc. chim France *1956*, 987.

[24] *W. G. Dauben, D. F. Dickel, O. Jeger*, and *V. Prelog*, Helv. chim. Acta *36*, 325 (1953).

[25] *V. Prelog* and *H. J. Meier*, Helv. chim. Acta *36*, 320 (1953).

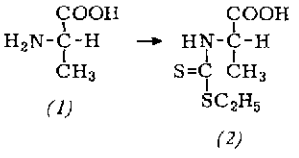
[26] *W. Kuhn, K. Freudenberg*, and *J. Wolf*, Ber. dtsch. chem. Ges. *63*, 2367 (1930); see also [28].

[27] Summary: *C. Djerassi:* Optical Rotatory Dispersion, Applications to Organic Chemistry. McGraw-Hill, New York-London 1960.

[28] *H. G. Leemann* and *K. Stich*, Chimia *14*, 1 (1960); *17*, 184 (1963). These articles also contain a useful bibliography, including a list of all the publications by *W. Kuhn* on optical activity, and a list of the first 76 publications (up to the end of 1962) by *C. Djerassi et al.* on optical rotatory dispersion.

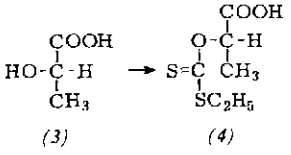
[29] A plot of $[\alpha]_D$ against λ gives the so-called optical rotatory dispersion curve.

It is significant that this method can also be applied to compounds which do not show the Cotton effect within experimentally accessible wavelength regions, provided that a chromophore can be introduced into the molecule close to its asymmetric center. For example, ethyldithiocarbamidocarboxylic acids *(2)*, which are readily prepared from amino acids *(1)* by successive treatment with carbon disulfide and ethyl bromide [30], have an absorption maximum at 345 mμ; as expected, they also exhibit a Cotton effect at this wavelength, the signs being the same for similar configurations [31].



(1) *(2)*

Optically active hydroxycarboxylic acids *(3)* were investigated by rotatory dispersion in the form of their xanthates *(4)* which are structurally very similar to the ethyldithiocarbamidocarboxylic acids *(2)* [32]. Once again, the rule was confirmed: identical configurations give Cotton effects of the same sign.



(3) *(4)*

Besides rotatory dispersion, the related phenomenon of circular dichroism is gaining practical importance in connection with problems of configurational analysis. Here, too, the basic principles were laid in the thirties [33], but an instrument for the measurement of circular dichroism [34] became commercially available only in 1961. Consequently, organic chemists are only now beginning to measure and make use of circular dichroism, the principle and the importance of which were discussed recently in detail [35]. It is especially important that circular dichroism can frequently be measured at wavelengths at which polarimetry can no longer be used, owing to high molar extinction.

4. Inclusion Method

The principle of the inclusion method [36] is the following: The hexagonal urea lattice can be regarded as a system of parallel channels. It can occur in two stereoisomeric forms: in one of these the urea molecules, representing the walls of the channels, are arranged in the form of a right-handed helix; in the other they form a left-handed helix. If crystallization is left to chance, right-handed and left-handed crystals are formed together. However, methods have been found by which one of the two helical lattices can be grown exclusively.

If such configuratively homogeneous crystals, *e.g.* right-handed crystals, are allowed to grow in the solution of a racemate, *e.g.* ethyl α-methylbutyrate, whose molecules can form urea adducts, it is found that one of the two enantiomorphs, *e.g.* ethyl (+)-α-methylbutyrate, is preferentially taken up by the right-handed crystals, since by virtue of its shape, the dextrorotatory molecule fits better into the urea helix than the enantiomorphic levorotatory molecule does. If the preferential inclusion of (+)-α-methylbutyrate is determined by its shape, it could be expected, that of other racemates with structures similar to that of ethyl α-methylbutyrate the enantiomorph with a similar shape, *i.e.* with the same configuration as (+)-α-methylbutyrate, would be taken up preferentially, too. This is in fact the case. Table 1 shows the results of such relative configuration studies for four sets of sterically related compounds.

Table 1. Configurative relationships of steric series found by the urea inclusion method (see text).

Carboxylic acid	Urea inclusion lattice
(+)-2-Methyl fatty acids (−)-2-Chloro fatty acids (−)-2-Amino fatty acids (−)-2-Mercapto fatty acids	Enantiomeric form A [a]
(−)/(−)-3-Methyl fatty acids (+)/(−)-3-Chloro fatty acids (+)-3-Mercapto fatty acids	Enantiomeric form A
(+)-Aspartic acid (−)-Malic acid (−)-Thiomalic acid (−)-Chlorosuccinic acid (−)-Methylsuccinic acid	Enantiomeric form A
(+)-Glutamic acid (−)-2-Hydroxyglutaric acid (−)-2-Chloroglutaric acid (+)-2-Methylglutaric acid	Enantiomeric form A

[a] As the absolute configuration of the lattice is not yet known, the enantiomeric forms are distinguished as "form A" and "form B".

The enantiomorphs bracketed together are taken up preferentially by the same helical lattice; these enantiomorphs should, therefore, have the same configuration. The (+)/(−) signs shown together for the 3-methyl and 3-chloro fatty acids are a result of the reversal of sign of configuration in this series: for a given configuration, the lower members of the series are dextrorotatory, while the higher members are laevorotatory. The results obtained with this method agree with the now generally accepted scheme of configurational relationships developed from the results of many methods during the last thirty years.

Like all methods based on analogy – (with the exception of X-ray, chemical, and mathematical methods, all methods of configuration analysis are based on analogy) – the inclusion method must be used with care. Detailed investigations have shown that the configuration of a molecule is not always the

[30] *A. Fredga*, Svensk kem. Tidskr. *53*, 221 (1941); *54*, 26 (1942).

[31] *B. Sjöberg, A. Fredga*, and *C. Djerassi*, J. Amer. chem. Soc. *81* 5002 (1959); *C. Djerassi, H. Wolf*, and *E. Bunnenberg*, J. Amer. chem. Soc. *84*, 4552 (1962).

[32] The configurations of the two groups of compounds had already been correlated by the quasi-racemate method, on the basis of their structural similarity, see [30].

[33] Summary: see *W. Kuhn* in *K. Freudenberg*: Stereochemie. Deuticke, Leipzig-Vienna 1933, p. 317–434.

[34] *M. Grosjean* and *M. Legrand*, C. R. hebd. Séances Acad Sci. *251*, 2150 (1960).

[35] *L. Velluz* and *M. Legrand*, Angew. Chem. *73*, 603 (1961); *L. Velluz, M. Legrand*, and *M. Grosjean*: Optical Circular Dichroism; Principle, Measurements, and Applications. Verlag Chemie, Weinheim/Bergstr., and Academic Press, New York 1965.

[36] Unpublished work by the author. A detailed publication is planned for 1965. For short reports see: Angew. Chem. *67*, 762 (1955); Svensk kem. Tidskr. *67*, 456 (1955).

only factor governing the preferential uptake of one or the other enantiomorph by the urea lattice. For example, introduction of an ether oxygen or sulfur atom into a carbon chain of a molecule can cause reversal of its configurative relationship to the inclusion lattice, although the configuration of the derivative is the same as that of the parent molecule and the geometry of the latter is scarcely altered by the hetero-atom. Such anomalies are useful for studies of the forces existing between the urea lattice and included molecules, but present an obstacle to routine configurational analysis.

5. Investigation of the Configuration of Optically Inactive Asymmetric Substances — A Problem of Biogenetic Triglycerides

Normally enantiomorphs can be recognized by their ability to rotate the plane of polarized light, one enantiomorph causing rotation to the right, and the other an equal rotation to the left. However, enantiomorphs can also be optically inactive, *i.e.* inactive for our methods of measurement Only one example of this is known at present, *viz.* the triglycerides of the higher fatty acids, which form the major constituents of natural fats.

All triglycerides with three different acid components or two different acid components in the 1- and 3-positions have an asymmetric carbon atom in the 2-position of the glycerol residue. However, no triglyceride with measurable optical activity has ever been isolated from natural fats. Glycerides containing optically active acids (*e.g.* ricinoleic acid) are not considered here. All the aliphatic triglycerides prepared by syntheses which should have yielded optically active products were also inactive. *Fischer* and *Baer* suggested that the absence of measurable optical activity despite an asymmetric structure was characteristic of triglycerides which contain only aliphatic acid residues, and that, although natural triglycerides do not exhibit rotatory power, they are not necessarily racemates, but may be present in one of their two enantiomorphic forms [37].

The first of these assumptions is not generally valid. With regard to the second point, it has been shown that certain triglycerides occurring in natural fats do not in fact exhibit measurable activity in their enantiomorphic form. It has also been shown how such optically inactive enantiomorphs can be distinguished from their racemates, and how their absolute configurations can be determined. Finally, it has been shown for one triglyceride isolated from natural material that it is a racemate and not an enantiomorph [38].

In natural glycerides, the fatty acid residues in the 1- and 3-positions are generally very similar, *e.g.* palmitoyl and stearoyl residues, and hence the asymmetry of the molecule is very slight. This is true of all the aliphatic triglycerides made by *Fischer* and *Baer*, which exhibited no rotation.

We assumed that optical activity would be observed only if the fatty acid residues in the 1- and 3-positions differed considerably in size and shape, and so we prepared a number of such triglycerides (starting in each case with an optically active monoglyceride), *e.g.* 1-trimethylacetyl-2,3-di-n-valerin, 1-myristo-2,3-diisovalerin, 1-palmito-2,3-diisovalerin, 1-lauro-2,3-dibutyrin, 1-myristo-2,3-dibutyrin, and 1-lauro-2,3-dipalmitin. All these triglycerides were found to be optically active, the first five in the visible region, the last only in the ultraviolet (the C_{12} and C_{16} residues are relatively large and differ only slightly). On the other hand, glycerides with large acid residues, *e.g.* 1-palmito-2-oleo-3-stearin, which were prepared by the same method, exhibit no measurable activity, even in the ultraviolet. A method for distinguishing between enantiomorphs and racemates in such molecules was based on the piezoelectricity of the triglyceride crystals.

When crystals belonging to one of the 21 classes without centers of symmetry are subjected to mechanical pressure in a direction of structural polarity, they acquire an electrical charge. All crystals consisting of one enantiomorph of asymmetric molecules must exhibit the piezoelectric effect. Thus, if asymmetric triglycerides are enantiomorphs and not racemates, they should be piezoelectric. In crystals of racemates, on the other hand, the absence of a center of symmetry, and hence the existence of a piezoelectric effect, is not entirely ruled out, but is unlikely. We know of no case in which a true racemate crystallizes in an asymmetric lattice.

With the aid of the piezoelectrometer recently developed by *Bergmann* [39], it was indeed possible, to detect the piezoelectric effect in glycerides which, according to their synthesis, should have been enantiomorphs, even though they did not exhibit optical activity. Moreover, as expected, the effect was not observed with racemates (Table 2).

Table 2. Piezoelectric measurements of glyceride crystals.

Triglyceride	Piezoelectric effect
Act. 1-lauro-2,3-dipalmitin	present
Racem. 1-lauro-2,3-dipalmitin	absent
Act. 1-stearo-2,3-dipalmitin	present
Racem. 1-stearo-2,3-dipalmitin	absent
Act. 1-palmito-2-oleo-3-stearin	present
Racem. 1-palmito-2-oleo-3-stearin	absent
Act. 1-oleo-2-palmito-3-stearin	present
Racem. 1-oleo-2-palmito-3-stearin	absent

Another method for distinguishing between racemates and enantiomorphs in the absence of measurable optical activity was afforded by comparative X-ray investigations. For every triglyceride examined, it was found that the "active" glycerides, even those which do not exert a measurable rotation, always crystallize in a lattice different from that of the corresponding racemates.

As an example, the X-ray diagrams for the two enantiomorphs of 1-lauro-2,3-dipalmitin are shown in I and II of Figure 1; these diastereoisomeric forms are naturally identical on X-ray examination, and the X-ray diagram of the racemate shown in III can be distinguished from these at a glance.

Diagram IV confirms that I and II represent enantiomorphs and that III represents the racemate, since IV is derived from the crystals obtained from a solution

[37] *H. O. L. Fischer* and *E. Baer*, Chem. Reviews *29*, 298 (1941).

[38] Unpublished work by the author. A detailed publication is planned for 1965. A short report appeared in a publication dedicated to *Carl Wurster*, BASF, Ludwigshafen 1960 (not on sale); see Chem. Abstr. *57*, 14930g (1962).

[39] *L. Bergmann*, Z. Instrumentenkunde *65*, 1 (1957).

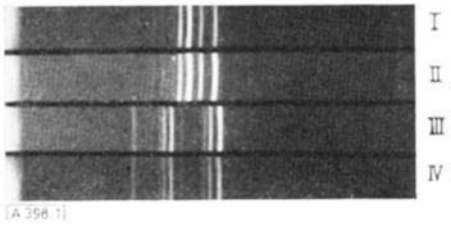
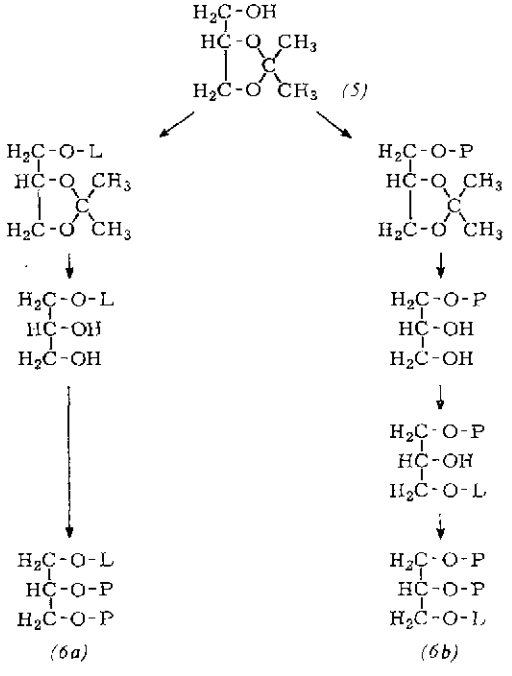


Fig. 1. X-ray diagrams of 1-lauro-2,3-dipalmitin (Cu-K_α radiation, Guinier). I and II: Enantiomorphs; III and IV: Racemate.

containing equal quantities of the two enantiomorphs. It is clear that the racemate IV, which was obtained by mixing the enantiomorphs, is identical with the racemate prepared directly.

The preparative routes leading to the two enantiomorphs of 1-lauro-2,3-dipalmitin, both starting with the same optically active raw material, *viz.* D-(+)-1,2,*O*-isopropylideneglycerol *(5)*, are shown in Scheme 1.



Scheme 1. Synthesis of the two enantiomorphs *(6a)* and *(6b)* of 1-lauro-2,3-dipalmitin (L and P denote the lauroyl and palmitoyl residues, respectively).

The configurations of the two compounds are predetermined by the synthesis and are represented in the projection formulae. Since the absolute configuration of the starting material is known, the two formulae also represent the absolute configurations of the two triglycerides, (−)-*(S)*-1-laurodipalmitin *(6a)* and (+)-*(R)*-1-laurodipalmitin *(6b)*.

On the basis of these results, the question, whether a sample of a given triglyceride of known constitution, *e.g.* 1-stearo-2,3-dipalmitin, is an enantiomorph or a racemate, can be resolved experimentally by synthesizing the respective racemate and one of the antipodes of the compound in question and comparing the X-ray diagrams of these three samples. If the X-ray diagram of the sample to be tested is the same as that of the racemate, the problem is solved. On the other hand, if the X-ray diagram of the sample to be tested is the same as that of the enantiomorph, it is an enantiomorph itself, though it cannot be said which one it is, since the X-ray diagrams of the enantiomorphs are identical.

Which enantiomorph is present, can then be resolved as follows: Some of the substance in question is mixed with an equal amount of the synthetic enantiomorph, and the X-ray diagram of the crystals of the mixed product is measured [40]. If the X-ray diagram remains unchanged, the enantiomorph in question is the same as that synthesized, the configuration of which is known. On the other hand, if the diagram is that of the racemate, the substance being examined is the enantiomer of the sample used for comparison.

Experience gained with synthetic materials make it possible to determine whether naturally occurring glycerides are optically active or racemic.

An investigation of this type was carried out on 1-palmito-2-oleo-3-stearin, a major constituent of cocoa bean oil. The glyceride was extracted from cocoa butter, from fermented unroasted cocoa beans, and from fresh germinable seeds of cocoa fruits harvested a few days before processing [41], since denaturation of the fat was possible during the technical preparation of the cocoa butter, or even during the fermentation of the beans.

The glyceride was isolated under mild conditions (extraction with ether, fractional crystallization from acetone) so that no racemization was to be anticipated on the basis of experience gained with synthetic glycerides exhibiting measurable optical activity. The glyceride obtained in all three cases was found to be a racemate.

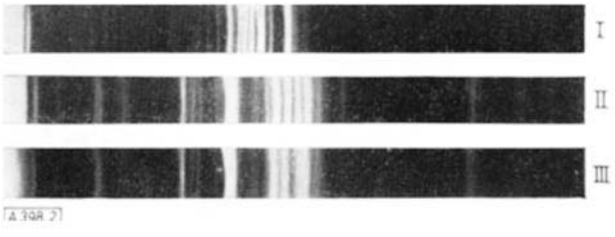


Fig. 2. X-ray diagram of 1-palmito-2-oleo-3-stearin (Cu-K_α radiation, Guinier). Active (I), racemic (III), and glyceride isolated from cocoa beans (II).

In the center of Figure 2, the X-ray diagram for the 1-palmito-2-oleo-3-stearin isolated from the natural fat is shown; above this is the diagram for the corresponding active glyceride, and below is that of the racemic form, both of which were synthesized. The central diagram is clearly identical with the lower one and not identical with the upper one. The racemic configuration of a biogenetic triglyceride was proved in this way for the first time. *Holman* [42] recently showed that the

[40] Mixed crystals of the sample and the synthetic enantiomorph are prepared by dissolving equal amounts of both substances in ether or in acetone/petrol ether and crystallizing them at a low temperature.

[41] We are indebted to Messrs. Schokinag, Mannheim (Germany), for procuring the fresh fruit from Nigeria.

[42] *R. T. Holman*, Fall Meeting of the American Oil Chemists' Society, J. Amer. Oil Chem. Soc. *40*, No. 9, 9 (1963). Prof. *Holman* kindly allowed the author to peruse the manuscript.

seed fat of two *Euphorbiaceae* [43] probably contains asymmetric triglycerides of measurable, and quite appreciable, optical activity ($[\alpha]_D \approx 19°$). The specific rotation is many times higher than that of the most unusual optically active triglycerides so far prepared by us. *Holman*'s view that the strong rotation may be due to the 2,4-hexadienecarboxylic acid which has been detected in the fat and which could act as a chromophore, is quite plausible. We prepared a triglyceride containing sorbic acid and found it to exhibit a relatively high specific rotation [44].

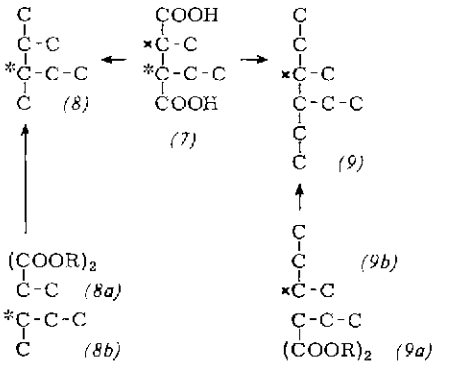
Naturally, these first findings on the configuration of fats cannot be generalized: neither the fact that the l palmito-2-oleo-3-stearin of cocoa butter is racemic, nor the supposition that glycerides of *Sapium sebiferum* and *Sebastiana lingustrina*, both of which contain 2,4-decadienoic acid, are produced in nature as enantiomorphs. If both findings are correct, then glycerides can be synthesized both stereospecifically and non-stereospecifically in nature.

6. Chemical Reactions

Despite the evolution of new physical methods of configurational analysis, the classical method of correlating asymmetric compounds by chemical reactions has certainly not become less valuable. With the exception of X-ray structural analysis, the chemical method has the advantage over all other methods in being invariably accurate. Its limitation is that the asymmetric carbon atom must not be affected by the reaction, *i.e.* none of the four bonds attached to it may be broken unless it is known with certainty whether or not Walden inversion occurs. A recent example of the remarkable achievements obtained using the chemical method is the success in relating the asymmetric tertiary carbon atom of (−)-dihydroshikimic acid to the asymmetric center of secondary hydroxy compounds, *e.g.* glucose, by oxidative ring cleavage of (−)-dihydroshikimic acid and reduction of the cleavage product to (+)-3-methylhexane [45].

This is the first case in which two steric series with different substituents on the asymmetric carbon atom have been related by chemical methods, without the asymmetric center itself being affected.

Of the many other examples the determination of the configuration of atropisomeric biphenyl derivatives using the chemical method [46] is noteworthy. The configuration of adjacent, non-equivalent, tertiary carbon atoms has also been determined by chemical methods [47]. The principle is shown in Scheme 2 for 2-ethyl-3-methylsuccinic acid.



Scheme 2. Chemical determination of the configuration of 2-ethyl-3-methylsuccinic acid.

The two asymmetric centers of the acid *(7)* are indicated by an asterisk and a cross. The acid is reduced to the hydrocarbon *(8)*, whereby the asymmetric center × is lost, while the asymmetric center * is retained. The hydrocarbon *(8)* can also be prepared in a sterically controlled reaction [48] from methylmalonate *(8a)* and optically active 2-bromobutane *(8b)*. This gives the configuration at the asymmetric center *.

The acid *(7)* can also be converted into the hydrocarbon *(9)* by chain extension followed by reduction. In this reaction the asymmetric center × remains intact, while center * disappears. The hydrocarbon *(9)* can be prepared in a sterically controlled reaction [48] from ethylmalonate *(9a)* and optically active 2-bromobutane *(9b)* by condensation, elimination of CO_2, chain extension, and reduction. This gives the configuration at the asymmetric center ×.

The configurations of both the active *threo*-form and the active *erythro*-form of the acid *(8)* were determined by this method. Any other 2,3-dialkylsuccinic acid can obviously be studied in exactly the same manner.

The method is simpler for 2,3-dialkylsuccinic acids with two identical alkyl residues, since the acid need be converted into only one hydrocarbon, and only this hydrocarbon need be synthesized from the malonic ester, because it contains two equivalent asymmetric carbon atoms.

The author is grateful to the management of Badische Anilin- und Sodafabrik for permitting him to devote time to work in this field. Thanks are also due to Dr. H. U. Lenné for the X-ray diagrams of the triglycerides, and to the author's colleagues of many year's standing, namely Josef Strubel, Herbert Esswein, Friedrich Schmidt, Günther Riewe, Edith Henn, and Johanna Wahl for the experimental results reported from the Ammonia Laboratory.

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Translated by Express Translation Service, London

[43] *Sapium sebiferum* and *Sebastiana lingustrina*.

[44] We prepared this glyceride after we had heard of *Holman*'s investigations.

[45] *K. Freudenberg, H. Meisenheimer, J. T. Lane*, and *E. Plankenhorn*, Liebigs Ann. Chem. *543*, 162 (1940); *K. Freudenberg* and *J. Geiger*, ibid. *575*, 145 (1951); *K. Freudenberg* and *W. Hohmann*, ibid. *584*, 54 (1953).

[46] *J. A. Berson*, J. Amer. chem. Soc. *78*, 4170 (1956). A detailed report on atropisomerism was recently published by *K. Mislow*: Angew. Chem. *70*, 683 (1958).

[47] Unpublished work by the author.

[48] The phrase "in a sterically controlled reaction" is intended to indicate that the absolute configuration of the malonic ester used as the intermediate is quite accurate.

Reduction of Acid Bromides to Aldehydes by Irradiation in a Hydrogen Donor [1]

By Prof. Dr. Ulrich Schmidt

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The acyl-bromine bond of acylbromides is homolytically split by radiation from a low-pressure mercury lamp. Aldehydes are produced in the presence of a hydrogen donor since the dissociation energy of the acyl-hydrogen bond is similar to or larger than that of the carbon-hydrogen bond of the hydrogen donor. The hydrogen donor is dehydrogenated or hrominated.

Benzaldehyde in 80 % yield was produced on irradiation of henzoylbromide (0.2 mole) in 100 ml ether for 30 h with a low-pressure mercury lamp (10 watts at 254 mμ). The irradiation of acetyl bromide in cumene led to acetaldehyde (isolated as the dinitrophenylhydrazone in 25 % yield) and to 2,3-diphenyl-2,3-dimethylbutane, the dehydrogenation product of cumene. In the absence of light but in the presence of radical initiators no reaction took place. The irradiation of valeroyl bromide in cyclohexane produces small amounts of n-butyl bromide (identified by gas chromatography) which may be formed by decarbonylation of the valeroyl radical and subsequent combination with bromine.

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[1] 2nd Communication on Photochemical Reactions of Carboxylic Acid Derivates. – 1st Communication: *U. Schmidt* and *K. H. Kabitzke*, Angew. Chem. 76, 687 (1964); Angew. Chem. internat. Edit. 3, 641 (1964).

8,8-Disubstituted Xanthines – a Novel Group of Purine Derivatives

By Dipl.-Chem. E. Bühler and Prof. Dr. W. Pfleiderer

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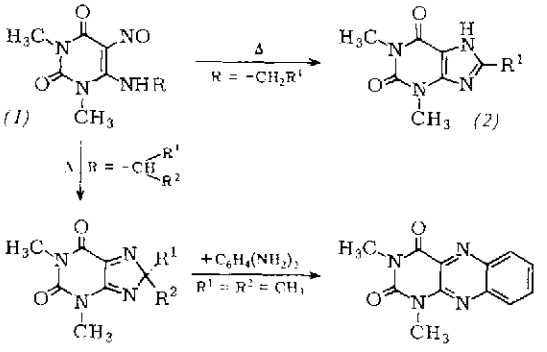
der Technischen Hochschule Stuttgart (Germany)

Fading or decomposition of various 5-nitroso-4-alkylaminouracils during melting point determination [1–4] are due to imidazole ring formation. This has recently been confirmed by other authors [5].

We have found that the presence of a substituent on N-3 or activation of the methylene group adjacent to the nitrogen in the 4-alkylamino side-chain is necessary for the reaction to occur; the cyclization proceeds either on heating the substances neat or on refluxing them for a short time in high-boiling solvents such as n-butanol, dimethylformamide, or *N*-methylpterolidone.

Novel purine derivatives *(3)* and *(4)* are obtained in this way from 1,3-dimethyl-5-nitroso-4-aminouracils whose 4-amino group is substituted by a secondary carbon atom; examples are shown in the formulae.



(1) *(2)* *(5)*

(3), $R^1 = R^2 = CH_3$
(4), $R^1 + R^2 = -(CH_2)_n-$ n = 4, 5, 6

Substance	M.p. [°C]	Yield [%]	pK_a [a]	Ultraviolet absorption [b]		Nature of molecule [c]	at pH [d]
				λ_{max} [mμ]	log ε		
(3)	140–142	74	0.08 ± 0.09	266 (306)	3.90 (3.43)	C	−1.9
				253 302	3.76; 3.43	N	5.0
(4), n = 4	115–118	23	0.47 ± 0.1	267 (310)	3.96 (3.54)	C	−1.9
				245; 302	3.80; 3.42	N	4.0
(4), n = 5	108–109	73	0.30 ± 0.06	270 (305)	3.96 (3.69)	C	−1.9
				253; 300	3.83; 3.50	N	5.0
(4), n = 6	100–103	29	0.40 ± 0.05	266 (303)	4.08 (3.72)	C	−1.9
				250; 302	3.94; 3.55	N	4.0

[a] Determined by spectroscopy. – [b] Values in parentheses: shoulders.
[c] C = cation, N = neutral molecule. – [d] Measured in water.

The *o*-quinonoid structures of the 8,8-disubstituted theophylline derivatives *(3)* and *(4)* led us to expect that these compounds would behave like masked alloxan derivatives. The reaction of *(3)* with the dihydrochloride of *o*-phenylenediamine in aqueous solution did in fact proceed smoothly to give 1,3-dimethylalloxazine *(5)*.

Because of the *o*-quinonoid structures, the long-wave absorption bands in the ultraviolet spectra of *(3)* and *(4)* are bathochromically displaced relative to those of coffeine and isocoffeine. The weakly basic properties resulting from these structures are reflected in the extremely low basic pK_a values of *(3)* and *(4)*.

Received, November 20th, 1964 [Z 872/698 IE]
German version: Angew. Chem. 77, 129 (1965)

[1] *W. Pfleiderer* and *K. Schündehütte*, Liebigs Ann. Chem. *612*, 158 (1958).

[2] *H. Wieland*, Diploma Thesis, Technische Hochschule Stuttgart, 1956.

[3] *W. Pfleiderer* and *G. Nübel*, Liebigs Ann. Chem. *647*, 155 (1961).

[4] *G. Nübel* and *W. Pfleiderer*, Chem. Ber. *95*, 1605 (1962).

[5] *H. Goldner*, *G. Dietz*, and *E. Carstens*, Naturwiss. *51*, 137 (1964); Belg. Pat. 616 174; Chem. Abstr. *58*, 6844 (1963).

Organometallic Derivatives of Cobaloximes and of Vitamin B_{12}

By Priv.-Doz. Dr. G. N. Schrauzer and Dipl.-Chem. G. Kratel

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Bisdimethylglyoximatocobalt(III) compounds of the type $X-(CoD_2H_2)B$ [1], where X = halogen, B = base, and D = the dianion of dimethylglyoxime, are coordination analogues

of vitamin B_{12}. We designate these compounds as "cobaloximes" [2]. On reduction, *e.g.* with $NaBH_4$ in methanol, they give blue to blue-green derivatives ("cobaloximes$_s$") which correspond to vitamin B_{12s} and can be regarded as hydrolysed salts of the weak acid $H-Co(D_2H_2)B$. Cobaloxime$_s$ compounds react with alkylating agents to form alkylcobaloximes $R-(CoD_2H_2)B$, or with organometal halides R_nMX to yield crystalline complexes of composition $R_nM-(CoD_2H_2)B$, where M can be Si, Ge, Sn, Pb, As, Sb, or Bi (see Table). With a few exceptions, these compounds are stable towards oxygen, soluble in organic solvents such as CH_2Cl_2, $CHCl_3$, benzene, and acetone, and resistant to alkali. They are decomposed by strong acids.

Compound [3]	Behavior on heating [4]	Color
$(C_6H_5)_3Si-(Co)-Py$	decomp. at 135–145 °C	yellow-orange
$(C_6H_5)_3Ge-(Co)-Py$	decomp. at 172–180 °C	orange
$(C_6H_5)_3Sn-(Co)-Py$	decomp. at 194 °C	red-orange
$(C_6H_5)_3Pb-(Co)-Py$	decomp. at 190–195 °C	dark brown
$(C_6H_5)_3Pb-(Co)-P(n\text{-}C_4H_9)_3$	m.p. 167–168 °C	brown
$(C_6H_5)_3Sn-(Co)-P(n\text{-}C_4H_9)_3$	m.p. 145–147 °C	orange
$(C_6H_5)_3Sn-(Co)-Sb(CH_3)_3$	decomp. at 164–168 °C	red-orange
$(C_6H_5)_2Sb-(Co)-Py$	decomp. at 185–195 °C	brown
$(C_6H_5)_2Bi-(Co)-Py$	decomp. at 225–230 °C	brown
$(CH_3)_3Sn-(Co)-Py$	decomp. at 172–178 °C	red

The presence of M–Co bonds in these complexes follows from their elemental analyses and from degradation reactions, which proceed by oxidative (*e.g.* with bromine) or by reductive (*e.g.* with $NaBH_4$) cleavage of the M–Co bond. The thermal stability of the compounds containing elements of the fourth and fifth main groups of the periodic table generally rises with increasing atomic weight of the element. Hence, for example, it has so far not been possible to isolate a tritylcobaloxime. Triphenylsilylpyridinatocobaloxime is very sensitive to air and decomposes at a lower temperature than the corresponding derivatives of Ge, Sn, and Pb. The stability of the complexes also depends upon the base component B and upon the effective ligand strength of the nitrogen atoms of the dioxime. Vitamin B_{12s} behaves very similarly to cobaloximes. Solutions possibly containing trialkyltin- and dialkylarsine derivatives of vitamin B_{12} have been obtained on reaction of vitamin B_{12s} with trialkyltin- and dialkylarsenic chlorides. However, these solutions are extremely sensitive to air and the desired compounds could not yet be isolated.

Received, November 23rd, 1964 [Z 864/691 IE]
German version: Angew. Chem. 77, 130 (1965)

[1] *L. Tschugaeff*, Ber. dtsch. chem. Ges. *40*, 3498 (1907).

[2] *G. N. Schrauzer* and *J. Kohnle*, Chem. Ber. *97*, 3056 (1964).

[3] (Co) is used as an abbreviation for (CoD_2H_2); Py = pyridine.

[4] The decomposition points are often very difficult to detect precisely and depend on the rate of heating.

Cyclization of "Nucleoside Dialdehydes" with Nitromethane

By Doz. Dr. F. W. Lichtenthaler, cand. chem. H.P. Albrecht, and Gertrud Olfermann

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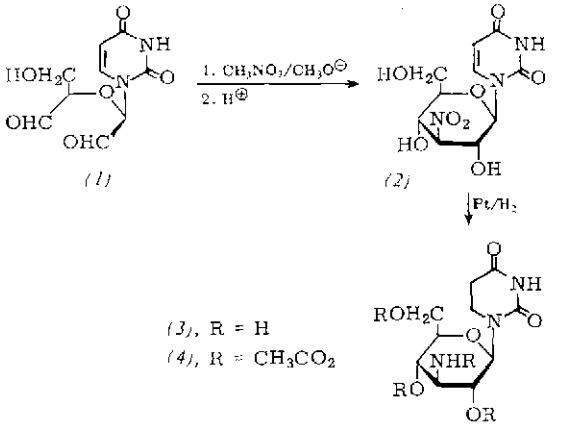
Application of the cyclization of dialdehydes with nitromethane [1] to the "uridine dialdehyde" *(1)* obtained from uridine by oxidation with periodate [2] led to a mixture of 3-nitrohexosides when *(1)* was condensed with nitromethane plus sodium methoxide in methanol and the reaction mixture was subsequently neutralized with methanolic hydrochloric acid. Due to its low solubility in water, 3-(3′-deoxy-3′-nitro-β-D-glucopyranosyl)uracil *(2)* could be isolated from this mixture in 40 % yield as the monohydrate, m.p. 162–164 °C, $[\alpha]_D^{20} = +36°$ in water. On catalytic hydrogenation of *(2)* over platinum the nitro group and the 4,5-double bond in the uracil moiety are reduced; the product obtained is 3-(3′-amino-3′-deoxy-β-D-glucopyranosyl)-4,5-dihydrouracil *(3)*, which was characterized in the form of its hydrochloride (decomposes above 180 °C, $[\alpha]_D^{20} = +20°$ in water) and its tetra-acetate *(4)*, m.p. 281 to 283 °C (decomp.), $[\alpha]_D^{20} = -7°$ in chloroform.



Proof for the *gluco*-configuration of *(2)* and its derivatives was derived firstly from the NMR spectrum of *(4)*, which has three signals in an intensity ratio of 2:1:1 in the region around 8 τ indicating three equatorial acetoxy groups (7.93 τ and 7.95 τ) and one equatorial acetamido group (8.07 τ) [3], and secondly from the hydrolysis of *(3)* with acid, which leads to 3-amino-3-deoxyglucose, which was isolated as its penta-acetate [4].

Analogous cyclization with nitromethane of the "adenosine dialdehyde" which can be isolated in crystalline form after oxidation of adenosine with periodate [2] afforded a mixture of 3-nitrohexosyladenines. The main product can be isolated from this mixture in crystalline form (decomposes above 150 °C) in 40–45 % yield by chromatography on a column of silica gel with water saturated with n-butanol as eluant, or can be precipitated as its picrate, m.p. 237–240 °C, in 67.5 % yield. According to its NMR spectrum, this product is 9-(3′-nitro-3′-deoxyhexopyranosyl)adenine and has the *gluco*-configuration.

Analogous treatment of "inosine dialdehyde" yields a mixture of 3-nitrohexosylhypoxanthines. This mixture contains one major product, which can be isolated in pure crystalline form [m.p. 194–196 °C (decomp.)] in 20 % yield (based on the inosine) by column chromatography on silica gel. Catalytic hydrogenation and subsequent acetylation of the mixture gives rise to a 9-(tri-*O*-acetyl-3′-acetamido-3′-deoxyhexopyranosyl)hypoxanthine, m.p. 265–268 °C, whose NMR spectrum indicates it to have the *talo*-configuration.

Received, November 27th, 1964 [Z 871/697 IE]
German version: Angew. Chem. 77, 131 (1965)

[1] *F. W. Lichtenthaler*, Angew. Chem. *76*, 84 (1964); Angew. Chem. internat. Edit. *3*, 211 (1964).

[2] *J. Davoll*, *B. Lythgoe*, and *A. R. Todd*, J. chem. Soc. (London) *1946*, 833.

[3] *F. W. Lichtenthaler*, Chem. Ber. *96*, 2047 (1963).

[4] *M. J. Cron*, *O. B. Fardig*, *D. L. Johnson*, *H. Schmitz*, *D. F. Whitehead*, *I. R. Cooper*, and *R. U. Lemieux*, J. Amer. chem. Soc. *80*, 2342 (1958); *M. J. Cron*, *D. L. Evans*, *F. M. Palermiti*, *D. F. Whitehead*, *I. R. Hooper*, *P. Chu*, and *R. U. Lemieux*, ibid. *80*, 4741 (1958).

Mass-Spectrometric Investigation of Rhenium Trichloride

By Dipl.-Chem. K. Rinke and Prof. Dr. H. Schäfer

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der Universität Münster (Germany)

In the compound Re_3Cl_9 and in the anions $(Re_3Cl_{12})^{3-}$, $(Re_3Cl_{11})^{2-}$, and $(Re_3Cl_{10})^{-}$, Re_3-groups with particularly short Re–Re distances are present as the main structural elements in the solid state and in solution [1]. In the crystal lattice of rhenium trichloride, the chlorine atoms are so arranged that Re_3Cl_9 units result. We evaporated rhenium trichloride in the mass spectrometer in order to see whether the Re_3Cl_9 group remains intact in the vapor phase [2].

Rhenium trichloride was prepared from its elements [3]. The crystals obtained had the empirical formula $ReCl_{2.92}$ and gave the familiar X-ray diffraction diagram of $ReCl_3$ [4].

The measurements were carried out in a 60° sector field mass spectrometer [a CH 4 model from Messrs. Atlas MAT, Bremen (Germany)]. The substance was evaporated out of a graphite crucible at about 280 °C. The ion-accelerating voltage was 2000 volts up to a mass number of 700, and 1000 volts up to a mass number of 1400. The ionization was effected by bombardment with electrons with an energy of 70 eV, and the spectrum was recorded over a secondary electron multiplier. The ions detected were identified by assignment of mass numbers and by comparison of the calculated and experimental isotope distributions [5].

Ion	Relative abundance [a]	Ion	Relative abundance [a]	Ion	Relative abundance [a]
Re^+	6	Re_2^+	1	Re_3^+	0
$ReCl^+$	4	Re_2Cl^+	2	Re_3Cl^+	1
$ReCl_2^+$	6	$Re_2Cl_2^+$	3	$Re_3Cl_2^+$	1
$ReCl_3^+$	12	$Re_2Cl_3^+$	10	$Re_3Cl_3^+$	2
$ReCl_4^+$	1	$Re_2Cl_4^+$	9	$Re_3Cl_4^+$	2
		$Re_2Cl_5^+$	31	$Re_3Cl_5^+$	4
		$Re_2Cl_6^+$	23	$Re_3Cl_6^+$	3
				$Re_3Cl_7^+$	3
				$Re_3Cl_8^+$	19
				$Re_3Cl_9^+$	100

[a] Based on $Re_3Cl_9^+ = 100$ with allowance for the isotope distribution, but without correction for the (differing) yields of secondary electrons.

The table shows that it is mainly Re_3Cl_9 molecules that are present in the vapor. The Re_3 configuration is therefore very stable.

Received, November 30th, 1964 [Z 867/694 IE]
German version: Angew. Chem. 77, 131 (1965)

[1] *W.T. Robinson, J. E. Fergusson,* and *B. R. Penfold,* Proc. chem. Soc. (London) *1963*, 116; *J. A. Bertrand, F. A. Cotton,* and *W. A. Dollase,* J. Amer. chem. Soc. *85*, 1349 (1963); Inorg. Chem. *2*, 1166 (1963); *J. E. Fergusson, B. R. Penfold,* and *W.T. Robinson,* Nature (London) *201*, 181 (1964); *J. Gelinek* and *W. Rüdorff,* Naturwissenschaften *51*, 85 (1964); *G. Lux,* Z. Chem. *4*, 232 (1964); *F. A. Cotton* and *J.T. Mague,* Proc. chem. Soc. (London) *1964*, 233; Inorg. Chem. *3*, 1402 (1964).

[2] For a review of compounds with M_n groups, see *H. Schäfer* and *H. G. Schnering,* Angew. Chem. *76*, 833 (1964).

[3] Cf. *G. Brauer:* Handbuch der präparativen anorganischen Chemie. Enke-Verlag, Stuttgart 1962, p. 1288.

[4] The X-ray diagram was identical with a diagram kindly furnished by Prof. *Rüdorff.*

[5] We gratefully acknowledge the assistance of *H. Rubeneck* in carrying out this work.

Synthesis of Diazonium Salts from Sulfinyl Imides and Nitrosyl Salts

By Dr. K. Bott

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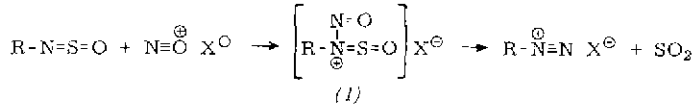
der Universität München (Germany) [1]

Nitrosyl perchlorate or nitrosyl hexachloroantimonate reacts with aromatic sulfinyl imides in ethylene dichloride at −10 to 0 °C to form the corresponding diazonium salts and sulfur dioxide. The salt *(1)* is assumed to be an intermediate but cannot be isolated.



(1)

X = ClO_4, $SbCl_6$

The yields of arenediazonium hexachloroantimonates are 93 % for R = *p*-nitrophenyl, 94 % for R = *m*-nitrophenyl, and 99 % for R = *p*-chlorophenyl. The elemental analyses of the products and comparison of their infrared spectra with those of authentic samples proved the purity of the salts obtained. The diazonium perchlorates are highly explosive and were not isolated, but were coupled in methanolic solution with β-naphthol to give azo dyes.

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[1] Present address: Wissenschaftliche Abteilung, Chemische Werke Hüls, Marl/Westfalen (Germany).

Synthesis of Tetrakis(trifluorophosphine)cobalt Hydride and Hexakis(trifluorophosphine)tungsten(0) [1]

By Priv.-Doz. Dr. Th. Kruck, Dipl.-Chem. W. Lang, and cand. chem. A. Engelmann

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The reaction of FeI_2 or NiI_2 [2] with PF_3 under pressure in the presence of hydrogen-containing compounds hitherto invariably led to the formation of trifluorophosphinemetal(0) complexes. We now found that the reaction of cobalt iodide with PF_3 in a copper-lined autoclave in the presence of only traces of moisture affords tetrakis(trifluorophosphine)cobalt hydride. Quantitative formation of this hydride is achieved by treating a mixture of anhydrous CoI_2 and copper powder in a molar ratio of 1:2 with 250 atm of trifluorophosphine and a slight excess of hydrogen at 190–200 °C.

$$2\,CoI_2 + 4\,Cu + 8\,PF_3 + H_2 \rightarrow 2\,HCo(PF_3)_4 + 4\,CuI$$

$HCo(PF_3)_4$ is a mobile, highly volatile liquid, m.p. −51 °C, b.p. 80 °C/730 mm, with a pale green cast. The infrared spectrum of the diamagnetic compound contains P–F valence vibrations at 961 (w), 917 (vs), 907 (sh), and 867 (vs) cm^{-1} [3]; its proton magnetic resonance spectrum has a broad signal at 12.5 ppm (relative to tetramethylsilane). The hydride remains unaltered in air for some time. Above 250 °C it decomposes with separation of metallic cobalt. In aqueous solution it behaves as a strong monobasic acid. When treated with potassium amalgam, it gives a quantitative yield of colorless crystals of potassium tetrakis(trifluorophosphine)cobaltate(-1), which is relatively stable towards oxygen.

$$2\,HCo(PF_3)_4 + 2\,K/Hg \xrightarrow{\text{ether}} 2\,K[Co(PF_3)_4] + H_2$$

The $[Co(PF_3)_4]^{\ominus}$ anion can be precipitated from aqueous solutions with voluminous cations. During the conversion of $HCo(PF_3)_4$ into $[Co(PF_3)_4]^{\ominus}$, a bathochromic shift of the P–F valence vibrations is observed which is probably due to a reduction in the double-bond character of the P–F bond.

At PF_3-pressures above 200 atm and temperatures above 200 °C, tungsten hexachloride reacts with copper powder as halogen acceptor to form colorless crystals of hexakis(trifluorophosphine)tungsten(0).

$$WCl_6 + 6\ Cu + 6\ PF_3 \rightarrow W(PF_3)_6 + 6\ CuCl$$

$W(PF_3)_6$ completes the series of hexakis(trifluorophosphine) complexes of the chromium group [4]. The new compound, m.p. 214 °C, is completely analogous to the corresponding chromium and molybdenum complexes. It sublimes rapidly in a high vacuum at 40 °C and decomposes only above 320 °C with formation of a tungsten mirror. Its infrared spectrum has P–F valence vibrations at 914 (vs) and 852 (s) cm^{-1} [3] and indicates an octahedral structure of the diamagnetic complex.

Received: December 3rd, 1964 [Z 876/704 IE]
German version: Angew. Chem. 77, 132 (1965)

[1] Trifluorophosphinemetal Complexes, Part VI. – Part V: *Th. Kruck* and *A. Prasch*, Angew. Chem. *76*, 892 (1964); Angew. Chem. internat. Edit. *3*, 754 (1964).

[2] The preparation of $Ni(PF_3)_4$ from nickel iodide or metallic nickel will be described in a separate report.

[3] Measured in the gas phase with a Perkin-Elmer Model 21 spectrophotometer with an NaCl prism; w = weak, s = strong, vs = very strong, sh = shoulder.

[4] *Th. Kruck*, Chem. Ber. *97*, 2018 (1964); *Th. Kruck* and *A. Prasch*, Z. Naturforsch. *19b*, 669 (1964).

On the Preparation of "Free Carbonic Acid"

By Priv.-Doz. Dr. G. Gattow and cand. chem. U. Gerwarth

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In continuation of our studies of chalkogenocarbonic acids [1], we attempted to isolate carbon monoxide bishydroxide $OC(OH)_2$, which in aqueous solution is carbonic acid H_2CO_3. A suspension of 5–10 g of finely pulverized anhydrous Na_2CO_3 in 100–150 ml of dimethyl ether was cooled to about −35 °C, and a solution of 5 N HCl in dimethyl ether (50–60 % of the equivalent amount) at −35 °C was added. The formal reaction

$$Na_2CO_3 + 2\ HCl \rightarrow OC(OH)_2 + 2\ NaCl$$

proceeds almost quantitatively without evolution of gas or alteration of the pressure, provided 1. traces of moisture are present, 2. the HCl solution is added only in minute portions (less than 2 ml) at prolonged intervals (one addition every 30 min), and 3. precautions are taken to ensure efficient removal of the heat of reaction.

The reaction mixture was filtered at about −35 °C, and the dimethyl ether was removed from the filtrate by evacuation at about −80 °C. The residue is a highly viscous solution from which a white crystalline substance precipitates out; this solid was purified from traces of dimethyl ether by evacuation at −80 °C for 2 weeks [2].

On warming, the solid melts at −47 °C to form a liquid which begins to decompose violently at or above 5 °C; the products of this decomposition are water, carbon dioxide, and dimethyl ether. The molar ratio $H_2O:CO_2$ was determined gravimetrically to be 1:1.02, and that of CO_2 to $(CH_3)_2O$ by infrared spectroscopy to be 1:1. It can be concluded from these results, together with the values obtained from measurements carried out on solutions and mixtures of HCl and/or CO_2 in water and/or dimethyl ether that the substance produced in the way described is the monoctherate of carbon monoxide bishydroxide $OC(OH)_2 \cdot O(CH_3)_2$. Interpretable infrared or NMR spectra could not be obtained. We were unable to repeat the preparation of $H_2CO_3 \cdot (C_2H_5)_2O$ already described [4].

The heat of fusion of $OC(OH)_2 \cdot O(CH_3)_2$ is 0.6 ± 0.2 kcal/mole. Its decomposition pressures were measured between −90 °C and +20 °C by isoteniscopy and used together with the known thermochemical data for water [5], carbon dioxide [5], and dimethyl ether [6] to calculate the enthalpy of formation of $OC(OH)_2 \cdot O(CH_3)_2$; at −70 °C, $\Delta H_f = -202 \pm 5$ kcal/mole. Using this value, the enthalpy of formation of solid $OC(OH)_2$ is calculated to be $\Delta H_f = -155 \pm 10$ kcal/mole. This value is in good agreement with the enthalpy of formation calculated by the increments method [7] and estimated from the thermochemical data for carbonates [5, 8] and trithiocarbonates [8, 9].

Received, December 4th, 1964 [Z 870/696 IE]
German version: Angew. Chem. 77, 132 (1965)

[1] *G. Gattow* and *B. Krebs*, Z. anorg. allg. Chem. *325*, 15 (1963) and earlier publications.

[2] A substance with identical properties is obtained by reaction of aqueous solutions of Na_2CO_3 and HCl in a modified "stopped flow" apparatus [3] with very rapid coling of the reaction mixture.

[3] *F. J. W. Roughton*, Proc. Roy. Soc. (London) B *115*, 473 (1934).

[4] *A. G. Galinos* and *A. A. Carotti*, J. Amer. chem. Soc. *83*, 752 (1961).

[5] *O. Kubaschewski* and *E. L. Evans*: Metallurgical Thermochemistry. Pergamon Press, London 1958.

[6] *R. M. Kennedy*, *M. Sagenkahn*, and *J. G. Aston*, J. Amer. chem. Soc. *63*, 2267 (1941).

[7] *J. L. Franklin*, Ind. Engng. Chem. *41*, 1070 (1949).

[8] *G. Gattow*, Pure appl. Chem. *2*, 121 (1961).

[9] *G. Gattow* and *B. Krebs*, Z. anorg. allg. Chem. *322*, 113 (1963).

Stereoisomeric 2,5-Dimethyl-2,3:4,5-dioxidohexanes as the Main Products of the Pyrolysis of Polymeric 2,5-Dimethyl-2,4-hexadiene Peroxide

By Dr. G. Bernhardt and Prof. Dr. F. Korte

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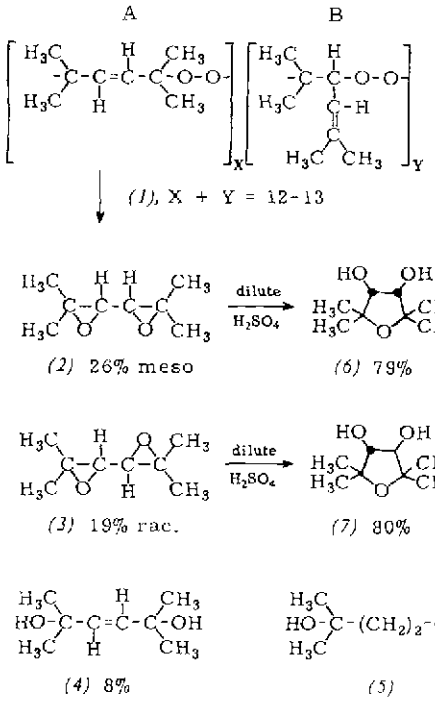
We have found that pyrolysis of polymeric 2,5-dimethyl-2,4-hexadiene peroxide *(1)* [1, 2] at 150 °C affords the two stereoisomeric dioxidohexanes *(2)* and *(3)* as the major products. In addition, small amounts of *trans*-2,5-dimethylhex-3-ene-2,5-diol *(4)*, acetone, and β-methylcrotonaldehyde are formed. To our knowledge, the occurrence of diepoxides during the thermal decomposition of polymeric peroxides has never been observed before. The formation of compounds *(2)*, *(3)*, and *(4)* requires that the –O–O– bridges in *(1)* be between the 1- and 4-positions.

The *meso*-diepoxide *(2)*, m.p. 60 °C, can be separated from the liquid racemate *(3)* [3], b.p. 62 °C/12 mm, by crystallization. Both isomers have characteristic infrared absorptions [4]: the epoxide bands of *(2)* are at 1237, 899, and 802 cm^{-1}; those of *(3)* are at 1241, 897, and 810 cm^{-1} [5]. Chemical proof of the structures of *(2)* and *(3)* is supplied by reduction with $LiAlH_4$ to give *(5)*, and by hydrolysis with acid to give the stereoisomeric tetrahydrofuran-2,3-diols; here *(2)* yields the *cis*-form *(6)*, and *(3)* leads to the *trans*-compound *(7)* [6].

Since only the *trans*-form *(4)* of hexene-1,4-diol, m.p. 93–94 °C, is formed, a *trans*-structure seems to be indicated for (A), which has recently been proved by an independent method [1].



The formation of acetone and β-methylcrotonaldehyde can be explained by cleavage of 1,2-peroxo-linked structures (B) [7]. Since the amount of acetone formed is 5%, it can be concluded that the ratio of $C_8H_{14}O_2$ units in *(1)* with a 1,4-peroxo structure (A) to units with a 1,2-peroxo link (B) is about 7:1.

Received: December 7th, 1964 [Z 877/705 IE]
German version: Angew. Chem. *77*, 133 (1965)

[1] *K. Griesbaum, A. A. Oswald,* and *W. Naegele,* J. org. Chemistry *29*, 1887 (1964).

[2] *S. H. Harper, H. W. B. Reed,* and *R. A. Thompson,* J. Sci. Food. Agric. *2*, 94 (1951).

[3] Compound *(3)* is identical with a diepoxide prepared by *J. Salkind* and *S. Sabojew,* Ber. dtsch. chem. Ges. *62*, 2169 (1929).

[4] The infrared spectra were taken on a Perkin-Elmer 421 spectrophotometer; CCl_4 was used as solvent for the range 4000–650 cm^{-1} and CS_2 for the range 850–650 cm^{-1}.

[5] *J. Bomstein,* Analytic. Chem. *30*, 544 (1958), where further references are given.

[6] *O. Heuberger* and *N. L. Owen,* J. chem. Soc. (London) *1952*, 910.

[7] *W. Kern* and *J. Stallmann,* Makromolekulare Chem. *7*, 199 (1951); *W. Kern* and *A. R. Heinz,* ibid. *16*, 81 (1955); *C. T. Handy* and *A. S. Rothrock,* J. Amer. chem. Soc. *80*, 5306 (1958).

The Influence of the Interfacial Energy of Organic Solvents on the Photochemical Dimerization of Thymidylyl-(3′→5′)-thymidine

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Irradiation of single-stranded deoxyribonucleic acid (DNA) with light of 254 mμ wavelength in aqueous solution produces more thymine dimer (T_D) than analogous irradiation of native double-stranded DNA [1]. However, when the irradiation is carried out in 96–100% ethylene glycol, single-stranded DNA gives less T_D than double-stranded DNA does in aqueous solution [2].

We have irradiated the model compound thymidylyl-(3′→5′)-thymidine (TpT) [3] in various solvents with light of 280 mμ wavelength and found that for equal radiation doses, the yield of T_D is greatest in water as solvent. When other solvents are used, the yields of T_D decrease in the series glycerol > formamide > ethylene glycol > n-butanol > methanol > ethanol > t-butanol.

Sinanoglu and *Abdulnur* [4] recently showed that the interfacial energy of the solvent is of decisive importance, in addition to van der Waals forces, for the formation of double-stranded DNA. If the percentage of T_D formed (determined by measuring the decrease in extinction at 267 mμ) in the various solvents is plotted against the change in free energy ΔF^0 of the TpT molecule [5] during its conversion from a form with mobile thymine bases into a form with stationary adjacent bases (which is suitable for dimerization) in each solvent, a linear relationship results [6].

Solvent	ΔF^0 [kcal/mole]	Formation of T_D [%]
t-Butanol	− 2.9	5
Ethanol	− 4.2	5.5
Methanol	− 4.5	6
n-Butanol	− 4.7	7.5
Ethylene glycol	−11.3	19
Formamide	−16.3	21
Glycerol	−16.5	33
Water	−22.3	35

This observation also explains the diminished thymine dimerization in single-stranded DNA with ethylene glycol as solvent [2]. Moreover, it can be concluded that the double helix of DNA is held together to a large extent by van der Waals forces (electrostatic and dispersion forces) and by solvation forces and only to a lesser extent by hydrogen bonds between the purine and pyrimidine bases [4].

Received: December 10th, 1964 [Z 878/699 IE]
German version: Angew. Chem. *77*, 133 (1965)

[1] *A. Wacker, H. Dellweg,* and *D. Jacherts,* J. molec. Biol. *4*, 410 (1962).

[2] *H. Dellweg* and *A. Wacker,* Z. Naturforsch. *17b*, 827 (1962); ibid., in the press.

[3] Prepared according to the procedure of *P. T. Gilham* and *H. G. Khorana,* J. Amer. chem. Soc. *80*, 6212 (1958).

[4] *O. Sinanoglu* and *S. Abdulnur,* Photochem. and Photobiol., in the press.

[5] *O. Sinanoglu* and *S. Abdulnur,* Feder. Proc., Supplement on Conference on Cryobiology, in the press. We wish to thank Prof. *O. Sinanoglu* and Dr. *S. Abdulnur* for making available their experimental values prior to publication and for valuable discussions.

[6] A grating monochromator of Messrs. Bausch and Lomb, Rochester, was used for the irradiation experiments. Grating: 1200 lines/mm. Light source: Osram HBO 200 W. Wavelength: 280 mμ. Ultraviolet dose: 10^5 erg/mm². Concentration of TpT: 25 μg/ml. Room temperature.

The Crystal Structure of a Phosphacyanine

By Dr. R. Allmann

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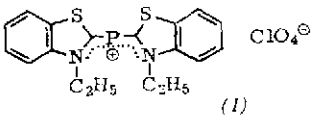
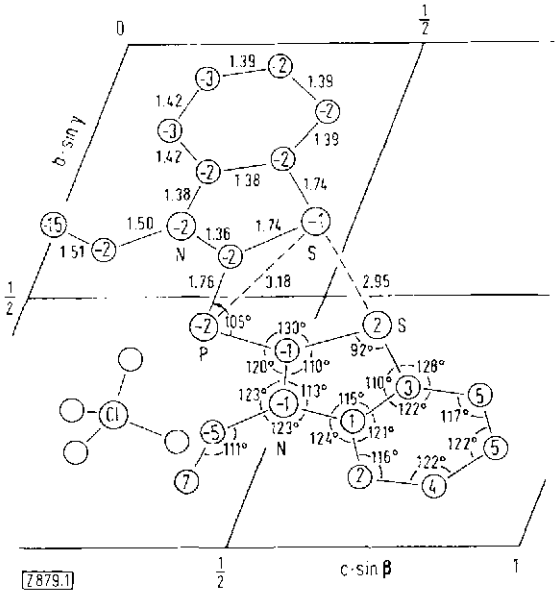
X-Ray analysis of *N*-ethyl-2-[(*N*-ethylbenzothiazolin-2-yl-idene)phosphino]benzothiazolium perchlorate *(1)*, which was recently prepared by *Dimroth* and *Hoffmann* [1], gave results that are in complete agreement with the constitution assumed.



(1)

The two C–P distances are 1.76 Å and are thus significantly shorter than those for C–P single bonds; the C–P–C angle is 105° (for comparison, $(H_3C)_3P$: 1.87 Å and 100° [2], and $(C_6H_5)_3P$: 1.83 Å and 103° [3]).

The planes of the two benzothiazole systems form an angle of only 3°. The two sulfur atoms are 2.95 Å apart and are thus relatively close together.



The figure shows the Y,Z-projection of a perchlorate anion and of a phosphacyanine cation with averaged interatomic distances in Å and averaged bond angles. The distortions out of the plane $2x + y + 2z = 2$ are given in tenths of an Ångstrom in the circles.

The phosphacyanine perchlorate *(1)* forms orange-red needles which belong to the space group $P\bar{1}$. Its lattice constants are [4]:

$a = 8.412 \pm 0.006$ Å	$\alpha = 107°17' \pm 15'$
$b = 11.673 \pm 0.009$ Å	$\beta = 66°41' \pm 15'$
$c = 11.713 \pm 0.011$ Å	$\gamma = 95°32' \pm 15'$

The density calculated for *(1)* from the volume of its unit cell (1008 Å³) and its molecular weight (456.9) is $D_x = 1.51$ g/cm³; the value found by experiment was $D_m = 1.50$ g/cm³. A total of 3634 intensities were estimated visually from Weissenberg photographs. The coordinates of the four heavier atoms (2 S, P, and Cl) were derived from a Patterson synthesis. The positions of the remaining light atoms (18 C, 2 N, and 4 O) were then obtained from a Fourier synthesis with the phases of the heavier atoms. After five cycles of refinement, the R factor (*i.e.* the mean difference between observed and calculated structural factors) was reduced to 16.4 %. From the error in the coordinates of about 0.01 Å, there results a mean error of about 0.02 Å for the interatomic distances and of 1–2° for the bond angles. Within the limits of these errors both halves of the molecule have identical structures.

Received: December 11th, 1964 [Z 879/700 IE]
German version: Angew. Chem. 77, 134 (1965)

[1] *K. Dimroth* and *P. Hoffmann*, Angew. Chem. *76*, 433 (1964); Angew. Chem. internat. Edit. *3*, 384 (1964).

[2] *H. D. Springall* and *L. O. Brockway*, J. Amer. chem. Soc. *60*, 996 (1938).

[3] *J. J. Daly*, J. chem. Soc. (London) *1964*, 3799.

[4] *P. J. Wheatley*, personal communication.

New Heterocyclic Ring Systems Containing Boron and Nitrogen

By Prof. Dr. F. Umland and Dipl.-Chem. C. Schleyerbach

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Institut für Anorganische Chemie der Technischen Hochschule Hannover (Germany)

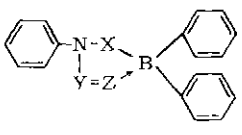
We have succeeded in preparing a series of five-membered heterocyclic ring systems containing a boron atom together with one to four nitrogen atoms in the ring:

1,1,3,4-tetraphenyl-1-bora-2,5-dioxa-3-aza-4-cyclopentene *(1)*, m.p. 153 °C (prepared from *N*-benzoyl-*N*-phenylhydroxylamine).

1,1,3-triphenyl-1-bora-2,5-dioxa-3,4-diaza-4-cyclopentene *(2)* [1], m.p. 102 °C (prepared from *N*-nitroso-*N*-phenylhydroxylamine).

1,1,3,5-tetraphenyl-1-bora-2-oxa-3,4,5-triaza-4-cyclopentene *(3)*, m.p. 139 °C with decomposition (prepared from 1,3-diphenyl-3-hydroxytriazene [2]).

1,1,3,5-tetraphenyl-1-bora-2,3,4,5-tetraaza-4-cyclopentene *(4)*, m.p. 130 °C with decomposition (prepared from 2,4-diphenyltetrazene [3]).



(1), X = O, Y = C_6H_5-C, Z = O
(2), X = O, Y = N, Z = O
(3), X = O, Y = N, Z = C_6H_5-N
(4), X = NH, Y = N, Z = C_6H_5-N

β-Aminoethyl diphenylborinate, Flavognost®, and equimolar amounts of the starting materials named above were dissolved separately in the smallest possible volume of ethanol or a 1:1 mixture of ethanol/benzene. The solutions were combined and a few drops of acetic acid were added to each mixture. To obtain *(1)* and *(2)*, the reaction mixtures were refluxed for 30 min, but short boiling sufficed to form *(3)* and *(4)*. The products crystallized out on cooling and were recrystallized from the same solvents, or *(3)* and *(4)* preferably from methanol. If Cupferron® (the ammonium salt of *N*-nitroso-*N*-phenylhydroxylamine) is used for preparing *(2)*, a little more than an equimolar amount of glacial acetic acid must be added.

All four compounds are yellow and stable in air. Their stability in solution decreases in the series *(1)* > *(2)* > *(3)* > *(4)*. The diphenylboryl group can be replaced by a heavy metal atom with aqueous solutions of heavy metal salts. However, only those metal ions participate in this reaction which form stable complexes with the chelate-forming compounds involved in *(1)*–*(4)*. Hence the new compounds, especially *(1)* and *(2)*, are selective analytical reagents.

Received: December 14th, 1964; Supplemented: January 4th, 1965 [Z 887/710 IE]
German version: Angew. Chem. 77, 169 (1965)

[1] *F. Umland* and *D. Thierig*, Z. analyt. Chem. *197*, 151 (1963).

[2] *N. C. Sogani* and *S. C. Bhattacharya*, Analytic. Chem. *28*, 81 (1955).

[3] *A. Wohl*, Ber. dtsch. chem. Ges. *26*, 1587 (1893).

Dichlorotrinitrosylvanadium $[V(NO)_3Cl_2]_n$

By Priv.-Doz. Dr. W. Beck, Dr. K. Lottes, and cand. chem. K. Schmidtner

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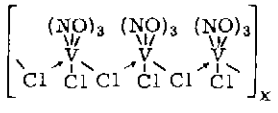
When nitric oxide is passed into a 0.2 M solution of VCl_4 in anhydrous CCl_4, dehalogenation of the vanadium occurs and dichlorotrinitrosylvanadium is obtained in almost quantitative yield.

$$VCl_4 + 5\ NO \rightarrow V(NO)_3Cl_2 + 2\ NOCl$$

The product is a light- to dark-brown solid depending on its grain size; it is sensitive to moisture and is practically insoluble in all the common organic solvents. In contrast to the nitrosyl chlorides of iron [1] and cobalt [2], the new compound cannot be sublimed and is therefore probably polymeric in nature. Its infrared spectrum in Nujol contains N–O absorptions at 1924 (s), 1761 (vs) cm^{-1} [3] plus two bands at 309 and 261 cm^{-1} which can be assigned to V–Cl stretching vibrations. Comparison of the infrared spectrum with those of other nitrosylmetal chlorides [3] showed that $[V(NO)_3Cl_2]_n$ has probably a polynuclear structure *(1)* with terminal and bridging chloro ligands. This structure contains sixfold coordinated vanadium with an inert-gas configuration



(1)

and has a trigonal bipyramidal arrangement of the NO groups; these features are in agreement with the fact that the compound is diamagnetic and gives only two N–O absorptions in the infrared.

Received: December 15th, 1964 [Z 880/701 IE]
German version: Angew. Chem. 77, 134 (1965)

[1] *W. Hieber* and *R. Nast*, Z. anorg. allg. Chem. *244*, 23 (1940).
[2] *W. Hieber* and *R. Marin*, Z. anorg. allg. Chem. *240*, 241 (1939); *W. Hieber* and *W. Beck*, Z. Naturforsch. *13b*, 194 (1958).
[3] *W. Beck* and *K. Lottes*, Angew. Chem. *76*, 574 (1964).

Synthesis of Dichlorogallane $HGaCl_2$

By Priv.-Doz. Dr. H. Schmidbaur, Dipl.-Chem. W. Findeiss, and cand. chem. E. Gast

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Trimethylsilane reacts at −20 °C with equimolar amounts of gallium trichloride to form trimethylchlorosilane (99.5 % yield) and pure dichlorogallane.

$$(H_3C)_3SiH + GaCl_3 \rightarrow (H_3C)_3SiCl + HGaCl_2$$

When the chlorosilane is pumped off at −30 °C, a residue of $HGaCl_2$ is obtained in 95 % yield as colorless crystals which dissolve well and without decomposition at low temperatures in anhydrous solvents such as benzene, cyclohexane, or diethyl ether [1].

Cryoscopic determinations of the molecular weight revealed that $HGaCl_2$ like $GaCl_3$ is dimeric in benzene. It cannot be kept unlimited at room temperature without decomposition, but rapid decomposition with evolution of hydrogen begins only at its melting point of 29 °C [2]. Pyrolysis of the compound at 150 °C gives a quantitative yield of hydrogen and gallium chlorogallanate ("gallium dichloride" $GaCl_2$).

$$(HGaCl_2)_2 \rightarrow H_2 + Ga[GaCl_4]$$

The infrared spectrum of dichlorogallane has a somewhat broadened but very intense band at 2018 cm^{-1} which is due to the Ga–H valence vibration. This band is at much higher frequencies than that for $GaH_3{\cdot}N(CH_3)_3$ [3] (1852 cm^{-1}) and indicates the higher force constant of the Ga–H bond in dichlorogallane. The proton resonance spectrum of $HGaCl_2$ in benzene has no proton signal between −33 and +16 ppm (relative to tetramethylsilane), but this is understandable in view of the high spin and quadrupole moments of the gallium isotopes.

When trimethylamine is passed into a solution of $HGaCl_2$ in benzene, colorless crystals of an adduct $HGaCl_2{\cdot}N(CH_3)_3$ precipitate. This melts at 70 °C and is more stable than the starting material. Here the Ga–H valence vibration lies at 1986 cm^{-1}, and the PMR signal for the trimethylamino group is observed at 5.01 ppm (in benzene and relative to benzene as standard). Here, too, no H–Ga signal could be detected.

Received: December 15th, 1964 [Z 882/703 IE]
German version: Angew. Chem. 77, 170 (1965)

[1] Neither H_3CGaCl_2 nor $(H_3C)_2SiHCl$ could be detected by spectroscopy in the products; these compounds might have resulted from a reaction analogous to that of tetramethylsilane with gallium trichloride [cf. *H. Schmidbaur* and *W. Findeiss*, Angew. Chem. *76*, 752 (1964); Angew. Chem. internat. Edit. *3*, 696 (1964)].

[2] GaH_3 which is not stabilized by coordination decomposes far below room temperature [3].

[3] *E. Wiberg* and *M. Schmidt*, Z. Naturforsch. *7b*, 577 (1952); *6b*, 172 (1951); *N. N. Greenwood*, Adv. inorg. Chem. Radiochem. *5*, 91 (1963). Cf. also *D. F. Shriver*, *R. W. Parry*, *N. N. Greenwood*, *A. Storr*, and *M. G. H. Wallbridge*, Inorg. Chem. *2*, 867, 1036, 1039, 1298 (1963).

Heterosiloxanes and t-Butoxy Compounds of Aluminum, Gallium, and Indium

By Priv.-Doz. Dr. H. Schmidbaur

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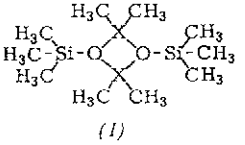
We have succeeded in preparing organoheterosiloxanes with Ga–O–Si and In–O–Si structural units [1,2]. Trimethylgallium and trimethylindium etherates react fast even below room temperature with equimolar amounts of trimethylsilanol to form the desired gallosiloxane and indosiloxane, respectively, with liberation of methane.

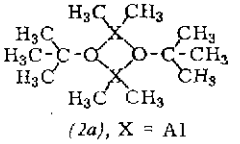
$$Me_3SiOH + Me_3X{\cdot}OEt_2 \rightarrow Et_2O + CH_4 + Me_3SiOXMe_2$$

(1a), X = Al [3]
(1b), X = Ga
Me = CH_3; Et = C_2H_5 *(1c)*, X = In

The yields are almost quantitative. The products *(1a)–(1c)* occur only as dimers, having the four-membered ring structure *(1)*, which probably has C_{2h} symmetry judging from infrared and NMR data [3]; compounds *(1b)* and *(1c)* are surprisingly stable toward oxidation and hydrolysis.



(1)



(2a), X = Al
(2b), X = Ga
(2c), X = In

When anhydrous t-butanol is used instead of trimethylsilanol, the corresponding t-butoxydimethylmetal compounds are formed. This type of reaction had already been described for other alcohol components [4,5]. It is remarkable that

	M.p. [°C]	B.p. [°C/mm]	NMR [6] δ_{CH_3Si}, C	NMR [6] δ_{CH_3X}
(1a)	45.5	35/1 [a]	−12.0	+49.0
(1b)	16.5	34–35/3	− 5.0	+17.0
(1c)	16.0	57–58/3	− 0.8	+ 7.5
(2a)	40.0 [b]	45/1.5 [a]	−82.0	+46.0
(2b)	60.0 [b]	60/1.5 [a]	−73.5	+16.0
(2c)	90.0 [b]	70/1.5 [a]	−70.3	+ 8.7

[a] Sublimes. [b] Waxy.

despite their lower molecular weights, the carbon compounds *(2a)–(2c)* are less volatile and higher melting than the corresponding silicon analogues.

Received: December 15th, 1964 [Z 883/706 IE]
German version: Angew. Chem. 77, 169 (1965)

[1] Cf. *H. Schmidbaur* and *W. Findeiss*, Angew. Chem. *76*, 753 (1964); Angew. Chem. internat. Edit. *3*, 696 (1964); *H. Schmidbaur, J. A. Perez-Garcia*, and *H. Hussek*, unpublished results.

[2] The only gallosiloxane known heretofore was tris(trimethylsiloxy)gallium: see *H. Schmidbaur*, Chem. Ber. *96*, 2696 (1963).

[3] *H. Schmidbaur*, J. organometal. Chem. *1*, 28 (1963); J. Amer. chem. Soc. *85*, 2336 (1963); *H. Schmidbaur* and *M. Schmidt*, ibid. *84*, 1069 (1962).

[4] *E. G. Hoffmann* and *W. Tornau*, Angew. Chem. *73*, 578 (1961).

[5] *G. E. Coates* and *R. G. Hayter*, J. chem. Soc. (London) *1953*, 2519; *G. E. Coates*: Organometallic Compounds. Methuen, London 1960.

[6] Measured in CCl_4 as solvent on a Varian A 60 instrument with 60 Mc. δ is in cps relative to tetramethylsilane as internal standard.

Trimethylaluminum Trimethylphosphorus Oxide and Trimethylarsenic Trimethylgallium Oxide

By Dr. F. Schindler, Priv.-Doz. Dr. H. Schmidbaur, and cand. chem. G. Jonas

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Trimethylphosphine oxide reacts rapidly in benzene with trimethylaluminum etherate to form a 1:1 adduct with a P–O–Al bond.

$$(H_3C)_3PO + (H_3C)_3Al \cdot O(C_2H_5)_2 \rightarrow (C_2H_5)_2O + (H_3C)_3P{-}O{-}Al(CH_3)_3 \quad (1)$$

The homologous ethyl compounds *(2)–(4)* are also formed readily, and so is the analogous compound *(5)* with an As–O·Ga grouping obtained from trimethylarsenic oxide and trimethylgallium etherate.

$$(H_3C)_3AsO + (H_3C)_3Ga \cdot O(C_2H_5)_2 \rightarrow (C_2H_5)_2O + (H_3C)_3As{-}O{-}Ga(CH_3)_3 \quad (5)$$

The chemical and spectroscopic properties of *(1)–(5)* indicate them to be isosteric with the hexaalkyldisiloxanes $R_3Si{-}O{-}SiR_3$ *(6)* and hexaalkyldigermoxanes $R_3Ge{-}O{-}GeR_3$ *(7)*. All the new compounds are surprisingly stable to heat and exhibit no tendency to dissociate or to undergo intramolecular redox reactions up to about 150 °C. Cryoscopic and osmometric determinations of their molecular weights in benzene revealed that they are all monomeric. Because the polarity of the P–O–Al grouping is much stronger than that of Si–O–Si or Ge–O–Ge bridges, the melting and boiling points of the new oxides lie by more than 100 °C above those of the corresponding disiloxanes or digermoxanes. The solubilities of *(1)–(4)* in non-polar solvents other than benzene are also lower than those of *(6)* or *(7)*. However *(5)* is much more soluble in such solvents than *(1)–(4)*, but cannot be distilled without decomposition.

The number, multiplicity, and area ratios of the proton signals in the nuclear magnetic resonance spectra [1] of the new compounds were invariably in accordance with the theoretical expectations. The isosterism of the new oxides with *(6)* and *(7)* is particularly obvious on comparison of the coupling constants $J(^1H{-}^{13}C)$. For *(1)* and for *(5)*, the arithmetic mean $\bar{J}$ of the two coupling constants is almost exactly equal to the values found for the isosters: hexamethyldisiloxane: 118.0; hexamethyldigermoxane: 125.5 cps [2, 3].

		M.p. [°C]	B.p. [°C/mm]	J(H–C) [cps]	J(H–*C) [cps]	$\bar{J}$ [cps]
(1)	$(CH_3)_3POAl(^*CH_3)_3$	+ 89	117/1	127	108.5	117.8
(2)	$(CH_3)_3POAl(C_2H_5)_3$	−23	121/1	127	—	—
(3)	$(C_2H_5)_3POAl(^*CH_3)_3$	+ 7	123/1	—	109.0	—
(4)	$(C_2H_5)_3POAl(C_2H_5)_3$	−13	142/1	—	—	—
(5)	$(CH_3)_3AsOGa(^*CH_3)_3$	54	decomp.	134.5	117.0	125.8

Received: December 15th, 1964 [Z 884/707 IE]
German version: Angew. Chem. 77, 170 (1965)

[1] Measured in benzene as solvent on a Varian A 60 instrument, 60 Mc. The mean error for J(H–C) is about ± 1 cps.

[2] *H. Schmidbaur*, J. Amer. chem. Soc. *85*, 2336 (1963).

[3] *H. Schmidbaur* and *I. Ruidisch*, Inorg. Chem. *3*, 599 (1964).

New Syntheses of the Adamantane Ring System

By Prof. Dr. H. Stetter, Dipl.-Chem. J. Gärtner, and Dr. P. Tacke

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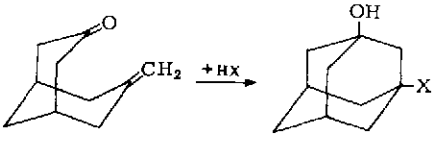
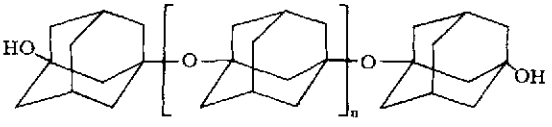
3-Methylenebicyclo[3,3,1]nonan-7-one *(1)* [1] readily undergoes cyclization in the presence of acids to give 1-hydroxyadamantane derivatives substituted at the 3-position.



(1) *(2)*, X = OH *(5)*, X = NH–Ac
(3), X = Cl *(6)*, X = NH_2
(4), X = OC_2H_5

1,3-Dihydroxyadamantane *(2)* is obtained in almost quantitative yield from *(1)* with dilute sulfuric acid. Treatment of *(1)* with hydrochloric acid produces 1-chloro-3-hydroxyadamantane *(3)*, m.p. 205.5 °C, while acids in ethanol lead to 1-ethoxy-3-hydroxyadamantane *(4)*, m.p. 77.5 °C. Acetonitrile reacts with *(1)* under the conditions of a Ritter reaction to give 1-acetamido-3-hydroxyadamantane *(5)*, m.p. 220 °C. The reaction of *(1)* with aqueous ammonia in a sealed tube at 130 °C yields 1-amino-3-hydroxyadamantane *(6)*, m.p. 267 °C.

The same principle can be applied to prepare polyethers *(7)* of adamantane by treating *(1)* with acids in inert solvents.

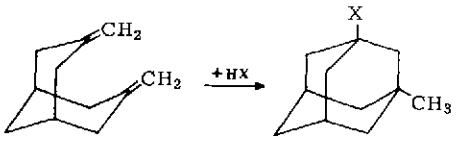


(7)

The same approach can be used to prepare adamantane derivatives from 3,7-dimethylenebicyclo[3,3,1]nonane *(8)*, m.p. 75 °C, which can be obtained from *(1)* in a Wittig reaction; ring closure of *(8)* with acids gives 1-methyladamantanes containing substituents at the 3-position.

Thus, 1-hydroxy-3-methyladamantane *(9)*, m.p. 131 °C, and 1-methyl-3-methoxyadamantane *(10)*, b.p. 99–100 °C/13 mm,

are readily obtained from *(8)* in water or methanol by acidic catalysis. Similarly, 1-acetamido-3-methyladamantane *(11)*, m.p. 112 °C, and 1-methyl-3-(*p*-methoxyphenyl)adamantane *(12)*, b.p. 145 °C/5 mm, are obtained with acids in acetonitrile and anisole, respectively.



(8) *(9)*, X = OH *(11)*, X = NH-Ac
(10), X = OCH_3 *(12)*, X = C_6H_4-OCH_3

It seems remarkable that the hydrocarbon *(8)* forms π-complexes with metal salts; the complex formed with CuCl, m.p. 196–198 °C, is unusually stable.

Received: December 16th, 1964 [Z 881/702 IE]
German version: Angew. Chem. *77*, 171 (1965)

[1] *H. Stetter* and *P. Tacke*, Angew. Chem. *74*, 354 (1962); Angew. Chem. internat. Edit. *1*, 333 (1962); Chem. Ber. *96*, 694 (1963).

Synthesis of 3-Phenyltetrazolopyridinium Bromides and 3-Phenyl-6-bromotetrazolo[5,1-a]-isoquinolinium Bromide

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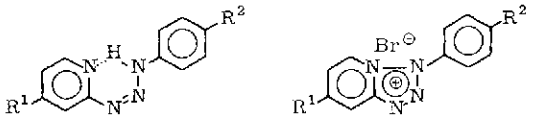
We have found that 1-(α-pyridyl)-3-aryltriazene *(1a)*, R^1 = R^2 = H [1], is dehydrogenated in ethyl acetate at room temperature by 2,4,4,6-tetrabromocyclohexadien-1-one [2] to give 3-phenyltetrazolopyridinium bromide *(2a)*, R^1 = R^2 = H, m.p. 278–280 °C, in 87% yield; the $BF_4^\ominus$ salt of *(2a)* melts at 246 °C.



(1) *(2)*

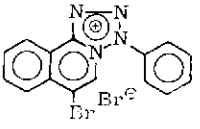
Further derivatives *(1b)–(1f)* of compound *(1)* were prepared by azo coupling of α-aminopyridines and the corresponding benzenediazonium salts.

(1b), R^1 = H, R^2 = OCH_3, m.p. 188–189 °C, 48%
(1c), R^1 = H, R^2 = Cl, m.p. 195–196 °C, 42%
(1d), R^1 = H, R^2 = Br, m.p. 206–207 °C, 39%
(1e), R^1 = CH_3, R^2 = H, m.p. 209–210 °C, 29%
(1f), R^1 = CH_3, R^2 = Br, m.p. 206–208 °C, 46%

All these compounds contain an intramolecular hydrogen bond (characteristic broadening of the infrared bands between 2600 and 3100 cm^{-1}) and on cyclodehydrogenation yield the following derivatives *(2b)–(2f)*:

(2b), m.p. > 360 °C, 89%; $BF_4^\ominus$ salt: m.p. 179 °C
(2c), m.p. 306–307 °C, 85%; $BF_4^\ominus$ salt: m.p. 227 °C
(2d), m.p. 310–311 °C, 84%; $BF_4^\ominus$ salt: m.p. 249 °C
(2e), m.p. > 360 °C, 78%; $BF_4^\ominus$ salt: m.p. 198 °C
(2f), m.p. > 360 °C, 92%; $BF_4^\ominus$ salt: m.p. 228 °C

The compounds *(2)* are all soluble in water. If 5–10% solutions of *(2)* in water are mixed with an equal volume of a 40% solution of HBF_4, beautiful crystals of the tetrafluoroborates precipitate out. None of the compounds *(2)* absorbs between 2600 and 3100 cm^{-1}. Their maxima in the ultraviolet are at shorter wavelengths than those of the compounds *(1)*, *e.g.* for *(2a)*, λ_{max} = 293 mμ, log ε = 3.55, whereas for *(1a)*, λ_{max} = 339 mμ, log ε = 4.32 in ethanol. The triazenes *(1)* can be reobtained from *(2)* by treatment with $Na_2S_2O_4$ in alkaline solution.



(3)

By analogy to the reaction of *(1)*, dehydrogenation of 1-phenyl-3-(1-isoquinolyl)triazene, m.p. 136 °C, λ_{max} = 397 mμ, log ε = 4.28 in ethanol, leads to a 53% yield of 3-phenyl-6-bromotetrazolo[5,1-*a*]isoquinolinium bromide *(3)*, m.p. 292 °C, λ_{max} = 293 mμ, log ε = 3.95 in ethanol. To our knowledge, compound *(3)* is the first tetrazolo[5,1-*a*]isoquinoline prepared.

Received: December 16th, 1964 [Z 886/709 IE]
German version: Angew. Chem. *77*, 171 (1965)

[1] *A. E. Tschtschibabin*, J. russ. phys. chem. Soc. *57*, 301 (1925); Chem. Abstr. *20*, 2499 (1926).

[2] *A. Messmer, J. Varady*, and *I. Pinter*, Acta chim. Acad. Sci. hung. *15*, 183 (1958); Chem. Abstr. *53*, 3200e (1959).

Synthesis of β-Thioxo Ketones by Condensation of Ketones with Thionic Esters

By Doz. Dr. E. Uhlemann and Dipl.-Chem. Helmut Müller

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Thio derivatives of β-dicarbonyl compounds can be obtained by acid- or base-catalysed reaction of the oxygen compounds with hydrogen sulfide [1,2]. With highly unsymmetrical β-dicarbonyl compounds, the point of attack of the hydrogen sulfide is largely determined by the constitution of the starting material, whereas for β-diketones with only slightly different substituents two isomeric thio derivatives are to be expected.

We have found that β-thioxo ketones of uniform structure can be readily obtained by a Claisen-type condensation of ketones with dithioic esters or thionic esters. Yields of over 50% are obtained.

Monothiodibenzoylmethane

Acetophenone (40 g or 0.33 mole) is added slowly with stirring to a suspension of 13 g of sodamide (0.33 mole) in 200 ml of ether. After 15 minutes, a solution of 24 g of *O*-methyl thiobenzoate (0.16 mole) in 50 ml of ether is added dropwise. The mixture is stirred for 3 h at room temperature and left standing overnight. The precipitate is dissolved by adding ice-water, and the aqueous solution is extracted with ether. On passing carbon dioxide into the aqueous solution, monothiobenzoylmethane separates out in the form of shiny red crystals, m.p. 82–83 °C. The yield is 26 g or 68%.

Received: December 21st, 1964 [Z 885/708 IE]
German version: Angew. Chem. *77*, 172 (1965)

[1] *S. K. Mitra*, J. Indian chem. Soc. *10*, 11 (1933).

[2] *R. Mayer* et al., Angew. Chem. *75*, 1011 (1963); Angew. Chem. internat. Edit. *2*, 370 (1963).

Effect of Steroids on the Activity of DNA-Dependent RNA-Polymerase

By Prof. Dr. A. Wacker, Dr. J. Drews, Dr. W. B. Pratt, and P. Chandra

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Dedicated to Professor Gustav Erhart on the occasion of his 70th birthday

We allowed *Pseudomonas testosteroni* to grow for 4–5 h in the presence of tritium-labelled testosterone and then isolated from the cells the fraction which contained radioactivity. Cells grown in the absence of testosterone were processed in the same fashion: Moist cells (0.7–0.8 g) were homogenized by shaking with glass beads. The suspension was centrifuged for 10 min at 1500 g. The cell-free extract was then centrifuged at 105000 g for 45 min and the supernatant was fractionated on a column (2 cm in diameter and 42 cm long) of Sephadex G-100 using 0.06 M phosphate buffer (pH 7.5) as eluant. The first fraction which showed absorption at 280 mμ was used for the further experiments.

Both fractions, *i.e.* that from cells grown in the presence and that from cells grown in the absence of testosterone, inhibited the DNA-dependent RNA-polymerase in a cell-free system synthesizing m-RNA, but the degree of inhibition was higher with the fraction from cells grown without testosterone (Table 1). If testosterone is subsequently added to this fraction, its inhibitory effect falls off to equal that of the fraction from cells grown in the presence of testosterone. Additions of cortisone are without effect [1].

Table 1. Effect of a fraction isolated from cells grown in the presence (IF) or in the absence (NIF) of testosterone on the activity of the DNA-dependent RNA-polymerase. The reaction mixture (0.38 ml at pH 7.5) contained: 100 mμmoles each of GTP, CTP, UTP, and [^{3}H]-ATP; 10 μmoles of tris; 0.25 μmole of $MnCl_2$; 1.0 mμmole of $MgCl_2$; 1.0 μmole of β-mercaptoethanol; 2 optical units of DNA from salmon sperm; and 20 μg of RNA-polymerase from *Escherichia coli* [2].

System	[^{3}H]-ATP incorporated [mμmole]
Complete	0.455
– Polymerase	0.004
+ NIF	0.192
+ IF	0.245
+ NIF + Testosterone	0.255
+ NIF + Cortisone	0.145

The different effects of testosterone and cortisone are also observed *in vivo* (Table 2): although testosterone induces in growing cells of *P. testosteroni* a maximum activity of Δ^5-3-ketosteroid isomerase (and of 3α- and 3β,17β-hydroxysteroid dehydrogenase) cortisone has almost no effect. Parallel results *in vivo* and *in vitro* are obtained for other steroids as well (Table 2). It appears particularly remarkable that m-RNA synthesis is inhibited by cortisone, which has an antianabolic and catabolic action, but is promoted by methenolone, which has an anabolic effect.

Table 2. Effect of various steroids on the activity of DNA-dependent RNA-polymerase *in vitro* (cf. Table 1) and upon Δ^5-3-ketosteroid isomerase *in vivo*. Reaction mixture as in Table 1.

System	[^{3}H]-ATP incorporated [mμmole]	Δ^5-3-ketosteroid isomerase [units/ml of bacterial suspension][a]
Complete + NIF	0.080	0.3 [b]
+ Testosterone	0.125	15.6
+ Menthennlone [c]	0.108	11.6
+ Substance S [d]	0.100	11.2
+ Progesterone	0.090	
+ Cnrtisone	0.065	0.55

[a] One unit of enzyme isomerizes 1 μmole of Δ^5-androstene-3,17-dione to Δ^4-androstene-3,17-dione within one minute.
[b] Control experiment without steroid.
[c] 1-Methyl-Δ^1-androsten-17β-ol-3-one (Primobolan®).
[d] 11-Deoxycortisone.

Preliminary studies (incubation with enzymes, inactivation by heat) suggest that the fraction isolated from *P. testosteroni* contains a protein which reacts with the steroids; this protein possibly is a repressor of RNA-polymerase, such as postulated by *Jacob* and *Monod* [3].

Received: December 23rd, 1964 [Z 890/713 IE]
German version: Angew. Chem. 77, 172 (1965)

[1] Similar results have been obtained with fractions isolated from the uterus of ovarectomized rats by *G. P. Talwar, S. J. Segal, A. Evans*, and *O. W. Davidson*, Proc. nat. Acad. Sci. USA *52*, 1059 (1964).

[2] *M. Chamberlin* and *P. Berg*, Proc. nat. Acad. Sci. USA *48*, 81 (1962).

[3] *F. Jacob* and *J. Monod*, J. molecul. Biol. *3*, 318 (1961).

Phosphinoalkanoic Acids [1]

By Prof. Dr. K. Issleib, Dipl.-Chem. R. Kümmel, and Dipl.-Chem. H. Zimmermann

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The procedure for preparing tertiary carboxyalkylphosphines from alkali diorganophosphides MPR_2 and halogenoalkanoic esters [2] in tetrahydrofuran or ether cannot be used directly to synthesize primary or secondary carboxyalkylphosphines, since here side reactions such as metal-halogen and metal-hydrogen exchange or nucleophilic attack of the phosphide anion at the ester group occur to a significant extent. However, when the anhydrous sodium salts of the halogenoalkanoic acids are used instead of the esters, a smooth reaction occurs and good yields of the sodium salts of the primary and secondary carboxyalkylphosphines are formed. The free phosphinoalkanoic acids *(1)*–*(8)*, which can be regarded as phosphorus analogues of the amino acids, are readily obtained from the sodium salts with dilute sulfuric acid.

$$MPHR + X\text{-}\underset{|}{(CH)_n}\text{-}COO^{\ominus} \rightarrow MX + RHP\text{-}\underset{|}{(CH)_n}\text{-}COO^{\ominus}$$

X = Cl or Br; M = Na or K

Compound	B.p. [°C/mm] or m.p. [°C]	Yield [%]	Derivative	B.p. [°C/mm]
(1), H_2P-CH_2-COOH	70–72/6	82	$H_2P-CH_2COOCH_3$	27–28/10
(2), $H_2P-CH(CH_3)-COOH$	73–74/5	85	$H_2P-CH(CH_3)COOCH_3$	33–34/13
(3), $H_2P-CH(C_2H_5)-COOH$	87–89/6	76	$H_2P-CH(C_2H_5)-COOCH_3$	39–41/10
(4), $H_2P-CH_2-CH_2-COOH$	86–87/6	69	$H_2P-CH_2-CH_2-COOCH_3$ [5]	37–38/10
(5), $C_6H_5HP-CH_2-COOH$	35–37	70	$[H_3P^{\oplus}-CH_2-COOH]I^{\ominus}$	m.p. 112 °C from C_2H_5OH
(6), $c\text{-}C_6H_{11}HP-CH_2-COOH$	oil	70	–	
(7), $C_2H_5HP-CH_2-COOH$	oil	75	–	
(8), $C_6H_5HP-CH(CH_3)-COOH$	29–31	57	–	

The reactions are carried out in liquid ammonia, in which the majority of the alkali phosphides MPH_2 and MPHR dissolve without decomposition owing to the difference in pK_a between phosphine and ammonia [3]. The alkali phosphides are prepared in liquid ammonia from sodium or potassium and PH_3 [4] or a primary phosphine (color change to yellow). The sodium salt of the halogenocarboxylic acid is then simply added to the solution.

The carboxylic acids *(1)–(4)* are colorless liquids with a characteristic odor; they decompose in air but can be distilled unchanged *in vacuo* and form colorless crystals slightly below room temperature. Vacuum distillation of *(5)–(8)* is not recommended. Compounds *(1)–(4)* dissolve in ether and in water with an acidic reaction, but *(5)–(8)* dissolve in organic solvents only. Polarographic studies revealed that *(1)–(8)* have a partially zwitterionic structure. Almost quantitative yields of the corresponding methyl esters (see Table) are obtained from *(1)–(4)* with diazomethane in ether; the esters are colorless, low-boiling liquids which ignite spontaneously when finely divided in air. Analogous derivatives are obtained from *(5)–(8)*. The phosphine portions of *(1)–(8)* can be quaternized with hydrogen iodide.

Received: January 4th, 1965 [Z 889/712 IE]
German version: Angew. Chem. 77, 172 (1965)

[1] Alkali-Phosphorus Compounds and their Reactions, Part 34. – Part 33: *K. Issleib* and *L. Brüsehaber*, Z. Naturforsch., in the press.

[2] *K. Issleib* and *G. Thomas*, Chem. Ber. *93*, 803 (1960).

[3] *K. Issleib* and *R. Kümmel*, J. organometal. Chem., in the press.

[4] *R. J. Wagner* and *A. B. Burg*, J. Amer. chem. Soc. *75*, 3869 (1953).

[5] *A. R. Stiles*, *F. F. Rust*, and *M. E. Vaughan*, U.S.-Patent 2803597 (1957); Chem. Abstr. *52*, 2049b (1958).

An Optically Active Derivative of Methylenetribenzocycloheptatriene

By Dr. W. Tochtermann and Dr. H. Küppers

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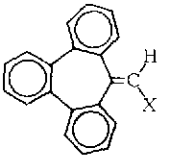
Inversion of the seven-membered ring occurring in the nonplanar boat form is more difficult in di- and tribenzocycloheptatrienone acetals than in cycloheptatriene [1]. Suitable substituted tribenzocycloheptatriene derivatives ought therefore to be separable into optically active antipodes.

To test this prediction, we prepared bromomethylenetribenzocycloheptatriene *(1a)*, m.p. 127–129 °C, by bromomethylenation [2] of tribenzocycloheptatrienone (yield: 75%) and treated it with lithium in dimethoxymethane [3] at –20 to –25 °C to form the lithio compound *(1b)*. Carboxylation of *(1b)* and subsequent hydrolysis produced a 60% yield of 1-carboxymethylenetribenzo[*b,d,f*]cyclohepta-2,4,6-triene *(1c)*, m.p. 249–251 °C. The structure of *(1c)* was proved by its



(1a), X = Br
(1b), X = Li
(1c), X = COOH

elemental analysis, molecular weight, NMR, ultraviolet, and infrared spectra, and by its oxidation with potassium permanganate to tribenzocycloheptatrienone.

The carboxylic acid *(1c)* was resolved *via* its brucine salt into its optical antipodes, which were quite stable and exhibited specific rotations ($[\alpha]_{546}^{25} = +31.7°$ and $[\alpha]_{546}^{25} = -30.9°$, c = 0.026 g/cm³ in acetone) which were strongly dependent on the solvent used. No loss of the optical activity was observed even on prolonged standing of solutions of the optical antipodes at room temperature [*].

Racemization of the optical isomers in diethylene glycol dimethyl ether at 139 °C showed that the rotations decrease by a first order mechanism with $k_{exp} = 1.1 \times 10^{-4}$ sec^{-1} on the average. Thus, since $k_{inversion} = 0.5\ k_{exp}$ [4], a free energy of activation $\Delta F^{\neq} = 31$ kcal/mole is calculated for the inversion at 139 °C. Thus racemization caused by inversion of the seven-membered ring appears to proceed somewhat slower than the racemization of bromodibenzocyclooctatetraenedicarboxylic acid [5].

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German version: Angew. Chem. 77, 173 (1965)

[*] Note added in proof: Two optically active derivatives of methylenedibenzocycloheptatriene were recently described by *A. Ebnöther*, *E. Jucker*, and *A. Stoll*, Chimia *18*, 404 (1964).

[1] *W. Tochtermann*, *U. Walter*, and *A. Mannschreck*, Tetrahedron Letters *1964*, 2981.

[2] *G. Köbrich*, Angew. Chem. *74*, 33 (1962); Angew. Chem. internat. Edit. *1*, 51 (1962). We wish to thank Dr. *Köbrich* for supplying a sample of bromomethyltriphenylphosphonium bromide.

[3] *U. Schöllkopf* and *H. Küppers*, Tetrahedron Letters *1964*, 1503.

[4] *R. Huisgen* in *Houben-Weyl*: Methoden der organischen Chemie. Thieme, Stuttgart 1955, Vol. III/1, p. 99; *A. A. Frost* and *R. G. Pearson*: Kinetics and Mechanism. Wiley, New York 1961, pp. 99, 186, 373.

[5] *K. Mislow* and *H. D. Perlmutter*, J. Amer. chem. Soc. *84*, 3591 (1962).

CONFERENCE REPORTS

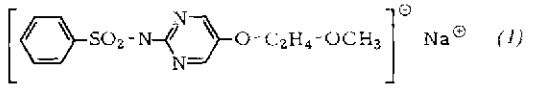
Therapy Congress and Pharmaceutical Exhibition

The lectures delivered at the 16th German Therapy Congress, which took place in Karlsruhe (Germany) from August 30th to September 5th, 1964, dealt *inter alia* with the therapy of liver and bile-passage ailments, the treatment of thyroid disorders, the application of tissue extracts, the treatment of cardiac and circulatory diseases, the therapy and prophylaxis of thromboembolic illnesses, and physical therapy during convalescence. – A seminar lasting several days was held to discuss disorders of the water-electrolyte balance as an adverse factor influencing therapeutic treatments.

The exhibition of pharmaceuticals had products from about 250 companies on display. Of the many new preparations introduced, only those which contain hitherto unknown chemical compounds or substances which are appearing for the first time on the German market are listed in the following report.

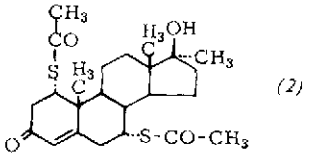
A new oral antidiabetic, Redul®, was developed jointly by Farbenfabriken Bayer and Schering AG. Its ingredient does not belong to the sulfonylurea group but is a representative of a class of substances which is new in diabetes therapy, namely sulfapyrimidine derivatives. Redul contains the sodium salt of 2-benzenesulfonamido-5-(methoxyethoxy)-pyrimidine *(1)* – generic name: glycodiazine – which is readily soluble in water and methanol; its molecular weight

is 331, its m.p. 221–226 °C. Redul stimulates the β-cells of the Langerhans islets and thus evokes a greater physiological incretion of insulin, which in turn results in a reliable depletion of blood sugar. It is degraded rapidly and completely in the organism but maintains its full antidiabetic activity during the first stage of its catabolism.



(1)

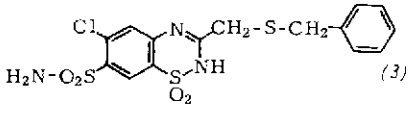
Emdabol® is a hormone preparation for promoting protein synthesis introduced by E. Merck AG., Darmstadt (Germany); it is for oral administration and consists of 1α,7α-bis-acetylthio-17β-hydroxy-17α-methyl-4-androsten-3-one *(2)*, a new substance, m.p. 205–206 °C, $[\alpha]_D = -66°$ in dioxane. Its anabolic activity is twice that of 17α-methyltestosterone. It has an extremely favorable anabolic/androgenic index and is said to exhibit no gestagenic or mineralocorticoid side-effects. Emdabol is indicated for all consumptive illnesses and for cachectic states, *etc.*



(2)

New saluretics were introduced by several companies:

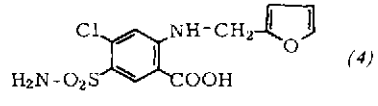
Exosalt® is a new preparation of the benzothiadiazine group issued by Farbenfabriken Bayer and consists of 3-benzylthiomethyl-6-chloro-7-sulfamyl-1,2,4-benzothiadiazine 1,1-dioxide *(3)* – generic name: benzothiazide – a white crystalline



(3)

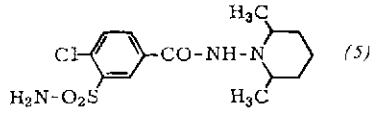
substance, m.p. 238–239 °C, molecular weight 432. It induces a high excretion of sodium and chloride ions in equivalent amounts and is remarkable for the rapidity of its action: diuresis commences within two hours after ingestion of the drug. In animal experiments, Exosalt had about ten times the activity of chlorothiazide.

Although the saluretic called Lasix® developed by Farbwerke Hoechst is also a sulfonamide derivative, its structure differs from those of the benzothiadiazines frequently employed. It consists of 4-chloro-*N*-(2-furylmethyl)-5-sulfamylanthranilic acid *(4)* – generic name: fursemide. Lasix leads to an increased excretion of water and sodium chloride in cases where a diuretic effect cannot otherwise be achieved; it is therefore assumed that *(4)* has a mode of action different from that of the diuretics currently in use.



(4)

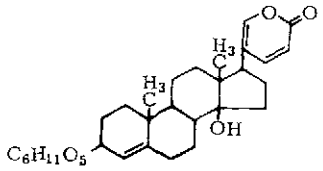
Brinaldix® from Sandoz AG., Nürnberg (Germany), is another new sulfonamide diuretic. Chemically, it is a derivative of 3-sulfamyl-4-chlorobenzoic acid, namely *N*-(*cis*-2,6-dimethyl-1-piperidyl)-3-sulfamyl-4-chlorobenzoamide *(5)*, a solid of m.p. 244–245 °C. Brinaldix is characterized by its



(5)

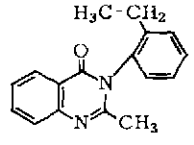
reliable and rapid induction of excretion of sodium and chloride ions and particularly by its broad therapeutic range. It produced no toxic symptoms in animals which were given 100000 times the normal dose.

Proscillaridine, a glycoside long known to occur in *Scilla maritima var. alba*, has now undergone clinical testing and has been introduced into practical therapy as Talusin® bei Knoll AG., Ludwigshafen (Germany), and as Caradrin® by Asta-Werke, Brackwede (Germany). Proscillaridine is 3β-rhamnosido-14β-hydroxy-$\Delta^{4,20,23}$-bufatrienolide *(6)*, m.p. 219–222 °C, $[\alpha] = -92°$ C in methanol, and acts as rapidly as strophanthin, but can be administered *per os*. Since it does not accumulate in the organism and has a broad therapeutic spectrum, the drug is easy to dose.



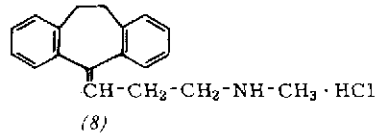
(6)

A new daily sedative and mild soporific is Aolan®, which is produced by P. Beiersdorf & Co. AG., Hamburg (Germany); it is recommended for normalizing disturbances in the functions of the central and vegetative nervous systems due to overstimulation. It consists of 2-methyl-3-(*o*-ethylphenyl)-4-quinazolone *(7)* – generic name: ethinazone.



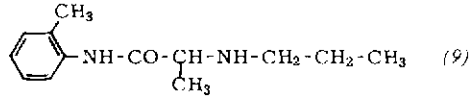
(7)

A new psychopharmaceutical for treating fits of depression, psychosomatic disturbances, *etc.* is marketed by Troponwerke, Köln-Mühlheim (Germany), under the name Nortrilen® and by Eli Lilly GmbH., Gießen (Germany), as Acetexa®. It is composed of 5-(3-methylaminopropylidene)-dibenzo[*a*,*d*]-[1,4]cycloheptadiene hydrochloride – generic name: nortryptiline – a white powder, m.p. 216–219 °C, which dissolves in water, chloroform, or alcohol but not in other organic solvents. Its molecular weight is 299.86. Nortryptiline differs from another long-known antidepressant, amitryptiline, by the absence of a methyl group.



(8)

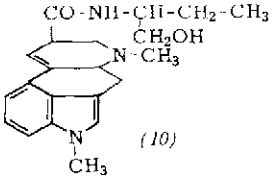
A new local anaesthetic called Xylonest® being marketed by Pharma-Stern AG., Wedel/Holstein (Germany), has already been tested abroad, where it is sold under the trademark Citanest. The structure of Xylonest is closely allied to that of Xylocaine. It contains racemic α-propylamino-2-methylpropionanilide *(9)*, a base which is only slightly soluble in water but readily soluble in alcohol, ether, and acetone, in the form of the water-soluble hydrochloride (molecular weight 256.8, m.p. 167–168 °C). Xylonest is reputed to anaesthetize as well as Xylocaine but to exhibit more prolonged blockage of the nerve fibres.



(9)

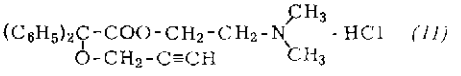
A drug called Deseril® for prophylactic treatment of migraine was introduced by Sandoz AG., Nürnberg (Germany). Its active principle is *N*-[(+)-1-hydroxymethylpropyl]-1-methyl-D-lysergamide *(10)* – generic name: methysergide – which has proved to be the strongest serotonin antagonist known to date. Deseril is incorporated into retarder tablets as its dimaleate. Deseril is applicable for the treatment of all

illnesses with symptoms which arise owing to the participation of serotonin, and can therefore be given for migraine headaches, allergies, and carcinoid syndromes.



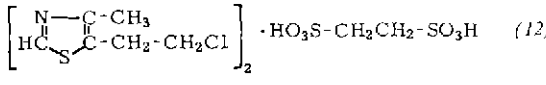
(10)

Ventrinerval®, a new preparation for the treatment of stomach disorders from Rhein-Pharma GmbH., Heidelberg (Ge many), contains aluminum glycinate plus a new spasmolytic benzilic ester, β-dimethylaminoethyl α,α-diphenyl-α-propargoxyacetate, in the form of its hydrochloride *(11)*. This is a white crystalline substance, m.p. 162- 163 °C, molecular weight 373.89, which effects neurotropic and musculotropic spasmolysis plus central analgesia and anaesthetizes the mucous membranes, inhibits secretion, and reduces intestinal motility.



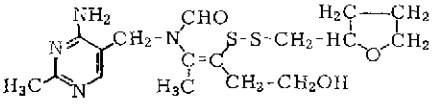
(11)

An anticonvulsive, hypnotic, and sedative agent long known abroad as Hemineurine has now been brought to the German market under the mane of Distraneurin® by Pharma-Stern AG., Wedel/Holstein. It consists of the thiazole moiety of thiamine (vitamin B_1) in which the hydroxyl group has been replaced by a chlorine atom. This 4-methyl-5-(β-chloroethyl)thiazole is administered as the salt *(12)* of ethanedisulfonic acid, a crystalline, relatively stable substance which dissolves easily in water. Distraneurin is a reliable tranquillizer for application particularly in psychomotoric schizophrenia following acute alcoholic intoxication or after abrupt deprivation of alcohol during *delirium tremens*, or for paranoid states due to cerebral sclerosis.



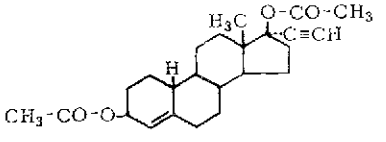
(12)

Another interesting derivative of thiamine (vitamin B_1) developed by Takeda Chemical Industries Ltd., Osaka (Japan), was presented by M. Woelm, Eschwege (Germany), under the name of Judolor®. This comprise the open-ring form of thiamine-tetrahydrofurfuryl disulfide, TTFD *(13)*, which was discovered during attempts to find a better resorbable form of thiamine. Even when large doses of vitamin B_1 are given, a maximum of only 5 mg is absorbed by the organism, whereas Judolor is fully effective when taken orally. The concentration of the cocarboxylase required for metabolism can thus be increased in the tissues by about 100 %. Judolor has analgetic, antiphlogistic, and spasmolytic activity and is recommended for treating neuralgias, neuritis, myalgias, rheumatism, and myocardial defects, as well as for hepatopathy.



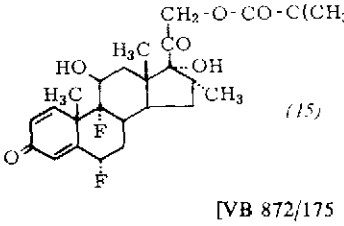
(13)

Ovulen® is a new contraceptive drug containing Mestranol as estrogenic component plus a new gestagenic principle developed by Searle, Chicago, Ill. (U.S.A.), and tested in cooperation with C. F. Boehringer GmbH., Mannheim (Germany), *viz.* the diacetate of 17α-ethynyl-4-estrene-3β,17β-diol *(14)* – generic name: ethynodiol diacetate – a white, odorless, crystalline compound, which is insoluble in water but soluble in oil. The diacetate *(14)* proved to be one of the most effective and best tolerable gestagens; a dose of only 1 mg daily ensures reliable contraception.



(14)

A new special corticoid for dermatological use is Locacorten® from Ciba AG., Wehr/Baden (Germany); its active constituent is a newly developed pharmaceutical called flumethasone, *i.e.* 6α,9α-difluoro-11β,17α-dihydroxy-16α-methyl-21-trimethylacetoxy-1,4-pregnadien-3,20-dione *(15)*, as its pivalate. This substance exerts a rapid inhibitor effect on inflammation due to dermatitis, especially from eczemas, and has antiallergic, antiexudative, and antipruriginous activity.



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[VB 872/175 IE]

German version: Angew. Chem. 77, 174 (1965)

Advances in Electron Microscopy

The Third European Regional Conference on Electron Microscopy was held in Prague (Czechoslovakia) from August 26th to September 3rd, 1964. This was the first international meeting on this topic to be held in a socialist country. In consequence, the number of participants from socialist countries was significantly higher than in corresponding symposia in western European countries. The reports thus presented an excellent survey of the research topics being studied in eastern Europe and of the quality of the work being done there, and hence aroused great interest on the part of visitors from western countries.

Advances in applied electron microscopy can be made mainly by increasing the resolving power of the microscopes, by adaptation of the instruments for special tasks without loss of their electron-optical resolution, and by introducing new methods of preparation and investigation.

All reports on the theory and practical aspects of the limits of resolution of electron microscopes confirmed the opinion that the highest theoretically attainable resolution is almost achieved on current commercial high-resolution instruments (maximum beam potential 100000 volts). Some of the differences in the values quoted for the limit of resolution are probably the consequence of different measuring techniques.

A remarkable demonstration was the direct projection by *T. Komoda*, Tokyo (Japan) of lattice network planes in single crystals of gold, where the lattice planes were 2.35 Å apart. The gold sample was 40 Å thick and was prepared by epitactic sublimation; the electron beam impinged upon its surface at an angle such that the central beam and diffracted beam (111 reflection) lay symmetrical to the optical axis of the microscope.

Although this resolution demonstrates the potentialities of modern electron microscopes, a value as low as 2.35 Å cannot be expected from other preparations and other modes of examination. *J. Heydenreich*, *H. Bethge*, and *U. Ruess*, Halle/Saale (Germany) proposed a method for the first time for objective evaluation of resolution test exposures using equidensitometry according to *Lau* and *Krug*. If their proposal achieves general acceptance, then it would at last be possible to compare data for the resolving power of electron microscopes which were determined in different laboratories with different instruments.

In order to adapt electron microscopes for special purposes, it is essential to be able to exert clearly defined physical or chemical influences on the specimens. Several lectures were devoted to the description of suitable appliances. *K.-H. Herrmann* and *W. Loebe*, Berlin (Germany) reported on a method for cooling the sample chamber in the Siemens & Halske Elmiskop I which prevents contamination of the sample due to decomposition of hydrocarbons in the electron microscope. *U. Valdre*, Bologna (Italy) and *R. M. J. Cotterill*, Illinois (U.S.A.) reported on their independent work concerning the development of techniques for cooling the sample chamber in electron microscopes down to the temperature of liquid helium. Devices of the kind described are important for the observation of radiation damage and of superconductors. *M. J. Goringe* and *U. Valdre*, Bologna (Italy) described the application of sample-cooling devices for the investigation of superconducting lead with the electron shadow microscope: a magnetic field was applied normal to the electron beam, and alterations in magnetic field on attaining a critical temperature could be observed in the electron shadow image.

It is well known that the preparation of sufficiently thin sections (*e.g.* for direct transmission of electron beams through metals) still entails considerable difficulties. *G. Dupouy*, *F. Perrier*, and *L. Durrieu*, Toulouse (France) showed that good quality photographs of metals and metal alloys could still be obtained with beam potentials of 1×10^6 volts even if the thickness of the sample is 6 μ or 9 μ.

Numerous lectures dealt with precipitation processes, phase changes, nucleation processes, dislocations, and stacking defects in metals and metal alloys. Almost without exception it was the method of direct transmission through thin etched metal foils that was used. Again it was apparent that this aspect of metal-physical research is popular mainly in English-speaking countries. Only a few of the numerous reports on this subject can be mentioned here and these because of their mainly chemical interest. *S. A. Jansson*, Stockholm (Sweden) reported on the continual observation of the oxidation of a stainless chrome-nickel steel made possible by passing gases through a special sample chamber during observation. The partial pressure of the oxygen during observation was approximately 10^{-2} mm. The rate of oxidation varied widely from one grain of metal to another. Diffraction photographs showed two kinds of oxide nuclei which could be differentiated by their sizes and orientations. In addition, oxide nuclei could often be seen at the ends of dislocations.

M. H. Lewis and *J. W. Martin*, Oxford (England) discussed the growth of oxide particles during internal oxidation of copper alloys. The dispersed oxides (MgO, BeO, Al_2O_3, and ZrO_2) had progressively smaller particle sizes as the distance of the particles from the surface increased.

The detection of lattice defects by transmission electron microscopy is still restricted to metallic samples. For ionic crystals, the metal decoration (shadow casting) procedure introduced by *H. Bethge*, Halle/Saale (Germany) has been developed into a powerful tool. Thus, for example, after deformation of a sodium crystal glide steps with a height of 2.8 Å could be made visible. It also proved possible to resolve dislocation lines 50 Å apart in a replica specimen by using palladium decoration to obtain micrographs of small-angle grain boundaries with a large dislocation density on the surface of NaCl crystals. Finally, *M. Krohn* and *H. Bethge*, Halle/Saale (Germany) gave an explanation for the occurrence of growth spirals with a large step-height: these spirals are made up of approximately round growth lamellae whose centers do not overlap. A high step then forms to cover up the ends of a host of these circular lamellae, but the fine structure of the step cannot be resolved in a light microscope.

Several lectures dealt with the properties of thin semiconducting layers. *V. E. Yurasova* et al., Moscow (U.S.S.R.) reported on their production of single crystal samples by cathodic atomization. A plasma of these samples (InSb or GaAs) at 10^{-3} mm is bombarded with positive ions. In order to observe the dynamic processes occurring in p-n junctions, *V. G. Diikov* et al., Moscow (U.S.S.R.) fitted an emission electron microscope with a stroboscopic attachment. A basic impulse is directed onto the p-n junction to be studied and a second impulse of much shorter duration onto an ion cannon, which induces the emission of electrons from the sample. Since the phase of the second impulse can be displaced relative to that of the basic impulse, stationary images of the p-n junction can be observed on the screen of the microscope at various times after release of the first impulse. *A. D. G. Stewart* et al., Cambridge (England) observed the images of a p-n junction using a scanning electron microscope.

M. Schulz, Berlin-Teltow (Germany) found that defects in the lattices of single crystals of germanium were preferred nuclei for the start of oxide formation. Extensive outgrowths of oxide particles occur at the breakthrough points of individual dislocations; smaller outgrowths indicate the distribution of the doping agent. The method used is remarkable, for no undesirable chemical or thermal strains are applied to the material being examined. *G. I. Distler* et al., Moscow (U.S.S.R.) described a new method for the chemical decoration of active regions in crystal surfaces, where chemical reactions leading to crystallization cause the decoration effect. An example given was the crystallization of PbS caused by the slow decomposition of lead acetate with thiourea. This decoration method was used for single crystals of silicon; here the decoration became attached in strips corresponding to the inclusion of impurities inside the crystal.

The influence of various impurities on the growth of Fe_2O_3 whiskers was examined by *R. A. Ploc* and *J. P. Chilton*, Cambridge (England), who found that every impurity has a characteristic effect on the crystal size and shape. Silver produces prismatic needles of the oxide, indium causes a grass-like structure to form, and zinc gives a mixture of fine needles and platelets.

J. A. Gard, Aberdeen (England) gave a typical example for the study of a chemical reaction using the electron microscope. The calcium fluoride crystals formed by the action of sodium fluoride on calcite appear as pseudomorphoses of calcite. This reaction could be followed in detail by carbon replication, and it was shown that the $(10\bar{1}2)$ surface of the calcite becomes the (110) surface of the fluoride.

Following the magnificent successes which transmission electron microscopy has achieved in metallurgy – particularly in the field of the physics of metals – it was an obvious next step to apply this investigational technique to inorganic, non-metallic substances. Naturally considerable difficulties with regard to preparation techniques had to be overcome in order to acquire sufficiently thin samples for transmission.

O. E. Radczewski and *E. Wanderer*, Aachen (Germany) applied the thin-section method to study single asbestos fibers and managed to observe the cross-sectional shape of individual fibers and simultaneously to record their electron diffraction diagrams. *D. H. Warrington* and *M. H. Lewis*, Sheffield (England) investigated extremely fine inflated glass foils. Various different phases could be differentiated in the resultant electron micrographs. Different phases can also be distinguished by coupling a special etching prodecure with replication techniques, as *T. L. Tran* and *C. Sella*, Paris (France) were able to show. The main difficulty involved in direct transmission and replica electron microscopy is the interpretation of the pictures obtained. [VB 869/177 1E]

German version: Angew. Chem. 77, 179 (1965)

Glycosaminoglycans, Glycoproteins, and Glycolipids

At the suggestion of *R. W. Jeanloz* the Retina Foundation of Boston organized an international symposium on the chemistry of the three title substances at Swampscott, Mass. (U.S.A.) from July 22nd to July 25th, 1964. The following topics were discussed: 1. the sugar sequences in glycolipids and glycoproteins; 2. the degradation of glycosaminoglycans and glycoproteins by redox systems and radiation; 3. the physicochemical properties and biological importance of glycosaminoglycan and glycoprotein solutions; 4. the covalent bonds between amino acids and sugars in glycoproteins; and 5. the biosynthesis of the carbohydrate portion of glycoproteins and glycolipids.

1. Sugar Sequences in Glycolipids and Glycoproteins

Richard Kuhn (Heidelberg, Germany) reported on the isolation of a chromatographically pure glycoliposialoprotein (mucolipid A) which gave a uniform sedimentation pattern in the analytical ultracentrifuge and exhibited high acetylcholine esterase activity. After mild treatment with chloroform plus methanol, this afforded a ganglioside-rich component. All the analyses carried out on this product to date indicate an ester-like and/or lactone-like linkage between the gangliosides.

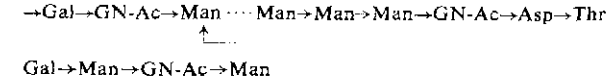
E. Klenk (Köln, Germany) reported on the occurrence of Tay-Sachs gangliosides in normal brain.

P. Stoffyn (Belmont, Mass., U.S.A.) reported on a general method for estimating the α- or β-configuration of the glycosidic bond in cerebrosides. Hydrolysis and hydrogenation of phrenosine affords psychosine which was oxidized with $NaIO_4$, the palmitaldehyde formed being extracted with ether and estimated by gas chromatography. The aldehydes from the aqueous phase were compared with the products obtained from control substances. In the case of phrenosine, they agreed with the aldehydes obtained from 1-D-glyceryl β-D-galactoside, indicating a β-linkage. The method cannot be applied to disaccharides.

G. T. Barry (Knoxville, Tenn., U.S.A.) hydrolysed the glycopeptides from *Citrobacter Freundii* with acid and obtained an amino acid which gave a yellow coloration with ninhydrin and had the same R_f-values on paper chromatograms as synthetic 4-hydroxyleucine. This is formed during the hydrolysis from L-fucosamine, which has thus been detected for the first time in Gram-negative bacteria. *G. F. Springer* (Evanston, Ill., U.S.A.) carried out the isolation and partial characterization of specific haptenes from M and N blood group substances. NN- and N-like blood group substances from erythrocytes and meconium have the structure hexosamine-sialic acid-methylpentose as long as they are still biologically active. *H. Hotta* (Evanston, Ill., U.S.A.) called attention to the high content (33–34 %) of sialic acid in N-active haptenes. *G. M. W. Cook* (Los Angeles, Calif., U.S.A.) achieved a successful separation of M and N blood group glycoproteins by treatment with pronase and subsequent chromatography on Sephadex and DEAE-cellulose. Preliminary identification of the cleavage products indicated that their primary structures are different.

F. Egami (Tokyo, Japan) found the acidic heteropolysaccharides hovatin-sulfuric acid and hovaminic acid in the liver of marine gastropods; these acids contain fucose, mannose, glucose, galactose, and galactosamine; the former also contains sialic acid. But hovaminic acid also reacts with thiobarbituric acid.

On hydrolysis of ovomucoid, *J. Montreuil* (Lille, France) obtained 15 cleavage products which led to the following tentative structure for ovomucoid [*]:



R. G. Spiro (Boston, Mass., U.S.A.) degraded thyreoglobulin by four different methods into two glycoproteins with molecular weights of 1250 and 4100. The smaller fraction contains no sialic acid.

2. Degradation of Glycosaminoglycans and Glycoproteins by Redox Systems and Radiation

L. Sundblad (Stockholm, Sweden) and *W. Pigman* (New York, U.S.A.) spoke about the effect of X-rays on the viscosity of hyaluronic acid and on the redox depolymerization of the same substance and other polymers. The viscosities of solutions containing polysaccharides or synthetic polymers are reduced both by irradiation and by the action of autoxidants such as ascorbic acid or cysteine. Chemical bonds are cleaved by the free radicals formed. *G. O. Philips* (Cardiff, Britain) was able to show that the same radiation dose had different effects, depending on the state of aggregation (crystalline, freeze-dried) of the substrate. *K. S. Dogson* (Cardiff, Britain) irradiated the 6-*O*-sulfates of various monohexoses with X-rays and found that the glucose ester was the most stable.

3. Physicochemical Properties and Biological Importance of Glycosaminoglycan and Glycoprotein Solutions

M. B. Mathews (Chicago, Ill., U.S.A.) reported on the molecular evolution of connective tissue. Although its content of chondroitin sulfate C has remained unaltered, that of chondroitin sulfate A is much higher in evolutionary primitive animals and decreases on rising in the evolutionary scale.

L. Sundblad (Stockholm, Sweden) studied the ratios of some proteins and mucoproteins in the synovial fluid and serum of patients with and without arthritis. In those with rheumatic arthritis only alterations in the proteins were observed.

H. Faillard (Köln and Bochum, Germany) reported on the effect of enzymes on the physiological activity of intrinsic-factor mucoids. The loss of activity after treatment with neuraminidase could be compensated by the addition of strongly acidic ion exchangers. Both its bonded sialic acid and the ion exchanger make the mucoid trypsin-resistant. Its bonding capacity for vitamin B_{12} is not affected by the treatment with neuraminidase.

4. Covalent Bonds between Amino Acids and Sugars in Glycoproteins

A. Dorfman (Chicago, Ill., U.S.A.) found that patients suffering from gargoylism do not have chondroitin sulfate B attached in the normal fashion to a protein; instead, it is extremely soluble. *L. Rodén* (Chicago, Ill., U.S.A.) studied the sugar-protein bond in acidic mucopolysaccharide/protein complexes and isolated xylosylserine and galactosyl-xylosylserine from heparin; this shows the significance of xylose as the bonding unit for attaching the mucopolysaccharide to the protein. The following structure was proposed:

[*] GN = glucosamine, Ac = acetyl.

5. Biosynthesis of the Carbohydrate Portion of Glycoproteins and Glycolipids

The intermediates in the biosynthesis of plasma glycoproteins were discussed by *R. J. Winzler* (Chicago, Ill., U.S.A.). [^{14}C]Glucosamine is rapidly removed from the plasma and converted by microsome fractions from liver homogenates into UDP-*N*-acetylglucosamine *via* a series of still unknown intermediates. The product transfers the acetylglucosamine residue to an acceptor (peptide chain). Since no radioactive oligosaccharides were found, it is assumed that oligosaccharide units are formed by interlinking of individual sugars. *S. Roseman* (Ann Arbor, Mich., U.S.A.) gave an excellent survey of the investigations being carried out in his laboratories. Four enzyme systems catalyse the transfer of sialic acid (as CMP-sialic acid) to acceptors: 1. *E.coli* extracts (transfer to colominic acid); 2. mammary tissue from lactating rats (transfer to low molecular-weight β-D-galactosides, *e.g.* lactose); 3. an enzyme from the submaxillary glands of sheep (transfer to sheep mucin and fetuin treated with neuraminidase); and 4. a soluble enzyme from goat colostrum, which incorporates sialic acid into high and low molecular-weight substances. With the last enzyme and lactose as substrate, 2→3-sialyllactose is not formed as with the enzyme from the mammary tissue of lactating rats, but the 2→6-isomer is formed instead. The isolation of nucleotides with the general structure sialic acid→Gal→GN-Ac→UDP makes it again appear less likely that the transfer of sialic acid is the last step in the biosynthesis of the carbohydrate chains in glycoproteins.

[VB 864/168 IE]

German version: Angew. Chem. 77, 176 (1965)

4th International Congress on Detergents

The 4th International Congress on Detergents was held in Brussels (Belgium) from September 7th to 12th, 1964 [*]. The program was divided into three main groups: The chemistry of detergents (Section A), the physics of detergents (Section B), and applications of detergents (Section C).

The world output of surfactants in 1963 was 2×10^6 tons, according to *W. Hagge*, Leverkusen (Germany). The increase in production of detergents since 1958 lies above the average increase for the overall production of chemicals and approaches the rate of increase of plastics production. If the index of 100 is taken for the year 1958, then the index for the world output of surfactants in 1963 is 177, for plastics it is about 200, and for the average of all chemical products it is about 155.

G. G. Eberhardt and *W. A. Butte*, Marcus Hook, Pa. (U.S.A.), reported on a catalytic telomerization using aromatic hydrocarbons as telogens and ethylene as taxogen; this process leads to liquid or wax-like products, depending on the partial pressure of the ethylene. The catalyst for the reaction is an organolithium compound, *e.g.* butyl-lithium in hexane, which is chelated by a tertiary amine such as triethylenediamine or *N,N'*-tetramethylethylenediamine. Catalytic systems of this type accelerate the rates of chain propagation and transmetallation so much that the telomerization can proceed under mild conditions. The amine component must not contain any active hydrogen (including aromatic, allylic, or benzylic hydrogens). This is why tertiary aliphatic amines are used; moreover, an excess must be used, since the equilibria (a) and (b) must be displaced to the right as much as possible.

$$LiR + NR_3 \rightleftharpoons R_3N{\cdot}LiR \qquad (a)$$

$$R_3N{\cdot}LiR + NR_3 \rightleftharpoons (R_3N)_2{\cdot}LiR \qquad (b)$$

The telomerization can only be carried out with ethylene as taxogen, for all other olefins tend to act preferentially as telogens because of their acidic allylic hydrogens. If benzene is used as telogen, then 1-phenylalkanes are obtained with alkyl chain lengths in statistical distribution. In contrast, with toluene, the transmetallation occurs in the side chain. Here, too, a statistical distribution results, the products being 90 % 1-phenylalkanes with uneven numbers of carbon atoms and 10 % 1-(*m*-methylphenyl)alkanes. The optimum temperature for the reaction lies between 105 and 115 °C.

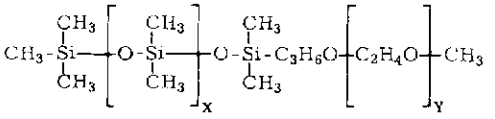
Two lectures were devoted to alkylation of aromatics. *H. M. Friedman*, Cranford, N.J. (U.S.A.), described the reaction of naphthalene with nonene (propene trimer), which is carried out as a discontinuous process. The catalyst used consists of 50 % BF_3 in 85 % H_3PO_4 and has the advantages over conventional Friedel-Crafts catalysts such as H_2SO_4 and 96 % Al_2Cl_6 or $AlCl_3$·HCl [cf. the lecture by *R. Martinez-Gayol*, Madrid (Spain), on the production of dodecylbenzene by alkylation of benzene with propene tetramer] of affording higher yields of monoalkylated naphthalenes and of yielding products of better color. The highest yields of monoalkylnaphthalenes are obtained between 45 and 50 °C (0.8 mole plus 0.03–0.05 mole of dialkylnaphthalenes and 0.15 mole of unchanged naphthalene). Increase in the concentration of catalyst from 8.1 to 15.0 % does not result in any significant increase in the yield of monoalkylated product. The olefin: naphthalene ratio used is 1:1; this is remarkable, since in all other alkylation reactions the aromatic component must be used in excess.

Another important topic dealt with was the synthesis of non-ionic detergents. *W. T. Weller*, Port Sunlight, Cheshire (England), isolated pure poly(ethylene glycols) of formula $HO(C_2H_2O)_nH$, where $n = 1-6$, by fractional distillation of a complex mixture of polyglycols (SHELL PEG 200); the purity of the products was checked by gas chromatography. The monosodium salts of the pure glycols were then treated with the *p*-toluenesulfonate of a fatty alcohol; this led to non-ionic detergents of general formula $RO(C_2H_4O)_nH$, where $R = C_{10}H_{21}$ or $C_{12}H_{25}$, and $n = 1-6$. *R. Celades*, Barcelona (Spain), and *C. Paquot*, Bellevue (France), reported on the preparation of esters of poly(ethylene glycols) by alcoholysis (transesterification) of fatty acid methyl esters with the polyglycols.

G. L. Hollis, Billingham, Durhamshire (England), spoke about some regularities in systems containing ethylene-oxide condensation products. Straight-chain and branched primary alcohols and branched alkylphenols were condensed with ethylene oxide, and the surfactant properties of the products were investigated. These properties vary with the content of ethylene oxide, but nonetheless in every series there is a limiting value for the hydrophobic chain length beyond which no improvements in surfactivity can be obtained independent of the ethylene-oxide content. Examples were given of how the incorporation of propylene oxide into the chains can improve the surfactant properties.

D. L. Bailey, *J. H. Petersen*, and *W. G. Reid*, Tonawanda, N.Y. (U.S.A.), considered siloxane/alkylene oxide copolymers as an unusual class of non-ionic detergents. The properties of methylsiloxane/alkylene oxide copolymers(1) were compared with those of conventional surfactants.

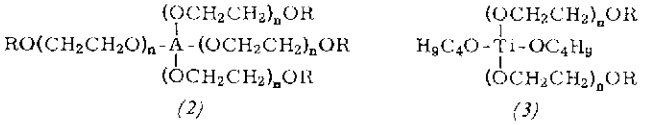
[*] The reports given at the Congress are to be published in three volumes by Gordon and Breach, Science Publishers, Inc., 150 Fifth Avenue, New York 11, N.Y. (U.S.A.), by the middle of 1965.



(1)

Copolymers of this type lead to extremely low values for the surface tension ($\sigma \approx 20$ dynes/cm) in their solutions, even at very high dilutions. They are excellent wetting agents for polyethylene and other hydrophobic surfaces and, in contrast to most other organic products, they exhibit surfactivity in non-aqueous polyglycol systems; this explains their commercial importance as stabilizers for polyurethane foams.

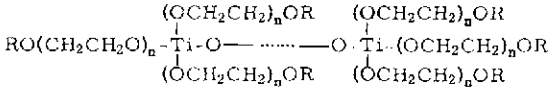
K. Meguro and *M. Ochi*, Tokyo (Japan), prepared organometallic surfactants and examined their suitability as dispersing agents. They synthesized surface-active poly(ethylene oxide) titanates and silicates of general formulae *(2)*, *(3)*,



(2)

A = Ti, Si

(3)



(4)

and *(4)* by the reaction of titanium tetrabutoxide or silicon tetraethoxide with higher oxethylated alcohols. These esters are soluble in water and in many organic solvents and have good dispersing effects on inorganic pigments.

R. Heusch, Leverkusen (Germany), dealt with the surface tension σ of alkylphenol polyglycol ethers. The curves of σ *vs.* temperature for aqueous solutions of alkylphenol polyglycol ethers with alkyl and polyether chains of varying lengths were used to construct σ *vs.* c curves [*] for a measuring time of 90 min; the latter were then used to derive the molecular surface requirements in the interface with the aid of the Gibbs equation. The logarithm of the saturation concentration taken from the σ *vs.* c curves is plotted against the number of carbon atoms in the alkyl residue or against the number of moles of ethylene oxide and the resultant curves used to estimate the energy relationships in the interfaces for hydrophobic and hydrophilic films. The interfacial phenomena were contrasted with the behavior of the molecules in solution.

B. Mitev, Montreal (Canada), and *G. Khanzada*, Montreal (Canada), described the synthesis and properties of biologically degradable detergents based on wheat gluten which had been partially hydrolysed in the presence of alkali at high temperatures under pressure; the resultant polypeptides were acylated with fatty acid chlorides. Further lectures dealt with surfactant 2-alkyl-2-imidazolines [*J. Tornquist*, Stenungsund (Sweden)], the rates of reaction of primary and secondary hexadecyl chlorides with pyridine [*M. Kajl*, Warsaw (Poland)], the synthesis of alkylphenol polyglycerol ethers and their effects on photographic emulsions [*K. Koda* and *S. Kikuchi*, Tokyo (Japan)], and with the removal of electrolytes from a mixture of detergents [*R. C. Mast*, Cincinnati, Ohio (U.S.A.)]. Another interesting topic dealt with was the sulfonation of alkylbenzenes, fatty alcohols, condensates of fatty alcohols and alkylphenols with ethylene oxide, *etc.* to give anionic surfactants.

M. Brunier and *M. Carlotti*, Bonneuil/Marne (France), investigated the effect of various sulfonating agents such as sulfuric acid or oleum plus SO_3 and of different sulfonating conditions on the properties of the sulfonates obtained. During sulfonation with SO_3, the reaction conditions must be maintained much more exactly than with other conventional sulfonating agents. The effect of temperature is one determinant factor, for at high temperatures partial degradation can occur and at low temperature the proportion of non-sulfonated material increases. It could be shown that alkylates with straight side-chains are easier to sulfonate than those with a branched side-chain.

W. Fricke, Frankfurt/Main (Germany), spoke about "Advances in the production of surfactant detergents by sulfonation using SO_3 gas" and discussed a batch process and a continuous multistep process as well as a continuous short contact-time process used by the Chemithon Corporation. The advantages of this method are as follows. The surfactant material is more soluble in liquid detergents because of its lower salt content; fatty alcohols and their condensates with ethylene oxide can be treated to give up to 90 % conversion without discoloration; working costs are reduced because storage and starting-material costs are less even though the power consumption is higher; by-products such as 78 % sulfuric acid and hydrochloric acid are not produced; using a Chemithon plant, for example, straight-chain and branched alkylbenzenes, C_4 to C_{18} fatty alcohols, oxethylated fatty alcohols, and oxethylated alkylphenols can be sulfonated. These advantages are counterbalanced by higher investment costs and – especially in the case of sulfonation of alkylbenzenes – by a higher free-oil content than in the sulfonation with oleum.

A. Davidsohn, Haifa (Israel), talked about practical aspects of sulfonations using SO_3 gas. Following sulfonation experiments with tetrapropylenebenzene, both straight-chain and slightly branched alkylated products were sulfonated. Sulfonation with SO_3 gas appears to offer especially great advantages over conventional methods particularly for these types of substrate; it is only necessary to maintain a lower temperature (about 50 °C towards the end of the reaction). The proportion of non-sulfonated material is estimated as follows. A solution of 5 % sulfonic acid in 50 % aqueous alcohol causes turbidity in a mixture of methyl alcohol and diacetonyl alcohol if the content of non-sulfonated product is greater than 1.5 % based on 100 % detergent. Fatty alcohols or synthetic alcohols (alfols) can also be sulfonated. Another factor of great importance is the possibility of sulfonating toluene and alkylbenzenes in admixture, since as little as 5–10 % toluenesulfonate confers better properties on alkylbenzenesulfonates. In addition to toluene and higher alkylbenzenes, polynuclear aromatics, *e.g.* naphthalene, can also be sulfonated. Petroleum fractions, *e.g.* that boiling between 180 and 240 °C, can also be sulfonated with SO_3 gas.

M. Crauland and *A. Courtier*, Anthony/Seine (France), and *J. Bolle*, Vert-le-Petit (France), lectured on the influence of structure on detergent action and the biological degredability of some alkyl sulfates, alkylbenzenesulfonates, and alkanesulfonates. They reported the syntheses of 1. sodium n-dodecylbenzenesulfonate, 2. a sodium dodecylbenzenesulfonate which was prepared in three different ways and which in contrast to 1. had a branched side-chain; 3. the sodium salts of 2-pentyl-1-nonyl sulfate, 9-heptadecyl sulfate, octadecyl sulfate, and of the sulfates of the products obtained by condensing 2-n-pentyl-2-nonanol, n-heptadecanol, and octadecanol with 2 moles of ethylene oxide; 4. the product of a sulfochlorination of a gasoline fraction with an average of 12 carbon atoms; this product is a sulfonate obtained by addition of $NaHSO_3$ onto 1-dodecene; 5. tetrapropylenebenzene as standard for comparison. The abilities of these products to act as foaming and wetting agents and as detergents and to undergo biological degradation were determined. The sulfates of oxethylated alcohols are better foaming agents than the sulfates of the simple alcohols. The foaming and wetting properties and the stability of the resultant foams increase when the hydrophobic portion of

[*] c = log of concentration.

the detergent is branched. The detergent action was determined by washing artificially soiled natural silk in distilled water at 40 °C containing 1.75 g of detergent per liter. None of the compounds examined attained the detergent action of myristyl sulfate or Marseille soap, which were taken as standards. The biological degradability is significantly facilitated by the oxethylated side-chains, since bacterial growth is apparently promoted by groupings of this type. Thus, for example, condensates of alcohols with ethylene oxide are extremely susceptible to biological degradation.

J. H. McAteer, Linden, N.J. (U.S.A.), and *L. M. Kinnard*, East Hendred, Wantage-Berkshire (England), reported on the dependence of the properties of sodium alkanesulfonates on the molecular weights. A mixture of hydrocarbons consisting of straight-chain paraffins with 12 to 20 carbon atoms per molecule was separated into sharp fractions each containing about 90–95 % of molecules with an equal number of carbon atoms. These fractions were converted into their sulfonates by irradiation with γ-rays. The $-SO_3H$ groups are distributed statistically over the whole molecule. The sulfur content was 1.3 atoms per mole. The decrease in solubility with rising molecular weight was determined at 25 °C. The solubility of the C_{18} sulfonate is similar to that of n-dodecylbenzenesulfonate. Subsequently, the surface tension, critical micelle concentration, foaming action in soft and hard water, and the detergent action of the products were determined. These properties increase as the carbon content per molecule rises from 13 to 17. The detergent action of a sulfonate containing 15 carbon atoms is roughly equivalent to that of tetrapropylenebenzene under the same conditions. The biological degradability of each product was determined by the method of *M. S. Kenecky*, *R. I. Kelly*, *J. M. Symonds*, and *P. L. McCarty* ["The Determination of the Biodegradability of Detergents, Esso Research Biodegradation Test", presented at the 36th Annual Meeting of the Water Pollution Control Federation, Seattle, Wash. (U.S.A.), October 1963]. All the products are readily degradable, the sodium alkanesulfonates of higher molecular weight requiring about 10 days for complete degradation, *i.e.* about the same time as for 2-phenyldodecanesulfonate.

[VB 866/171 IE]

German version: Angew. Chem. 77, 140 (1965)

Organic Semi-Conductors and Inorganic Semi-Conductors with Molecular Lattices

A meeting of the "Semi-Conductor Chemistry" Group of the Gesellschaft Deutscher Chemiker was held in Munich (Germany) on October 12th and 13th, 1964. As *G. M. Schwab* emphasized in the introduction, the meeting should provide a survey of the state of work carried out in recent years in the field of organic semi-conductors. The lectures were concerned not only with methods of measurement and mechanisms throwing light on conductivity in molecular lattices, but also with the possible uses of organic semi-conductors.

In the first plenary lecture *O. Le Blanc, jr.* (New York, U.S.A.) considered the problem of electronic transport in organic crystals on the basis of results obtained by the impulse-photoconductivity procedure developed by him and *Kepler* (1960). Since this procedure makes it possible to follow through the crystal the migration of charge-carriers, which are released by a flash of light of 1 μsec duration at the crystal surface, information can be obtained about mobility, trapping processes and the mechanism of charge-carrier formation (quantum yield *etc.*). By these means it was established that in anthracene crystals the mobilities of holes and electrons, of the order of 1 $cm^2/V/sec$, decreased with increasing temperature, a result which is in accordance with the band model. The change in mobility from 1 $cm^2/V/sec$ observed in pyrene on transition from the solid to the liquid state indicates that a "jump process" replaces the band-model mechanism in this transition. Measurements of the lifetime τ of electrons and defect-electrons in tetracene gave values of up to 10 μsec. A marked increase in the time of transit T for holes on doping was observed, which ranged from 50 μsec in undoped anthracene to 5000 μsec after adding 2 p.p.m. of naphthacene. The dependence on wavelength of the number of charge-carriers released by a flash of light conforms with the absorption spetrum. The number of negative carriers in anthracene is about ten times that of the positive ones. The relationship between the number of charge-carriers formed by irradiation and the intensity of the light is linear.

To explain the results it is assumed that the charge-carriers (electrons, holes) formed by irradiation at the surface of the crystal result from disintegration of an "exciton" which has diffused to the surface; the transport through the crystal can apparently be described in terms of the band model.

Ph. Traynard (Grenoble, France) in his paper on "Catalysis and Organic Semi-Conductors" – reported by *Nechtschein* – referred to the possible technical uses of organic polymers on the basis of their surface-catalytic activity. Eka-conjugated polymers (*e.g.* polybenzimidazoles) were shown to catalyse the decomposition of N_2O and the cleavage of hydrogen from alcohols and formic acid. The close correlation between the number of unpaired electrons determined by measurements of the paramagnetic resonance and the catalytic activity is worthy of note. In accordance with this, the catalytic activity of the polymers is enhanced by addition of radicals. A relationship between the catalytic activity and the chemical structure of the polymers could so far not be found.

H. Meier and *W. Albrecht* (Bamberg, Germany) reported on "The Problem of Doping Organic Photoconductors". It was shown that the dark- and photoconductivity of p-type dyes purified by high-vacuum sublimation (merocyanine, phthalocyanine) can be increased by a factor of up to 1.7×10^3 or 5×10^4, respectively, by addition of electron-acceptors (iodine, tetraiodophthalic anhydride, tetracyanoethylene *etc.*). Acceptor concentrations of 10^{-7} M were effective. The dark conductivity of high-resistance phthalocyanines was of the order of 0.02 $ohm^{-1}\,cm^{-1}$ after doping. To explain the effect of doping it was assumed that after addition of acceptors the concentration of electron-deficiencies in the p-type dye increases on irradiation due to charge-transfer processes and a simple acceptor action between dye and doping material somewhat as in inorganic semi-conductors.

As evidence for the validity of this mechanism, which assumes that theories used for inorganic semi-conductors are applicable to organic photoconductors, some experimental results were discussed: mobilities of the order of 100 $cm^2/V/sec$ (*Delacote* and *Schott* et al.), ESR measurements (*Kearns*, *Tollin*, *Calvin* et al.), quantum yields > 1 on doping, enhancement of the photovoltaic effect of inorganic/organic semi-conductor combinations (CdS/phthalocyanine, *etc.*) of the order of 300 to 400 mV on doping the dye component.

J. Voitländer (Munich, Germany) spoke about the "Dark- and Photoconductivity of Ferrocene" – reported by *Eichhorn*. In ferrocene single-crystals purified by vacuum sublimation, the specific dark-resistance, of the order of 7×10^{13} ohm·cm, obeys the equation $\log R = (E/kT)\log R_0$ with an energy of activation $E = 0.61 \pm 0.02$ eV. The current-potential characteristic shows an ohmic relationship up to 5000 V/cm, above 5000 V/cm, however, the relationship between dark current and voltage is $i = \sinh(bV)$. By comparing the intensity functions of the photoelectric current on positive and negative polarity of the electrodes of the sand-

wich cell used, a ratio $i_+/i_- = 2.3$ is obtained. The dependence of photoelectric current on wavelength (using filters for measurement) shows that the photoelectric current is produced by photons of wavelength 2025 Å. Thus the transition of iron at 2700 Å does not contribute to the photoconductivity of ferrocene. The mobility of the electron-deficiencies is 0.43 $cm^2/V/sec$, that of the electrons 0.36 $cm^2/V/sec$.

In explaining the photoconductivity it is assumed that on absorption of light excitons result, which diffuse to the surface and dissociate into electrons and defect-electrons. On the basis of the ratio $i_+/i_- = 2.3$, holes were considered to be the major carriers.

"New Polymers of Aromatic and Heterocyclic Compounds and their Electrophysical Properties" was the subject of the paper by *H. Naarmann* and F. *Beck* (Ludwigshafen, Germany). They prepared insoluble, infusible, deep-colored, high-molecular compounds by reductive polymerization of aromatic and heterocyclic compounds (benzene, naphthalene, thiophene, Cu-phthalocyanine, *etc.*) in the presence of Friedel-Crafts catalysts. The degree of polymerization obtained from infrared measurements is about 60 for the polymerisation of benzene, but depends on the reaction temperature and the components used. The interference with polymerization by oxygen and the varying activities of the dehydrogenating agents, which in the series $CuCl_2 < FeCl_3 < PdCl_2$ cause an increase of the degree of polymerization, is noteworthy.

Conductivities of the order of 10^{-1} to 10^{-15} $ohm^{-1}\ cm^{-1}$ (25 °C) for powders at a pressure of 300 atm increase with temperature; the Arrhenius plots gave activation energies between 0.025 and 0.96 eV. The specific conductivity of the compounds increases with the temperature of polymerization (*e.g.* from 10^{-11} $ohm^{-1}\ cm^{-1}$ at 20 °C to 10^{-6} $ohm^{-1}\ cm^{-1}$ at 300 °C) while the energy of activation of the conductivity decreases. Since this effect was recently connected with the relationship between conductivity and chain-length, the connection between conductivity and type of dehydrogenating agent, as well as the effect of the oxygen content of the species to be polymerized, is understandable. On using $PdCl_2$ as the dehydrogenating agent for polymerization a conductivity of 10^{-2} $ohm^{-1}\ cm^{-1}$ is obtained, while with $CuCl_2$ the conductivity is 10^{-11} $ohm^{-1}\ cm^{-1}$; on decreasing the oxygen content the conductivity increases. From the sign of the thermal e.m.f. (which is of the order of up to 125 $\mu V/°C$) it is concluded that the polymers, which also exhibit photoconductivity, are p-type conductors.

In the second plenary lecture *N. Riehl* (Munich, Germany) spoke on "Protonic Semi-Conductors". Since the conductivity of these semi-conductors is due to transitions of protons from one site to another, especially substances with hydrogen bonds, in which the proton can occupy various positions, behave as protonic semi-conductors.

Ice was chosen as the model substance for investigating protonic conductivity. In ice proton transitions account for the high diclectric constant (DK). The activation energy (0.6 eV) of these transitions was determined from the variation of dispersion frequency with temperature. It agrees with the activation energy of conductivity from which it is concluded that the conductivity, too, can be accounted for by proton transitions.

The values recently found for the proton concentration in ice yielded information about the mobility of the protons. It is about fifty times higher than in water and is about 0.1 $cm^2/V/sec$, *i.e.* of the same order as the mobility of electrons in some organic semi-conductors. This result is of great significance for the charge-transfer mechanism in organic molecules of biological importance since hydrogen bonds are present in these as in ice.

J. Mulder (Eindhoven, Netherlands) reported on "The Photoconductivity of Perylene Crystals". The investigations, in which aqueous solutions were used as electrodes, showed that the quantum yield of the photoelectric current of the metastable β-modification of perylene is similar to that for anthracene, namely 10 %, while the value is markedly lower (<2 %) for the stable α-perylene. The spectral sensitivity of the photoelectric current bears a great resemblance to the absorption spectrum. There is a shift in the spectral sensitivity on adsorption of rhodamine B at the positively charged crystal faces.

The ratio of the photoelectric currents with positive or negative polarity of the illuminated electrode ($i_+/i_- > 100$) indicates a preferential hole current in the crystals. Presumably the charge carriers are formed from excitons which diffuse to the positive crystal faces.

The paper by *K. Hauffe* (Frankfurt/Main, Germany) was concerned with "The Influence of Gaseous Atmospheres on the Dark- and Photoelectric Current of Some Phthalocyanines". Measurements of the conductivity of metal-free phthalocyanine and Cu-, Zn-, Ni-, and Fe-phthalocyanines in O_2, NO, NO_2, NH_3, and in vacuum (10^{-5} mm) between 20 and 150 °C gave the following results: O_2 causes a reversible increase in conductivity; by the influence of NO or NO_2 the conductivity is irreversibly increased by 5 to 6 powers of 10, but on subsequent treatment with NH_3 the original value is restored. The influence of the central metal atom on the conductivity is slight; also the effect of the gas is not influenced by the metal atom.

In the third plenary lecture, *J. Kommandeur* (Groningen, Netherlands) dealt with "Donor-Acceptor Effects in Organic and Inorganic Molecular Crystals", which determine the electrical behavior of numerous organic semi-conductors. As examples, pyrene-iodine complexes *(1)* and perylene-iodine complexes *(2)* display high conductivities [specific resistance of *(1)*: 75 ohm·cm, of *(2)*: 8 ohm·cm] and energies of activation for dark conductivity which are of the same order of magnitude as kT at room temperature [*(1)*: 0.07 to 0.14 eV, *(2)*: 0.019 eV]. The energy of activation obtained from the temperature-dependence of conductivity is in good agreement with that derived from ESR measurements, showing a connection between concentration of unpaired spins and concentration of charge-carriers.

The electrical behaviour of donor-acceptor crystals can be discussed in terms of the molionic lattice. These lattices contain ion-pairs (donor-acceptor pairs) together with molecules and, owing to the polarizing action of the ions, are much more stable than purely molecular lattices.

H. Hoegl (Carouge-Genève, Switzerland) reported on the "Photoconducting Properties of Poly-*N*-vinylcarbazoles", determined by electrophotographic methods or by measurement of the light-induced decrease in potential of layers charged by corona discharge. The results from the electrophotographic methods at the same time indicated a potential use of the photoconductors examined in electrophotography. The investigations showed that the spectral sensitivity of thin films (2 to 10 μ) of polyvinylcarbazoles can be shifted by the addition of sensitizers (rhodamine B, *etc.*). Moreover, the photoconductivity is much increased by doping with electron acceptors. The following electron acceptors were effective: Lewis acids (*e.g.* BF_3, $AlCl_3$); nitro compounds (1,3,5-trinitrobenzene, 2-nitroindane-1,3-dione), cyano compounds (tetracyanoethylene; 1,5-dicyanonaphthalene); carboxylic acid anhydrides (tetrachlorophthalic anhydride, *etc.*); esters (tetraethyl ethylenetetracarboxylate); halogen compounds (triphenylchloromethane, *etc.*); quinones (*p*-chloroaniline, *etc.*); keto compounds (benzil, pyrene-3-carboxaldehyde); aza compounds (acridine, *etc.*). Similarly, using electron acceptors as the basic material marked increases of photoelectric sensitivity are measured after doping with electron donors.

An obvious relationship exists between the concentration of electron acceptors and the photoelectric sensitivity of the doped polyvinylcarbazoles. To explain the formation of charge carriers in the doped layers it is assumed that a light-induced electron transition occurs between the vinylcarbazole residues and the acceptor-defects.

In a discussion on the problem of semi-conductor properties of phthalocyanines, *C. Haman* (Dresden, Germany) pointed

to the fact that differing results by different authors were probably due to their disregarding the differing electrical properties of phthalocyanine modifications. For example, measurements of thermal e.m.f. gave the following values: β-form: +50 μV/°C; α-form: +1100 μV/°C; α'-form: +1350 μV/°C; γ-form: +900 μV/°C. A mixture of β- and α-forms gave a negative thermal e.m.f. of −70 μV/°C. While the α'-modification is formed by precipitation from H_2SO_4, the β-modification results from heating the α-form at 280 °C. The γ-modification is obtained by mechanical treatment of the β-form, *e.g.* by grinding with phthalic anhydride.

[VB 871/176 IE]
German version: Angew. Chem. 77, 177 (1965)

Structure and Function of the Red Blood Cells

The Institute for Physiological Chemistry and the Institute for Pharmacology and Toxicology of the Humboldt University were the organizers of the IVth International Symposium on Structure and Function of the Red Blood Cells that was held in Berlin (Germany) from August 25th to 27th, 1964 under the auspices of the Gesellschaft für experimentelle Medizin der DDR. Of the 130 participants 34 were foreign guests. The scientific program was organized by *S. Rapoport* and *F. Jung*. Problems of transport through membranes, of metabolic regulation, and of the structure of red blood cells were of foremost interest.

W. Wilbrandt (Bern, Switzerland) described the three possibilities for transport of substances (free diffusion, mediated diffusion, exchange diffusion with active transport). He dealt particularly with sugar transport with the participation of carriers and was able to show that the speed of transport under conditions of constant concentrations within and without the membrane decreased with increasing absolute concentration. The kinetics of transport mediated by carriers did not correspond to enzyme kinetics. The transport of one substrate (D-glucose) occurring in high concentration, is competitively accelerated by a second substrate (D-mannose). This acceleration changes to competitive inhibition at saturation with the second substrate. Investigations and calculations, jointly with *Kotyk* (Prague), indicate a mechanism involving 1 carrier molecule per 2 substrate molecules.

W. F. Widdas (London) dealt with the irreversible inhibition of glucose transport by 2,4-dinitrofluorobenzene (DNFB) and *N*-ethylmaleimide. ^{14}C-Labelled DNFB was recovered in the butanol-soluble lipid fraction. The mechanism of this transport inhibition is not yet clear.

K. Repke and *H. J. Portius* (Berlin, Germany) reported that the inhibitory action of steroid lactones on transport-ATPase and the ion transport in erythrocytes depends on the presence of a conjugated unsaturated lactone ring occurring in the 17β-position. Ca^{2+} acts synergistically, K^+ antagonistically. According to *Steinbrecht* (Magdeburg, Germany), the permeation of 2-deoxy-D-ribose into rabbit erythrocytes is a simple diffusion process with a large entry velocity.

F. Müller (Leipzig, Germany) found that the inhibition by strophantin of galactose and ion transport is counteracted by fructose. Whether a true coupling between monosaccharide and ion transport is involved has not yet been elucidated. Iodoacetate and 2,4-dinitrophenol inhibit the transport.

S. Rapoport (Berlin, Germany) described the following principles for the regulation of the metabolism of the red blood cell: 1. Regulation by synthesis and breakdown of enzymes. Red blood cells are unsuitable for the investigation of genetic control of enzyme induction and repression because of the lack of DNA. On the other hand, they have proved to be particularly suitable for the investigation of metabolic regulation by enzyme degradation which is characteristic of the process of maturation. – 2. Regulation by changes of enzyme activity without participation of substrates, cofactors and metabolites. In this connection, the formation of active enzymes from precursors, changes in activity through polymerisation or depolymerization, and unmasking of enzymes was discussed. At the same time reference was made to the regulation by compartmentization, *i.e.* to the limitation of metabolism by membranes. – 3. Regulation by the effect of immediate or later metabolites and cofactors on the enzyme (comparable with the allosteric effect).

The contributions on the regulation of glycolysis led from different starting points to concordant conclusions:

1. Glucose transport is not limiting for glycolysis. *Augustin* and *Häcker* (Magdeburg, Germany) came to this result from a comparison of maximal glycolysis capacity and maximal transport capacity. *L. Garby* and *C. H. de Verdier* (Uppsala, Sweden) concluded the same from the fact that the glucose gradient at the membrane changes only slightly with marked alterations of the external glucose concentration.

2. The rate of glycolysis is influenced in some species by the phosphate concentration. *L. Garby* and *C. H. de Verdier* found an increase of glycolysis with increasing phosphate concentration and on addition of EDTA. They explain this effect by a fall in the actual Ca^{2+} concentration and a consequently higher activity of Mg^{2+} ions on hexokinase.

G. Jacobasch and *J. Syllm-Rapoport* (Berlin, Germany) found the same effect of inorganic phosphate with erythrocytes from patients with short-term vitamin D deficiency rickets. Triose phosphate dehydrogenase is discussed as the enzyme involved.

Investigations on the relationship between amino acid breakdown, respiration and carbohydrate metabolism showed that the amino acids, as endogenous substrates of respiration, participate to different degrees in the total CO_2 formation (*M. Schultze* and *J. Scholz*, Berlin). The participation of some amino acids changes during maturation. Among the free amino acids of the reticulocyte, glycine occurs in the greatest concentration, and at the same time, plays the biggest role in CO_2 formation (*R. Buchmann*, Berlin). The concentrations of free amino acids decrease in the course of maturation. The same occurs on short term incubation. Addition of α-ketoglutarate or glucose keeps the concentrations of free amino acids low for longer incubation times, so that a prolonged synthetic activity must be assumed. The same may be observed with 2,4-dinitrophenol. The cause in this case certainly is a reduced amino acid liberation from the stroma since this is energy-dependent.

[u-^{14}C]Serine and [3-^{14}C]serine yield hydroxylamine and glycine (*M. Schultze* and *M. Müller*, Berlin), which are used in the biosynthesis of purines and porphyrins and form CO_2 to a large extent. In addition, serine forms pyruvate which again yields CO_2. As the addition of glutamine leads to an increased glycine concentration, glutamine causes either an enzyme inhibition or brings about a regression of the Shemin cycle. Addition of methylene blue increases amino acid breakdown in the soluble phase, whereby CO_2 formation, from the substrates of the citric acid cycle, is diminished.

L. Ababei (Bucharest, Rumania) showed that no equilibrium is established between lactate and pyruvate in the erythrocyte. The reason lies in the presence of NADH- and NADPH-oxidases, which were enriched. Besides, two lactic dehydrogenases with different coenzyme specificities (NAD and NADP) were detected in erythrocytes.

In investigations on the 2,3-diphosphoglycerate-splitting enzyme of human erythrocytes, the question of the importance of the diphosphoglycerate cycle in erythrocyte glycolysis was taken up again.

H. Roigas (Berlin) was able to show that addition of ADP and NADH in physiological concentrations can increase the small 2,3-PGase [1] activity in haemolysates up to five-fold. This effect is interpreted as the degradation in the direction pyruvate-lactate of accumulated 3-phosphoglycerate, which inhibits the 2,3-PGase competitively. *G. Sauer* and *D. Scholz* (Berlin), who purified erythrocyte 2,3-PGase up to 220 times, came to the same conclusions. The findings indicate a preference for the diphosphoglycerate pathway in intact erythrocytes. *C. H. de Verdier* (Uppsala, Sweden) confirmed the presented data in a detailed discussion from his own investigations with purified PGase from human erythrocytes. The existence of two isoenzymes seems probable. It can be assumed that the 2,3-PGA [2] pathway is only of small significance for red blood cells (sheep erythrocytes) which contain only traces of 2,3-PGA (*G. Jacobasch* and *S. Rapoport*, Berlin).

S. Rosenthal, *K. Jagemann*, and *G. Heinemann* (Berlin) reported on enzymatic determinations of the purity of reticulocyte ribosomes (rabbit) and characterized a ribosomal RNase. Pure ribosome preparations (50 % protein, 50 % RNA) contain only 0.1 % (referred to the whole haemolysate) or less of acid phosphatase. Such pure ribosomes possess an RNase, which is activated at pH 7.5 by monovalent cations (tris, collidine, K^+, Na^+, Li^+) at varying degrees.

[VB 870/174 IE]

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[1] 2,3-PGase = 2,3-diphosphoglyceratase.

[2] 2,3-PGA = 2,3-diphosphoglycerate.

The Chemistry of Carbohydrates

An international symposium on the chemistry of carbohydrates was held from July 13th to 17th, 1964 in Münster (Germany). Participants from nineteen countries heard almost fifty lectures on problems from the fields of mono- and polysaccharides, amino sugars, and the biochemistry of carbohydrates.

From the lectures:

K. Freudenberg, Heidelberg (Germany), reported on the linkage between lignin and carbohydrates in plants. During the formation of lignin by dehydrogenation of *p*-hydroxycinnamyl alcohols, *p*-quinone methides occur as intermediates which can combine, for example, with one or two molecules of sucrose to give aliphatic ether-type compounds which again undergo phenol dehydrogenation and are condensed into the growing lignin molecule. Lignin is grafted onto the polysaccharides in wood by the same mechanism.

G. G. S. Dutton and *A. M. Unrau*, Vancouver (Canada), investigated the structures of synthetic polysaccharides (glucosans, xylans, mannans, and arabans) which had been prepared by *Mora* et al. by polymerization of monosaccharides at 120 °C using phosphoric acid as catalyst. The structures of the products were found by hydrolysis of their methyl derivatives, reduction with $NaBH_4$, oxidation of the sugar alcohols with periodate, and renewed reduction with $NaBH_4$. The products of this series of operations were separated by gas chromatography and revealed that all the polysaccharides are strongly branched and that their monosaccharide constituents are mainly in the furanoid form.

E. Husemann and *G. M. J. Müller*, Freiburg/Breisgau (Germany), polycondensed 2,3,6-tricarbanilylglucose with P_4O_{10} in chloroform/dimethylsulfoxide. The products obtained had degrees of polymerization of 200–600 and could be converted by alkaline hydrolysis into compounds which were comparable with strongly degraded celluloses. After partial hydrolysis, cellobiose and cellotriose were obtained. The polymers are therefore β-1,4-polyglucosans and can be degraded by *Acetobacter xylinum*, for example, but not with amylase.

P. S. O'Colla and *E. E. Lee*, Galway (Ireland), reported on the polymerization of β-1,2,3,4-tetra-*O*-acetylmannose and -galactose with $ZnCl_2$ as catalyst. The mannose derivative yields oligosaccharides and a polymer. Degradation of the polymer with periodate and subsequent methylation revealed that it consists mainly of an α-1,6-mannan with a degree of polymerization of 10.

E. J. Bourne et al., London (England), studied the structures of branched dextrans by hydrolysis with acid, acetolysis, methylation, and oxidation with periodate. Catalytic oxidation and hydrolysis afforded α-D-glucuronido-D-glucoses which represent the points of branching in the dextrans. α-1,3-Branched dextrans submitted to oxidation with periodate, reduction, and partial hydrolysis yielded α-D-glucosidoglycerol and α-isomaltosidoglycerol. The degradation products supply information on the size and distribution of the side chains in the dextrans.

The structure of the plant gum from *Sterculia* species was studied by *G. O. Aspinall* et al., Edinburgh (Scotland). The gum is a partially acetylated polysaccharide, containing D-glucuronic acid, D-galacturonic acid, D-galactose, and L-rhamnose. Isolation of the products of hydrolysis of the methylated polysaccharides indicated the type and extent of branching in the gum.

E. Percival, Englefield Green (England), isolated a β-1,3-linked glucosan and a mannan containing 27 % uronic acid and 7.5 % sulfate esters from *Phaeodactylum tricornutum*, a marine alga. The glucuronidomannan containing sulfuric acid is the first polymer of this type that has been encountered in nature.

I. Bremner and *K. C. B. Wilkie*, Old Aberdeen (Scotland), extracted the stems of *Pteridium aquilinum*, a species of fern, and isolated two hemicellulose-type polymers, a water-soluble xylan, and a branched glucomannan, in which mannose and glucose in a ratio of 4:1 are linked by β-1,4-linkages. The xylan consists of β-1,4-linked xylose residues, some of which are etherified glycosidically in the 2-position with 4-methyl-D-glucuronic acid residues.

A. S. Perlin and *W. Klöker*, Saskatoon (Canada), investigated the carbohydrates from the spores of *Puccinia graminis tritici*, the fungus which causes wheat-rust. The polysaccharides extracted contained D-mannose linked by β-1,4- and occasionally by β-1,3-linkages, together with smaller amounts of D-glucose and D-galactose. Numerous mono- and oligosaccharides including xylose, ribose, and glucosamine were isolated after partial acetolysis and hydrolysis of the residue.

V. C. Barry and *J. E. McCormick*, Dublin (Ireland), oxidized simple glycosides with periodate and treated the products obtained with isonicotinylhydrazine and thiosemicarbazide. They thus obtained condensation products which had previously been isolated after oxidation of polysaccharides with periodate. Hence the two aldehydic groups in the oxidized sugar react with only one molecule of the hydrazine compound to form a cyclic derivative and not a bis-hydrazone.

G. Henseke and *G. Hanisch*, Freiberg/Sachsen (Germany), used dimethylsulfoxide for oxidations in the sugar series. If 1,2-*O*-isopropylidene-6-*O*-tosyl-D-glucose is converted into its 5,6-epoxide, the latter can be oxidized with dimethylsulfoxide in the presence of boron trifluoride to give the 1,6-dialdose. Analogously, α-methyl 2,3-epoxy-4,6-*O*-benzylidene-alltopyranoside can be oxidized to the corresponding mannopyranosidc. Simultaneously, migration of the formyl residue into the interior of the sugar chain occurs with formation of 1,5:2,6-dianhydro-3,4-D(L)-*threo*-hexodiulose.

B. Lindberg, Stockholm (Sweden), treated carbohydrates, *e.g.* glucose, with sulfite at various temperatures and pH values. This results in oxidation of hydroxyl or aldehydic groups, and rearrangements and sulfonations occur.

H. Zinner, Rostock (Germany), reported on the synthesis and reactions of di-*O*-benzylidenepentonic acids, which are prepared by oxidation of the di-*O*-benzylidenepentoses with chromic oxide in dimethylformamide. The acids yield the methyl esters with diazomethane; when treated with ammonia or hydrazine hydrate in methanol, the esters give rise to the di-*O*-benzylidenepentonamides and the corresponding hydrazides. Reduction of these three derivatives of the acids with $LiAlH_4$ yielded the dibenzylidenepentitols and their 1-deoxy-1-amino and 1-deoxy-1-hydrazino derivatives. The structures of the dibenzylidene compounds all correspond to the rules set forth by *R. M. Hann* and *C. S. Hudson* for the formation of cyclic acetals of polyhydric alcohols.

The last two unknown 3-*O*-methyl-6-deoxyhexosides with the *allo*- and *gulo*-configurations have been synthesized by *H. Kaufmann* and *T. Reichstein*, Basel (Switzerland). Of the eight possible stereoisomers with two antipodes each, six isomers are known either from natural sources or from syntheses. The 3-*O*-methyl-6-deoxy-D-allose was made by partial methylation from 3-methyl 6-deoxy-D-allopyranoside. For the synthesis of the 3-*O*-methyl-6-deoxy-D-gulose, β-methyl D-glucopyranoside was converted into β-methyl 6-deoxy-3,4-anhydro-D-galactopyranoside, which was treated with sodium methoxide to yield the D-gulo derivative by diaxial opening of the epoxide ring.

N. K. Kochetkov, Moscow (U.S.S.R.), reported on a new synthesis of glycosides. 1,2-Alkylidene orthoacetates of acetylated monosaccharides react with alcohols in the presence of $HgBr_2$ in nitromethane to give 1,2-*trans*-glycosides. Di- and oligosaccharides can be synthesized using the same reaction.

M. Schulz, Berlin-Adlershof (Germany), treated α-acetobromoglucose *(1)* with t-butyl hydroperoxide in benzene in the presence of silver carbonate and obtained t-butyl tetra-*O*-acetylperoxyglucoside. The reaction of *(1)* and t-butyl hydroperoxide in nitromethane/collidine, on the other hand, yielded tri-*O*-acetyl-1,2-[t-butylperoxyortho-*O*-acetyl]-α-D-glucose. The carbon atom in position 1 of the sugar is split off from the peroxyglucoside with 0.01 N sodium methoxide in ethyl formate. This reaction is a new sugar degradation of general applicability.

V. Prey, Vienna (Austria), treated di-*O*-isopropylideneglucose and -fructose with trimethylchlorosilane, dimethyldichlorosilane, and methyltrichlorosilane and obtained the corresponding methylsilyl compounds containing one, two, or three molecules of sugar. Similar derivatives are formed with $SiCl_4$ in which one silicon atom is linked to four molecules of sugar.

R. Bognár, Debrecen (Hungary), reported on the synthesis and properties of onic acid derivatives. Acetylated onic acids can be converted with dichloromethyl methyl ether into the acid chlorides, which are suitable as acylating agents for amines, phenols, and monosaccharides with only one free hydroxy group; 1- and 6-gluconyl-D-glucose were prepared in this way. Tetra-*O*-acetylgalactonyl chloride reacts with NaN_3 to form the azide, which reacts with acetic anhydride to yield *N*-[D-galactopenta-*O*-acetyloxyamyl]acetamide. The latter can be degraded with ammonia to D-lyxosyldiacetamide or with HCl to D-lyxose.

B. R. Baker et al., Buffalo, N.Y. (U.S.A.), studied the conditions under which *cis*-2,3-diamino sugars are formed with regard to neighboring group effects and conformation. α-Methyl 2-*O*-mesyl-3-deoxy-3-amino-4,6-*O*-benzylidene-D-altroside (with a *trans*-diaxial conformation of the substituents on C-2 and C-3 and with a urea, thiourea, guanido, or nitroguanido residue instead of the amino group, if desired) undergoes cyclization under strongly alkaline conditions to give an aziridine derivative, with formation of an anion as an intermediate. In the presence of an acid acceptor, *e.g.* pyridine, an oxazolidine, imidazolidine, or thiazolidine derivative is formed. By contrast, β-methyl 2-*O*-mesyl-3-deoxy-3-thioureido-4,6-*O*-benzylidene-D-glucoside, which has a *trans*-diequatorial conformation of the substituents, does not form an aziridine but yields only a thiazolidine derivative under both sets of conditions.

The synthesis and properties of epimino sugars were studied by *L. Hough* et al., Bristol (England). α-Methyl 2-deoxy-2-acetamido-3-*O*-mesyl-4,6-*O*-benzylidene-D-altroside reacts with sodium ethoxide in ethanol with inversion of the configuration at C-3 to give a mixture of an *N*-acetylepimino sugar (an aziridine derivative) and an oxazoline derivative. *trans*-Diaxial ring opening of the *N*-acetylepimine with hydrogen halide leads to a mixture of the 2-halogeno-3-acetamido and 2-acetamido-3-halogeno derivatives of altrose.

R. D. Guthrie and *D. Murphy*, Brighton (England), treated α-methyl 2,3-dideoxy-2,3-epimino-4,6-*O*-benzylidene-D-alloside and the corresponding mannoside with azide to form the corresponding aminoazido sugars. Subsequent reduction yielded the same 2,3-diaminoaltroside from both starting materials, hence *trans*-diaxial opening of the epimino ring has occurred here, too.

H. Paulsen, Hamburg (Germany), reported on the reactions of 5-aminopentoses and 5-aminohexoses, which occur mainly in the form of piperidinoses and readily lose three molecules of water to yield derivatives of 3-hydroxypyridine. In addition, an Amadori rearrangement of the piperidinoses can also take place leading to derivatives of 4,5-dihydroxy-3-oxopiperidine. This reaction proceeds via a Δ^1-piperideine which rearranges to the final product.

In connection with the work by *Paulsen*, *Hanessian*, and *Haskell*, the investigations of *W. A. Szarek* and *J. K. N. Jones*, Kingston, Ont. (Canada), are of interest. These authors oxidized 1-deoxy-1-acetamido-D-rihitol carefully with periodate and obtained 4-deoxy-4-acetamido-L-erythrose, a sugar with nitrogen as hetero-atom in a five-membered ring. 4-Deoxy-4-acetamido-D-threofuranose has an analogous structure. 2-Oxopentose derivatives, *e.g.* 5-deoxy-5-acetamido-D-*threo*- and -L-*erythro*-2-oxopentose, on the other hand, do not form a five-membered nitrogenous heterocycle.

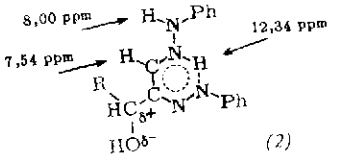
R. L. Whistler, Lafayette, Ind. (U.S.A.), reported on syntheses of pyranoses containing sulfur as hetero-atom in the ring (reaction of 5-*O*-tosylpentofuranose derivatives with sodium benzylmercaptide to give 5-mercapto sugars and cyclization to thiapyranoses) and on attempts to prepare thiafuranoses and hexose derivatives with a seven-membered ring containing sulfur. Thus, for example, 1,2-*O*-isopropylidene-5-*O*-tosyl-6-*O*-tritylglucofuranose reacts *via* an olefinic intermediate to give 5-deoxy-6-mercapto-D-glucose, which undergoes ring closure to yield a glucosan-type compound containing sulfur.

J. E. Hodge et al., Peoria, Ill. (U.S.A.), examined the degradation products obtained from sugars that had been prepared by Amadori rearrangement with secondary amines. L-Rhamnose yielded diacetyl and a reductone containing nitrogen which is derived from hydroxydiacetyl, together with 2,5-dimethyl-4-hydroxy-3(2*H*)-furanone. Maltose and lactose give rise respectively to 2-acetyl-3-hydroxyfuran and 2-methyl-3-hydroxy-1,4-pyrone. Under the conditions used,

all the aldo- and ketohexoses examined afforded betaine-like aminohexose reductones, *i.e.* methyl derivatives of reductinic acid containing nitrogen. It is assumed that the formation of these compounds starts with 2,3-enolization of the products of the Amadori rearrangement. The olefinic diols are in equilibrium with the tautomeric 3-oxo compounds, from which the nitrogen is eliminated to form α-diketone intermediates.

There is a close connection between the work by *Hodge* and the studies by *H. Simon* and G. *Heubach*, München (Germany), on the formation of alicyclic and open-chain reductones containing nitrogen from hexoses and secondary amines. The mode of formation of *N*-[1-methyl-1,2,3-trihydroxycyclopent-2-en-4-ylidene]piperidinium betaine, an aminohexose reductone, was clarified further by its synthesis from diacetylformoin and piperidine. The structure of the nitrogenous reductone derived from hydroxydiacetyl that was found by *Hodge* was proved by its synthesis from diacetyl bromide or D-erythrose and an amine.

L. Mester, Paris (France), spoke about the structure of sugar osazones. Long-range spin-spin coupling between the proton on C-1 and the non-chelated NH proton was detected in the nuclear magnetic resonance spectra of sugar osazones using the double resonance technique. The weak resolution ($J \approx 1$ cps) of the signal for the proton on C-1 disappears on deuteration of the non-chelated NH proton, whose position is identical with that of the methyl group in 1-methyl-1-phenyl-2-phenylosazones. These results indicate a quasi-aromatic chelate structure for sugar osazones such as is expressed by Fieser's chelate formula *(2)*.



(2)

The course of osazone formation was studied by *F. Micheel* and *I. Dijong*, Münster (Germany), starting from 4,6-*O*-benzylidene-D-glucose. They found that the reaction is initiated by partial decomposition of phenylhydrazine by disproportionation into aniline, ammonia, benzene, and nitrogen, transamination of the 4,6-*O*-benzylidene-D-glucose phenylhydrazone initially formed to give phenylamino-4,6-*O*-benzylidene-D-glucoside, and Amadori rearrangement of the latter compound. The phenylhydrazone of the product of the Amadori rearrangement reacts further with phenylhydrazine in acidic solution to give the osazone. The dehydrogenation occurring during osazone formation was studied using [^{14}C]-phenylhydrazine. This dehydrogenation is not part of an intramolecular redox reaction; instead, the phenylhydrazone formed from the product of the Amadori rearrangement is dehydrogenated by free phenylhydrazine.

J. O. Deferrari, Buenos Aires (Argentina), reported on the reaction of methanolic ammonia with acylated disaccharides. Ammonolysis of octa-*O*-benzoylcellobiose produced mono-*O*-benzoylcellobiose together with a mixture of cellobiose, *N*-benzoylcellobioside, and an *N,N'*-dibenzoyl derivative. Following the analogous treatment of hepta-*O*-benzoylmaltose, however, only partially debenzoylated derivatives could be isolated and no nitrogenous products were detected.

D. Horton, *M. L. Wolfrom* et al., Columbus, Ohio (U.S.A.), examined the properties of 1-thio derivatives of aldoses and amino sugars. Condensation of 2-deoxy-2-amino-acetohalogeno sugars with thiourea leads to 2-[2-deoxy-2-amino-β-D-glucosido]-2-isothiourea derivatives, which undergo an intramolecular rearrangement in neutral solution to 1-thio-2-deoxy-2-guanidinoaldose derivatives. Thio sugars of this kind can be used to produce acetohalogeno sugars or non-acetylated halogeno sugars under mild conditions. They may also be of importance as radiation-protecting substances.

P. F. Lloyd and *S. Peat*, Bangor (Wales), carried out a number of syntheses starting from 2-deoxy-2-[2,4-dinitrophenylamino]-D-glucose. The corresponding acetobromo derivative *(3)* reacts with alcohols to give either α- or β-glycosides, depending on the conditions used. These reactions were used to synthesize disaccharides and to elucidate the structures of aminopolysaccharides. For example, 6-[2-deoxy-2-amino-α(β)-D-glucosido]galactose can be prepared from *(3)* and 1,2:3,4-di-*O*-isopropylidene-D-galactose with pyridine as catalyst.

I. Jezo, Bratislava (Czechoslovakia), studied the reaction of sucrose with aqueous solutions of ammonia, methylamine, ethylenediamine, and ethanolamine at elevated temperatures. The sucrose is first hydrolysed, and then derivatives of D-glucosamine, D-fructosamine, *N*-glucosides, and *N*-fructosides are formed. Intermolecular or intramolecular condensation of these amino sugars and subsequent dehydrogenations or isomerizations then lead to the formation of pyrazine and imidazole derivatives.

H. Weidmann, Graz (Austria), prepared ulononitriles by dehydration of uronamides or ω-aldoaldoside oximes with dibromotriphenylphosphorane, benzenesulfonyl chloride, sodium borohydride, or trifluoroacetic anhydride.

J. Montreuil et al., Lille (France), investigated the structure of ovomucoid. Mild hydrolysis led to numerous sugars. Enzymatic degradation of ovomucoid afforded three glycoproteins; one of these contained only aspartic acid, the second aspartic acid and threonine in a 1:1 ratio, and the third aspartic acid and cystine in a 1:1 ratio. There is probably a general structural scheme for the carbohydrate moiety of these three glycoproteins.

E. D. Kaverzneva and *V. H. Lupac*, Moscow (U.S.S.R.), proved that, in contrast to the arrangement in ovalbumin, there are various types of bonding between the sugar and peptide chains in ovomucoid. The carbohydrate fraction in ovomucoid (21 %) is much higher than that in ovalbumin (3.15 %). Treatment of ovomucoid with hydroxylamine did not yield any free polysaccharides, but only high molecular-weight glycopeptides and low molecular-weight peptides. Glycopeptides were also obtained by the action of anhydrous hydrazine, but again, no free polysaccharides were released. It appears from these results that there are no ester linkages between the protein and carbohydrate.

F. Cramer et al., Göttingen (Germany), studied the rates of hydrolysis of protecting groups for hydroxy groups and phosphoric acid derivatives, since selective protecting groups which can be removed under mild conditions are required for the stepwise synthesis of oligonucleotides. Substituted benzaldehydes are suitable for protecting 2'- and 3'-hydroxy groups, while t-butyl and benzhydryl groups are acid-resistant protecting groups for phosphoric acid derivatives.

K. Onodera, Kyoto (Japan), synthesized numerous purine and pyrimidine nucleosides from 1-trichloroacetyl sugars. 1-*O*-trichloroacetyl-2,3,4,6-tetra-*O*-acetyl-α-D-glucose reacts with purine bases in the presence of $ZnCl_2$ to give *trans*-nucleosides (C-1'-C-2' *trans*). A mixture of the *cis*- and *trans*-derivatives is formed with 6-benzamidopurine and acidic catalysts. *trans*-Nucleosides are also obtained with pyrimidines from the 1-*O*-trichloroacetyl derivatives of D-glucose and D-xylose in the presence of acidic catalysts (*p*-toluenesulfonic acid).

L. Vargha and *J. Kuszmann*, Budapest (Hungary), condensed 6-benzamido-9-chloromercurypurine with 1,2-dideoxy-1,2-dichloro-3,5-di-*O*-acetyl-D-arabofuranose and obtained a mixture of α- and β-9-[2'-deoxy-2'-chloro-3',5'-di-*O*-acetyl-D-arabofuranosido]benzoyladenine, which can be separated into its components after Zemplen hydrolysis. Catalytic hydrogenation then gives either α- or β-[2'-deoxy-D-ribofuranosido]adenine. Both anomers react with sodium methoxide to give the α- and β-2',3'-epoxy-D-ribose compounds, whose specific rotations are not in accordance with Hudson's rule.

J. E. Courtois et al., Paris (France), studied trehalose and the properties of trehalases. In order to obtain information about the behavior of these enzymes, chemical or biochemical methods were used to prepare derivatives of α,α-trehalose in which the symmetry of the molecule relative to the glycosidic bond is disturbed. The purification of 6-*O*-monotosyl- and 6-*O*-monomesyl-trehalose required extensive chromatographic separations. α-D-Galactosido-6-trehalose was made by biosynthesis.

J. Kiss, Basel (Switzerland), reported on the chemical synthesis of thiamine-activated aldehydes, hydroxyaldehydes, and α-ketocarboxylic acids. These carbonyl compounds form a covalent bond with C-2 of the thiazole ring in thiamine. The products act as activated derivatives and are therefore particularly suitable for use in biochemical reactions. 2-Hydroxymethyl-4-methyl-5-[β-hydroxyethyl]thiazole was converted by oxidation into the 2-formyl compound ("activated formaldehyde"), which produces derivatives of methanol with Grignard reagents. These methanol derivatives can be converted into homologues of activated formaldehyde.

Z. Nikuni, Sakai (Japan), reported on some unusual illnesses. In 1960, a material, which gave with iodine the blue coloration typical of starch, was extracted for the first time from the granulates of wounds in a female patient. Systematic clinical, pathological, microbiological, enzymatic, and chemical investigations revealed that the material isolated was in fact starch which could be separated into amylose and amylopectin fractions. There are only slight differences in the absorption maxima of the iodine complexes formed from this human starch and potato starch. The infrared spectrum of human starch is identical with that of rice starch. No differences were observed in the degradation products obtained with α-amylase from human and potato starch. At approximately the same time, a "cotton-producing disease" was discovered, during which cellulose is formed in wound granulates in humans. The cellulose fibres are 1–3 cm long. Following acetylation and hydrolysis, octa-*O*-acetylcellobiose was isolated in 36–40 % yield.

M. L. Wolfrom, Columbus, Ohio (U.S.A.), reviewed the elucidation of the structure of heparin. New investigations were conducted in which the polysaccharide was partially desulfurized, reduced with diborane, and partially hydrolysed with acid. Two disaccharides were isolated: α-D-glucosido-1,4-α-D-glucosamine and α-D-glucosaminido-1,4-α-D-glucose. Every tetrasaccharide unit in heparin (made up of two amino sugar and two uronic acid residues) contains five sulfuric acid groups, two of which are attached to the nitrogens. Two sulfato groups are probably attached at C-6 of the two amino sugars and one sulfato group is at C-2 of one of the two uronic acid residues.

A. Klemer, Münster (Germany), reported on chemical studies of chondroitinsulfuric acid-protein complexes in connection with investigations of arteriosclerosis and ageing processes. No difference was observed in the nature of chromatographically pure chondroitinsulfuric acid-protein complexes isolated from the water-soluble fraction (which amounts to one-third of the fresh weight) of normal and arteriosclerotic human aortas. There was only a difference in yield, which was about twice as high from diseased aorta (0.25 %) as from healthy aorta (0.13 %). Extraction of the water-insoluble residue with an aqueous solution of calcium chloride gave another fraction containing mucopolysaccharides. The chondroitinsulfuric acid A-protein complexes isolated from this fraction (0.4 % from normal and 0.1 % from diseased aorta) had no differences in chemical composition or molecular weight.

In order to explain rearrangement reactions of unsaturated carbohydrate derivatives, *H. Isbell*, Washington, D.C. (U.S.A.), in 1943 proposed an electron transfer from positions of high to positions of low electron density in the molecule. This electron transfer would be coupled with the addition and liberation of ions. The same hypothesis may serve to interpret the rearrangement of phenylhydrazones of inositol derivatives into olefinic and aromatic phenylazo compounds.

A. B. Foster et al., Birmingham (England), determined the absolute configurations of 2-phenyl-1,3-dioxane and -1,3-dioxolane derivatives using NMR spectroscopy. The bonding shift δ of the signal of the benzyl proton is 4.98–5.25 ppm for 2-phenyl-1,3-dioxane derivatives with equatorial substituents in the 4-, 5-, 4,5- and 4,6-positions. 2-Phenyl-1,3-dioxolane (with *cis*-orientation of the benzyl proton and the hydrogen atoms at C-4 and C-5) exhibits only one signal at δ = 5.34. Products substituted at C-4, on the other hand, give signals at δ = 5.33–5.38 and 5.48–5.54 ppm (for *cis*- and *trans*-orientation of the benzyl proton and the substituents at C-4). These data were used to determine the absolute configurations of diastereoisomers of benzylidene derivatives of carbohydrates.

C. T. Greenwood et al., Edinburgh (Scotland), investigated the influence of ions on aqueous solutions of starch. The molecular size of the starch components can be estimated by viscosity measurements in alkaline solution. However, the viscosity number of potato amylose depends largely on the hydroxyl ion concentration, because this polysaccharide behaves as a polyelectrolyte. Additions of KCl eliminate alterations in the viscosity number. Light-scattering and sedimentation measurements showed that these changes in the viscosity number are due to alterations in the conformation of the molecules.

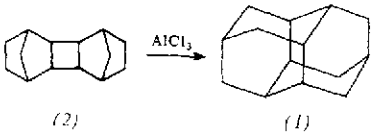
H. Scharmann, Hamburg (Germany), described the mass spectra of numerous derivatives of mono- and disaccharides. Permethylated sugars are best suited for mass spectroscopy, and the combination of this technique with gas chromatography permits investigation of minute amounts of material. Comparison of the mass numbers of the fragmentation products obtained from unlabelled and specifically deuterated monosaccharides proved an aid to the derivation of the fragmentation mechanism involved. The results can largely be applied to disaccharides as well. [VB 850/189 IE]

German version: Angew. Chem. 77, 135 (1965)

The Synthesis of Pentacyclo[7.3.1.1^{4,12}.0^{2,7}.0^{6,11}]tetradecane

P. v. R. Schleyer, Princeton, N.J. (U.S.A.) [1]

The preparation of "congressane" *(1)* (pentacyclo-[7.3.1.1^{4,12}.0^{2,7}0^{6,11}]tetradecane), a relative of adamantane also possessing the diamond structure, was reported. The name "congressane" comes from the use of *(1)* as the official Emblem of the XIXth International Congress of Pure and Applied Chemistry, held in London in July, 1963 [2]. The method used to make the compound was analogous to the isomerization of tetrahydrodicyclopentadiene to adamantane by the action of strong Lewis acid catalysts [3]. Norbornene was converted photochemically in the presence of photosensitizing agents to stereoisomeric dimers of structure *(2)*. When treated with $AlCl_3$ some isomers of *(2)* gave large quantities of tar, but others gave a cleaner reaction. From these reactions small amounts of a high melting substance were isolated [4].



(2) *(1)*

[1] At present (1964–1965) Fulbright Research Fellow, Institut für Organische Chemie der Universität München (Germany).

[2] See *V. Prelog*, Pure appl. Chem. 6, 545 (1963).

[3] Review: *R. C. Fort, Jr.* and *P. v. R. Schleyer*, Chem. Reviews 64, 277 (1964).

[4] Coworkers: *C. Cupas*, Princeton University; *D. J. Trecker*, Union Carbide Corporation, West Virginia (U.S.A.).

The properties of this new material, very similar to those of adamantane [3], were consistent with those expected of congressane *(I)*: melting point 236–237 °C; very simple infrared spectrum with only 6 bands in the 5000–700 cm^{-1} region; a relatively sharp (w_h *ca.* 3 cps) single peak in the nuclear magnetic resonance spectrum (at 8.32 τ); and a mass spectrum indicating a very stable ring skeleton, since the parent peak at m/e = 188 not only was the base peak, but its intensity was more than three times greater than that of any other ion. The congressane structure *(I)* was proven for the new material by X-ray analysis [5].

[GDCh-Ortsverband Aachen (Germany), December 4th, 1964] [VB 883/185 IE]
German version: Angew. Chem. 77, 180 (1965)

[5] Dr. *I. Karle* and Dr. *J. Karle*, U.S. Naval Research Laboratory, Washington, D.C. (U.S.A.), personal communication.

The Effect of Magnetic Susceptibility on Proton Resonance; Magnetic Measurements on New Organic Radicals

H. J. Friedrich, Würzburg (Germany)

Owing to magnetic susceptibility, proton resonance signals measured in cylindrical cells are shifted by $(\Delta H/H)_S = c \cdot \Delta\chi_V$. The susceptibility shift factor c was estimated from the proton resonance shifts of tetramethylsilane in solvents of varying volume susceptibility and from the proton resonance shifts of various standard substances produced by Goldschmidt's radical $(H_5C_6)_2N-\dot{N}-C_6H_2(NO_2)_3$ in various solvents [1]; the value found was 2.09 ± 0.1. It agrees with that derived from theory, *viz.* c = 2 π/3. Interfering effects on the susceptibility shift may be exerted by magnetic anisotropy and by electrical polarization of the medium and when the unpaired electron has a spin density on the resonating proton.

This method can be used to estimate the magnetic susceptibility of organic free radicals [2]. The radical cations prepared by *Hünig* [3] were examined in this way. The susceptibilities measured are indicative of monomeric free radicals with one unpaired electron [4]. Of the verdazyl radicals prepared by *Kuhn* and *Trischmann* [5], 1,3,5-triphenylverdazyl and 1,3,5,6-tetraphenylverdazyl gave susceptibility values for monomeric radicals with one unpaired electron in the concentration range from 3 to 12 mg/l.

[Colloquium, Marburg/Lahn (Germany), July 30th, 1964 and Heidelberg (Germany), October 19th, 1964] [VB 879/180 IE]
German version: Angew. Chem. 77, 181 (1965)

[1] *H. J. Friedrich*, Z. Naturforsch. *19b*, 663 (1964).

[2] *H. J. Friedrich*, Z. Naturforsch. *19b*, 279 (1964).

[3] *S. Hünig* et al., Liebigs Ann. Chem. *676*, 36 (1964); Tetrahedron Letters *1964*, 181; Angew. Chem. *76*, 818 (1964); Angew. Chem. internat. Edit. *3*, 701 (1964).

[4] *H. J. Friedrich*, Angew. Chem. *76*, 496 (1964); Angew. Chem. internat. Edit. *3*, 440 (1964).

[5] *R. Kuhn* and *H. Trischmann*, Mh. Chem. *95*, 457 (1964).

The Synthesis of Molecularly Uniform Polymers

G. V. Schulz, Mainz (Germany)

The synthesis of uniform polymers, *i.e.* of macromolecules with all chains of equal length, by stepwise addition or condensation has so far led into molecular-weight ranges of only a few thousand. To get into the range $M = 10^5$–10^6, chain reactions can be used under the following conditions: chain initiation and termination must be regulated in such a way that the *duration of growth* is exactly the same for all molecules; in addition, concentration and temperature must be controlled so that the *rate of growth* is equal for all molecules. However, even under ideal conditions, a narrow distribution in the molecular weights is unavoidable (Poisson distribution). Two series of experiments were described which aimed at attaining such a Poisson process; one involved a free-radical, the other an anionic polymerization.

According to *Bianchi*, *Price*, and *Zimm*, a free-radical Poisson process exists in emulsion polymerization when the chain-initiating and chain-terminating radicals are produced by intermittent irradiation. Analysis using a Baker-Williams column of the distribution of molecular weights during polymerization of styrene (*J. Romatowski* [1]) showed, however, that this method does not succeed. Reasons are: a low concentration of radicals leads to a spectrum of polymers, whose preferential degrees of polymerization correspond to whole multiples of the exposure time (*i.e.* some of the growing free-radical chains initiated during the first exposure are not terminated during the second exposure, but only during a third, fourth, or later exposure); a high concentration of radicals, on the other hand, produces polymers of random chain-length in the aqueous phase.

Anionic polymerization can give rise to a Poisson process if the initiator (sodium + naphthalene) and the monomer (styrene) are brought together very rapidly by means of a jet mixer, if the mixture is driven through a tube with turbulent currents at a definite rate, and if the polymerization is quenched at the end of the tube by injection of the polymerization-terminating reagent through a second jet. Control of the flow conditions in the tube (*G. Löhr* [2]) and limitation of the polymerization to a one-way mechanism (*R. V. Figini* and *H. Hostalka* [3]) by suppression of dissociation [by addition of $KB(C_6H_5)_4$] so that only ion pairs react, make it possible to come very close to a Poisson distribution.

The biosynthesis of uniform macromolecules apparently does not proceed via Poisson processes but instead by mechanisms controlled by matrices, as has been shown for cellulose (*M. Marx-Figini* [4]).

[Lecture in Ludwigshafen (Germany), November 4th, 1964] [VB 880/184 IE]
German version: Angew. Chem. 77, 181 (1965)

[1] *G. V. Schulz* and *J. Romatowski*, Makromolekulare Chem., in the press.

[2] *G. Löhr* and *G. V. Schulz*, Makromolekulare Chem. *77*, 240 (1964).

[3] *H. Hostalka*, *R. V. Figini*, and *G. V. Schulz*, Makromolekulare Chem. *71*, 198 (1964); *R. V. Figini*, ibid. *71*, 193 (1964); *R. V. Figini*, *G. Löhr*, and *G. V. Schulz*, Polymer Letters, in the press.

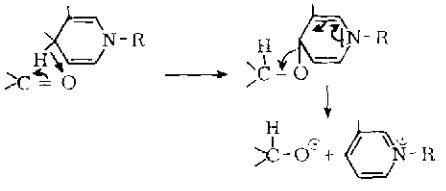
[4] *M. Marx-Figini*, Makromolekulare Chem. *68*, 227 (1963); *80*, 235 (1964).

SELECTED ABSTRACTS

The production of pure xenon hexafluoride was achieved by *I. Sheft*, *T. M. Spittler*, and *F. H. Martin* via its addition compound with sodium fluoride. XeF_6 produced by fluorination of xenon with excess fluorine always contains some $XeOF_4$, XeF_4, and XeF_2. In order to purify the hexafluoride, 10 g of the crude product is condensed in a nickel vessel containing 10g of NaF, heated for 2h at 50°C, and left standing overnight at room temperature. Fractionative evaporation is then carried out: the $XeOF_4$ is evolved first at room temperature followed by mainly the XeF_2 and XeF_4 at 50–55 °C. Extremely pure XeF_6 is then obtained as the third fraction at 125 °C; the yield is 8 g or 80 %. The XeF_6 is white but turns yellow at 43–43.5 °C and melts at 47.7 ± 0.2 °C to form a yellow liquid, which recrystallizes to a white solid on recooling. NaF dissolves in excess XeF_6 to form a yellow solution; when the latter is concentrated at 50 °C *in vacuo*, a pale yellow residue of the XeF_6/NaF adduct is left. / Science (Washington) *145*, 701 (1964) / –Ko. [Rd 162/349 IE]

A solution of an intermetallic compound, Li_3Bi, in a molten salt was observed for the first time by *M. S. Foster, C. E. Crouthamel, D. M. Gruen*, and *R. L. McBeth*. An Li–Bi alloy containing 70 atom-% Li forms clear, deep red solutions in an LiCl–LiF eutectic at 100–600 °C under helium. The Li/Bi ratio in the dissolved compound is 3:1. The spectrum of the red solution at 525 °C has a characteristic intense absorption band whose long-wavelength edge lies at 16300 cm^{-1} (2 eV). / J. physic. Chem. *68*, 980 (1964) / –Ma.
[Rd 72/356 IE]

An NADH model which reduces carbonyl groups almost quantitatively and non-enzymatically has been described by *D. C. Dittmer* and *R. A. Fouty*. These authors stirred 2 equivalents of hexachloroacetone and 1 equivalent of 1-benzyl-1,4-dihydronicotinamide in formamide at room temperature for 2 h and obtained hexachloroisopropanol in 97% yield. Addition of radical scavengers had no effect on the reaction.



A mechanism is proposed in which a hydrogen atom from C-4 is transferred to the carbonyl carbon directly in a charge-transfer complex formed from the carbonyl compound and the dihydropyridine derivative. / J. Amer. chem. Soc. *86*, 91 (1964) / –Sch. [Rd 66/354 IE]

New trisilyl compounds have been prepared by *E. Amberger* and *H. D. Boeters*. They isolated $HC(SiH_3)_3$, which is formed according to Equation (a) with $LiAlH_4$ as catalyst, $P(SiH_3)_3$ and $As(SiH_3)_3$, which are formed below 100 °C in dimethyl ether according to Equation (b), and $Sb(SiH_3)_3$, which is produced according to Equation (c) by reaction in dimethyl ether.

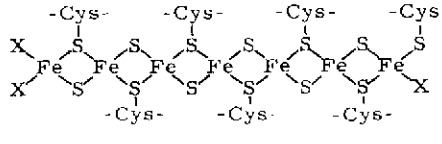
$$9\,LiH + HC(SiCl_3)_3 \rightarrow HC(SiH_3)_3 + 9\,LiCl \quad (a)$$

$$3\,KElH_2 + 3\,SiH_3Br \rightarrow El(SiH_3)_3 + 2\,ElH_3 + 3\,KBr \quad (b)$$
(El = P or As)

$$Li_3Sb + 3\,SiH_3Br \rightarrow Sb(SiH_3)_3 + 3\,LiBr \quad (c)$$

No mono- or disilyl compounds are formed. The trisilyl compounds are colorless liquids which ignite spontaneously on exposure to air; they are decomposed by 33% sodium hydroxide solution to give $HC(SiO_2Na)_3$ and hydrogen plus PH_3, AsH_3, or Sb and by-products. $Sb(SiH_3)_3$ decomposes on prolonged standing. / Chem. Ber. *97*, 1999 (1964) / –Gn.
[Rd 164/351 IE]

A model for the active center of ferredoxin has been proposed by *D. C. Blomstrom, E. Knight, W. D. Phillips*, and *J. F. Weiher*. The seven iron atoms in the protein having a molecular weight of 6000 are responsible for electron transfer during photosynthesis, and occur in two structurally different environments. Comparisons with the known structures of *Roussin*'s red salt and of polymeric $KFeS_2$ led to the assumption of structure *(1)* for the active center.



(1)

Electron transport along this iron-sulfur chain could proceed by a mechanism similar to that proposed by *D. W. Urry* and *H. Eyring* for the imidazole-pump model of the respiratory chain. / Proc. nat. Acad. Sci. U.S.A. *51*, 1085 (1964) / –Sch.
[Rd 137/324 IE]

Optically pure L-homocystine has been prepared in 92% yield by *D. B. Hope* and *J. F. Humphries*. Charges of up to 30 g of L-methionine can be rearranged with sodium in liquid ammonia:

$$H_3CSCH_2CH(NH_2)COOH \rightarrow HSCH_2CH_2CH(NH_2)COOH \quad (1)$$

The base-catalysed racemization which occurs in other processes is completely suppressed here by addition of ammonium chloride. The L-homocysteine *(1)* obtained in this way is oxidized with $K_3Fe(CN)_6$ to L-homocystine, $[\alpha]_D^{20} = -77.0°$ (c = 1 in 1 N HCl). / J. chem. Soc. (London) *1964*, 869 / –Rc.
[Rd 134/321 IE]

The addition of formamide onto terminal olefins to give carboxamides *(1)* was found by *D. Elad* and *J. Rokach* to proceed particularly well by photochemical initiation in acetone according to Equation (a); thus, up to 90% of 1:1 adducts were obtained from $HCONH_2$ and olefin in t-butanol/acetone mixtures at 20–30 °C within a few hours with $\lambda > 300$ mμ; steps (b) and (c) are chain reactions.

$$HCONH_2 \xrightarrow{h\nu} \cdot CONH_2 \quad (a)$$

$$RCH{=}CH_2 + \cdot CONH_2 \rightarrow R\dot{C}H{-}CH_2{-}CONH_2 \quad (b)$$

$$R\dot{C}H{-}CH_2{-}CONH_2 + HCONH_2 \rightarrow RCH_2{-}CH_2{-}CONH_2 + \cdot CONH_2 \quad (c)$$
(1)

$$R\dot{C}H{-}CH_2{-}CONH_2 + RCH{=}CH_2 \rightarrow R\dot{C}H{-}CH_2{-}RCH{-}CH_2{-}CONH_2 \quad (d)$$

$$R\dot{C}H{-}CH_2{-}RCH{-}CH_2{-}CONH_2 + HCONH_2 \rightarrow RCH_2{-}CH_2{-}RCH{-}CH_2{-}CONH_2 + \cdot CONH_2 \quad (e)$$

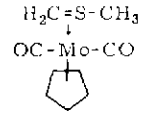
e.g. with $R = H_3C{-}(CH_2)_n{-}$, where n = 3–8, or with $R = H_3COOC{-}(CH_2)_n{-}$ or $H_2N{-}CO{-}(CH_2)_n{-}$, where n = 2–8.

Reactions (d) and (e) yield a few percent of 2:1 telomer. This amidation of olefins can be used to produce carboxylic acids and amines from cheap starting materials. The amides *(1)* crystallize well and are easy to purify. / J. org. Chemistry *29*, 1855 (1964) / –Jg. [Rd 117/304 IE]

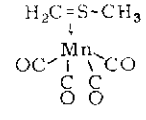
Di- and tripeptides from amino esters and hydroxamic acid dervatives of *N*-carbobenzoxyamino acids were obtained by *E. Hoffmann* and *I. Faiferman*. First *N*-Cbo-amino esters are converted into their hydroxamic acid derivatives with hydroxylamine in 70% yields. On boiling these derivatives with amino esters in dioxane or dioxane/ethanol, hydroxylamine is eliminated affording peptide esters in 30–80% yields. The peptide esters can in turn be activated with hydroxylamine and extended further. Compounds prepared include ethyl *N*-benzoyl- and *N*-Cbo-diglycylglycinate, and di- and tripeptide esters from glycine and alanine. / J. org. Chemistry *29*, 748 (1964) / –Rc. [Rd 93/363 IE]

Lipotropin, a new hypophyseal hormone, was discovered by accident in sheep pituitary by *Y. Birk* and *C. H. Li* while trying to work out a better method for isolating ACTH. The new hormone has a molecular weight of 6600 and consists of a single peptide chain containing 59 amino acids, with glutamic acid at the *N*-terminal and lysine at the *C*-terminal end. The new hormone appears to induce degradation of solid depot fat and thus to mobilize it for energy production. It was therefore termed lipotropic hormone (LPH) or lipotropin. The authors also succeded in detecting this biologically active peptide in the blood stream. / J. biol. Chemistry *239*, 1053 (1964) / –Sch. [Rd 67/366 IE]

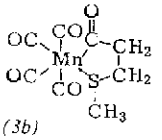
The production of carbonyls of transition metals which are stabilized by π-bonds between sulfur and the metal is described by *R. B. King* and *M. B. Bisnette*. Carbonyl anions and chloroalkyl methyl sulfides lead to the carbonyls *(1a)* to *(4a)*, which lose a carbonyl group on heating at 70 °C or on irradiation with ultraviolet light. On the basis of NMR and infrared spectra, structures were proposed for the carbonyls *(1b)* and *(2b)* in which the $H_3C-S=CH_2$ group and one alkyl group both contribute three electrons to the π-bond with the metal.



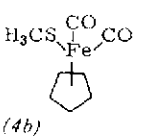
(1b)



(2b)



(3b)



(4b)

The very strong band in the infrared spectrum of the carbonyl *(3b)* at 1622 cm^{-1} is probably due to one carbonyl group being present as an acyl residue. Irradiation of *(4a)* leads to the carbonyl *(4b)*, which is the first example of a methylthio derivative of a transition metal in which the sulfur is coordinated with only one metal atom. / J. Amer. chem. Soc. *86*, 1267 (1964) / –Re. [Rd 92/362 IE]

***cis*-9-Octadecen-12-ynoic acid (crepenynic acid)** *(1)* is the first non-conjugated unsaturated acetylenic fatty acid of natural origin and was found by *K. L. Mikolajczak, C. R. Smith, M. O. Bagby*, and *I. A. Wolff* as 60 % of the seed oil of *Crepis foetida* L.

(1) $H_3C-(CH_2)_4-C\equiv C-CH_2-CH=CH-(CH_2)_7-COOH$

Hydrogenation of the methyl ester over platinum oxide yielded methyl stearate and over Lindlar catalyst afforded 71.4 % methyl linoleate plus 11.1 % unchanged starting material, 3.1 % conjugated triene, and 14.4 % low molecular-weight fragments. Epoxidation of the free acid with peroxyacetic acid produces an 85.5 % yield of the epoxyacetylenic acid, m.p. 37.5–38 °C, which on hydrolysis yielded *threo*-9,10-dihydroxyoctadec-12-ynoic acid, m.p. 72–75.5 °C. Hydrogenation of the latter over platinum oxide afforded *threo*-9,10-dihydroxystearic acid, m.p. 92–93 °C. Crepenynic esters undergo autoxidation extremely readily, even on storage at –18 °C. / J. org. Chemistry *29*, 318 (1964) / –W. [Rd 78/371 IE]

Biradical intermediates were detected by *L. K. Montgomery, K. Schueller*, and *P. D. Bartlett* during the cycloaddition of 1,1-dichloro-2,2-difluoroethylene *(1)* onto the stereoisomers of 2,4-hexadiene. When conditions were used (16.3 h at 80 or 100 °C) under which neither 2,4-hexadiene nor its adducts with *(1)* underwent stereoisomerization, the *cis,cis*-diene yielded two adducts, the *trans,trans*-diene yielded two adducts, and the *cis,trans*-diene afforded a mixture of all four adducts, whose structures were elucidated. During the addition partial isomerization of an intermediate occurs, but the ratio 82 % *trans*-:18 % *cis*-form of the cyclobutane derivative finally formed is never completely attained. It was calculated from the composition of the reaction mixture and from kinetic data that the internal rotation in the intermediate from *cis*- to the *trans*-form proceeds about ten times faster than the cyclization, that the half-life of the bifunctional intermediate is about 10^{-10} sec, and that the activation energy is very low. These results can be explained only by the occurrence of a biradical intermediate. / J. Amer. chem. Soc. *86*, 622 (1964) / –W. [Rd 79/372 IE]

The cycloaddition of 1,1-dichloro-2,2-difluoroethylene onto dienes was investigated by *P. D. Bartlett, L. K. Montgomery*, and *B. Seidel*. Butadiene and *cis*- and *trans*-piperylene react with an excess of 1,1-dichloro-2,2-difluoroethylene *(1)* at 80 °C in a sealed tube in the presence of a polymerization inhibitor such as hydroquinone to give exclusively 1,2-adducts. 1,2- and 3,4-cycloadducts were obtained in a ratio of 5.4:1 from isoprene, and in a ratio of 4:1 form chloroprene. Cyclopentadiene reacts with a fourfold excess of *(1)* to give the 1,4-adduct 2,2-dichloro-3,3-difluorobicyclo[2,2,1]-hept-5-ene in 44 % yield in addition to 9 % of the 1,2-adduct 6,6-difluor-7,7-dichlorobicyclo[3,2,0]hept-2-ene and 47 % *endo*-dicyclopentadiene. The butadiene, isoprene, and chloroprene adducts were degraded by mild oxidation to 2,2-dichloro-3,3-difluorocyclobutane-1-carboxylic acid, which is transformed readily by acids into 2-chloro-3,3-difluoro-1-cyclobutene-1-carboxylic acid, and by alkali into 2-chloro-3,3-difluoro-1-cyclobutene. NMR and infrared spectra prove that the chlorine atoms lie adjacent to the unsaturated side-chain; this confirms the theory of a biradical intermediate in the cycloaddition. / J. Amer. chem. Soc. *86*, 616 (1964) / –W. [Rd 80/373 IE]

Complexes of trivalent silver can be produced from AgO according to a report by *G. L. Cohen*. A mixture of KOH, KIO_3, and AgO is boiled in water and filtered. On addition of 40 g of NaOH, $Na_5H_2Ag^{III}(IO_6)_2 \cdot 16\,H_2O$ separates out as a voluminous orange precipitate.

$$6\,AgO + 2\,H_2O + 8\,OH^{\ominus} + 2\,IO_3^{\ominus} \rightarrow 5\,Ag(OH)_2^{\ominus} + Ag(IO_6)_2^{5\ominus} + 2\,H^{\oplus}$$

The Ag(III) apparently originates from the AgO, which according to recent findings is to be regarded as silver(I) silver(III) oxide. It is assumed that the first step in the reaction is the oxidation of iodate to periodate by Ag(III) and that this is followed by combination of further Ag(III) with the periodate formed to give the stable complex ion $Ag(IO_6)_2^{7\ominus}$. / Chem. Engng. News *42*, No. 16, p. 52 (1964) / –Ko. [Rd 84/369 IE]

Reactions of perfluoroallene which proceed via ionic intermediates have been investigated by *R. E. Banks, R. N. Haszeldine*, and *D. R. Taylor*. In contrast to perfluoro-olefins, perfluoroallene *(1)* combines smoothly with hydrogen halides in the absence of light, catalysts, and solvents to form quantitative yields of 1:1 adducts.

$$\underset{(1)}{F_2C=C=CF_2} + HX \rightarrow F_2XC-CH=CF_2 \quad X = F\ (2),\ Cl,\ or\ Br$$

When *(1)* is kept in an autoclave at –72 °C with excess HF for 12 h and subsequently heated to 20 °C, 2*H*-pentafluoropentene *(2)* is formed in 99 % yield; HCl at 20 °C gives 99 % 3-chloro-1,1,3,3-tetrafluoropropene, and HBr at –45 °C gives 89 % 3-bromo-1,1,3,3-tetrafluoropropene. Allene reacts rapidly with HCl at –78 °C in the presence of $BiCl_3$ to form a mixture of $H_3C-CCl=CH_2$ and $H_3C-CCl_2-CH_3$ in quantitative yield. When treated with excess chlorine in the dark at –72 °C for 12 h and then warmed up to 20 °C and left for 7 days, *(1)* gives 99 % $F_2ClC-CCl=CF_2$; in sunlight at 25 °C for 6 h, only 5 % of this compound is formed alongside 92 % $F_2ClC-CCl_2-CF_2Cl$. Like perfluoro-olefins, *(1)* also undergoes nucleophilic reactions, *e.g.* with moist CsF at 100 °C to form *(2)*:

$$F^{\ominus} + F_2C=C=CF_2 \rightleftharpoons F_3C-C-CF_2\,H_2O \xrightarrow{H_2O} F_3C-CH=CF_2 \quad (2)$$

$H_3C-O-CF_2-CH=CF_2$ is formed with methanol at –24 to 20 °C. It therefore follows that in reactions which proceed via ionic intermediates, *(1)* is present in the polarized form $F_2\overset{\delta+}{C}=\overset{\delta-}{C}=CF_2$. / Proc. chem. Soc. (London) *1964*, 121 / –Ma. [Rd 69/368 IE]

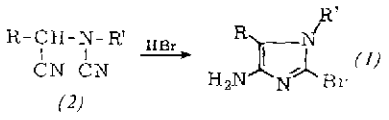
Spectra in the far infrared (down to 200 μ) for 12 organic liquids have been taken by *H. R. Wyss, R. D. Werder,* and *H. H. Günthard.* The compounds studied were benzene, chlorobenzene, bromobenzene, toluene, carbon tetrachloride, chloroform, methylene chloride, carbon disulfide, Nujol, n-hexane, cyclohexane, and pyridine. Band assignments were made for the spectra of the first eight liquids; the absorption curves indicate that all of these substances are suitable as solvents for spectroscopic studies in the far infrared. Suitable materials for sample cell windows include CsI (down to 170 cm^{-1}) and teflon or quartz for longer wavelengths. Although polyethylene is also transparent in this region, it generally swells in organic solvents. / Spectrochim. Acta *20*, 573 (1964) / –Hz. [Rd 59/365 IE]

An apparent prolongation of the half-life of radioactive nuclides has been demonstrated by *S. L. Ruby, R. R. Ferber, R. V. Babcock, L. M. Epstein,* and *Kuan H. Sun* using the Mössbauer effect. A radiation source with ^{119}Sn or ^{57}Fe (in their excited states) as emitter was enclosed in a jacket containing the same nuclides in their ground states. The γ-quanta emitted from the source are partially absorbed in the jacket (resonance absorption). The excited nuclei produced in the jacket in this way disintegrate with their characteristic half-lives leading to an overall prolongation of the half-life of the complete preparation by 2–3 %. The half-life of the excited nuclei originally present in the emitting source has, of course, remained unaltered. / Chem. Engng. News *42*, No. 25, p. 43 (1964) / –Ko. [Rd 85/370 IE]

The protein components of the tail T 2 bacteriophages were examined by *N. Sarkar, S. Sarkar,* and *L. M. Kozloff,* who succeeded in isolating the contractile protein from the sheath of the phage tail. The complete sheath has a molecular weight of 8×10^6 and consists almost exclusively of amino acids, comprising 144 subunits with molecular weights of about 55500 each. Each subunit contains a histidine residue to which ATP probably becomes attached to initiate contraction. The core of the tail is also a protein which was isolated. It has a molecular weight of 487000 and is in the form of a stiff hollow tube about 1000 Å long and 100 Å in diameter consisting of five intertwined peptide chains. The five SH groups of the core protein probably lie at the ends of the peptide chains and appear to be of importance for its attachment to the end-plate. The function of the core is not absolutely clear. It may be a prop which falls out on contraction of the sheath, but on the other hand, the hollow in its cable-like structure is just large enough to permit the DNA filament of the phage – which is 24 Å thick – to glide through. / Biochemistry *3*, 511, 517 (1964) / –Sch. [Rd 64/367 IE]

Crystalline polyvinylcyclobutane and polyvinylcycloheptane have been synthesized by *C. G. Overberger* and coworkers. Vinylcyclobutane was prepared from cyclobutanecarbonyl chloride in an overall yield of 13 % and purified by preparative gas chromatography. Polymerization with tri-isobutylaluminum / $TiCl_4$ (2:1) as catalyst for 7 days at 75 °C gave 24 % of a polymer of high crystallinity and with a softening point of 228 °C. Vinylcycloheptane, b.p. 160 °C, $n_D^{25} = 1.4589$, was synthesized for the first time from cycloheptyl bromide in 40 % yield. Its polymerization with tri-isobutylaluminum/$TiCl_4$ (3:2) as catalyst for 7 days at 72 °C led to 9.8 % of a highly crystalline polymer, m.p. 300 °C. / J. Polymer Sci. A *2*, 755 (1964) / –Re. [Rd 94/374 IE]

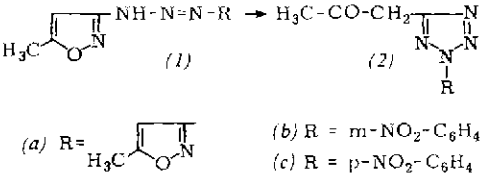
A new synthesis of imidazoles is described by *F. Johnson* and *W. A. Nasutavicus.* When treated with anhydrous HBr in inert solvents, dinitriles of general formula R'N(CN)CH(CN)R *(2)* undergo cyclization to form 2-bromo-4(5)-aminoimidazoles *(1)*. If R and R' are aryl residues, then the amino compounds can be isolated as the free bases; otherwise they



(2) *(1)*

are isolated as their *N*-acetyl derivatives. The dinitriles required for the synthesis, *i.e.* α-cyanoalkylcyanamides, can be prepared by the reaction of a monosubstituted cyanamide with an α-halogenoalkyl cyanide or an α-(*p*-toluenesulfonyl)-alkyl cyanide in anhydrous dimethylformamide in the presence of triethylamine. / J. org. Chemistry *29*, 153 (1964) / –Ma. [Rd 73/357 IE]

A novel conversion of 3-diazoaminoisoxazoles into tetrazoles is described by *H. Kano* and *E. Yamazaki.* 1,3-Bis-(5-methyl-3-isoxazolyl)triazene *(1a)*, which is obtained from 5-methyl-3-aminoisoxazole and $NaNO_2$ in 10 % HCl, undergoes an exothermic reaction on warming in alkaline solution to form

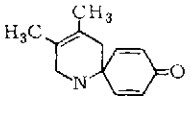


(1) *(2)*

(a) R = *(b)* R = m-NO_2-C_6H_4 *(c)* R = p-NO_2-C_6H_4

2-(5-methyl-3-isoxazolyl)-5-acetonyltetrazole *(2a)*, m.p. 147 to 149 °C, in 81 % yield. Analogously, *(1b)* gives *(2b)* in 94.5 % yield, and *(1c)* gives *(2c)* in 56 % yield. / Tetrahedron *20*, 461 (1964) / –Ma. [Rd 74/358 IE]

The action of light on the Diels-Alder system *p*-benzoquinone/2,3-dimethyl-1,3-butadiene was examined by *J. A. Barltrop* and *B. Hesp.* Irradiation of an oxygen free solution of benzoquinone in dimethylbutadiene at less than 0 °C with light of $\lambda > 300$ mμ or preferably of $\lambda > 400$ mμ and separation of the products by chromatography gave a fraction whose main component was a 1:1 adduct of the quinone and diene. This had a m.p. of 39–42 °C and on the basis of its NMR and infrared spectra was allocated the spiropyran structure *(1)*.



(1)

The yield was 33 %. This adduct is formed by excitation of the $n \rightarrow \pi^*$ carbonyl transition of the benzoquinone. / Proc. chem. Soc. (London) *1964*, 195 / –Ma. [Rd 75/359 IE]

BOOK REVIEWS

Ullmanns Encyklopädie der technischen Chemie (Ullmann's Encyclopaedia of Chemical Technology). 3rd Completely revised edition. Edited by *W. Foerst,* now edited by *Hertha Buchholz-Meisenheimer.* Vol 14: Pilzinfektionen bis Ruß (Fungal infections to soot). Verlag Urban & Schwarzenberg, München-Berlin 1963. xii + 810 pp., linen DM 128.– (about $ 32.25).

This new volume of Ullmann's encyclopaedia contains 48 articles arranged under alphabetical key-word headings. About 32 % of its content consists of the chemistry of high molecular-weight materials: polymers (203 pp.), polyesters (27 pp.), polyurethanes (26 pp.), polyamides (17 pp.), polyethers and polyacetals (16 pp.), press-moulding compositions (14 pp.), polycarbonates (4 pp.), and proteinoid plastics

(4 pp.). Other longer articles include: odoriferous substances (86 pp.), reproduction technology (33 pp.), proteins (33 pp.), reaction mechanisms (33 pp.), platinum and the platinum metals (29 pp.), polymethine dyestuffs (28 pp.), mercury (23 pp.), reduction and hydrogenation (19 pp.), soot (17 pp.), pyrotechnics (15 pp.), and rocket fuels (13 pp.). The remaining 176 pp. are filled by 29 shorter articles dealing mainly with topics from organic chemistry, *e.g.* pyridine and its derivatives, reactive dyes, pyrazolones, and purines and purine derivatives.

The authors of this volume comprise 78 experts, including eight collaborators from abroad (U.S.A., Great Britain, Italy, Switzerland, and Austria). Twenty-three contributers come from technical colleges, and the remainder are employeyd in the chemical industry. The reviewer observes with satisfaction that "Ullmann" is enjoying more and more interest and support from industrial foundations. Closer perusal of the staff of coauthors reveals that industry has frequently its acknowledged experts available. Thanks to their cooperation and the highly differentiated presentation of the text, the information offered is up-to-date and complete.

Nineteen authors have combined in the compilation of the long article on polymers. In the introduction (30 pp.), *H. Fikentscher* deals with the mechanism, technology, and peculiar features of polymerization, and thereby reveals the quintessence of his decades of industrial research work on polymerizations. High-pressure polyethylene (10 pp.) and the Phillips process for polyethylene (5 pp.) are described by BASF chemists, low-pressure polyethylene made by the Ziegler process (12 pp.) by chemists from Farbwerke Hoechst, and polypropylene, amorphous ethylene/olefin copolymers and isotactic polybutene (16 pp.) by *G. Natta*. All the other sections on polymers, polycondensates, and polyadducts are well written, and thus "Ullmann" gives the best presentation of the essentials of this subject available at present.

In the article on odoriferous substances (86 pp.), 106 complex perfumes of natural origin (23 pp.) and 164 chemically uniform compounds or classes of compounds with odoriferous properties are described. The introduction to this chapter (8 pp.) gives a short historical survey, an instructive section on odor and constitution, and a brief but interesting review of the specialized technology used in the production of odoriferous substances. This whole article is well done.

The article on furs deals with the production of tanned and prepared pelts. One of the admirable features of "Ullmann" is that it includes also borderline aspects of technological chemistry and presents them for comparative examination. – The article on soot is compiled by a team from the firm Degussa and gives a readily surveyable review of the development and present-day technical status of the production of amorphous carbon. Unfortunately no economic data are given.

It should be remarked that on the whole, far too little consideration has been given to economic data in the present volume, although they are essentially the decisive factors for all considerations about the technical production of chemical products. Of the 48 articles included, only seven quote economic data, which are sometimes even too short and general, *e.g.* as in the article on quartz and quartz glass. A short but lucid economic review with numerical data is given in the article on mercury. In addition, the comparisons given of various procedures which lead to the same product would have been more valuable if economic aspects such as the ratio of plant-construction costs to operational costs had been discussed. It should have been stressed that the question of costs does not arise solely in the commercial evaluation of the products of technical chemical processes but already participates decisively in determining the aims and structure of chemical technology as a whole.

The article on photomechanical reproduction techniques affords good insight into a new and rapidly developing field. A section on "reprography" describes the procedure for phototechnical production of permanent copies of originals. – Further well-written sections which deserve mention are those on fungal infections, rocket fuels, hydrogenation and reduction, and proteins.

Under the headings "Radicals" and "Reaction mechanisms", the physical chemist expects to find information on the theoretical fundamentals and practical applications of reaction kinetics, but will be amazed to find that physical chemistry has no part in these articles, and that gaseous systems are also entirely neglected. It is to be hoped that this basic field which has become so important in practice since the development of petrochemistry will be awarded the treatment it deserves in another part of the encyclopaedia.

The reviewer's critical remarks are not intended to obscure his general impression that this 14th volume of "Ullmann" maintains the excellent standard of its predecessors, so that it is to be wished that the undertaking can reach a speedy and successful conclusion.

H. Sachsse [NB 284/142 IE]

Die Entwicklung neuer insektizider Phosphorsäure-Ester (The Development of New Insecticidal Phosphoric Esters). By *G. Schrader*. Verlag Chemie, GmbH., Weinheim/Bergstr., 1963. 3rd Revised edit., VII, 444 pp. linen DM 44.– (about $11.–).

At the start of the fifties, a monograph on the development of new insecticidal organic fluorine and phosphorus compounds appeared in two editions and caught the attention of those working in the field. The impressive extension and broadening of developments in this field has led the author to prepare a revised edition; this is to be welcomed, for who could give better coverage than he, who not only had the honor and credit of having initiated this development but who has contributed to it in such an extraordinarily effective way, as a glance at the author index shows?

The originally small monograph has meanwhile become a distinguished and sizeable volume. It starts with an introduction to the general development of organophosphorus compounds, followed by 49 excellent chapters on important individual compounds. Each chapter gives complete details of the methods of preparation, and of the chemical, physical, toxicological, and insecticidal properties of the compound in question. Analytical problems, compounds of closely related structure, and the commercial importance are also discussed. In many cases (*e.g.* for TEPP, DDVP, and Rogor), a detailed historical commentary is included. Hence, because the subject is so intimately related with the experience of the author, and described from his experience, the book makes enthralling reading for the interested reader, a commendation which can seldom be conferred upon the current flood of relevant literature. *Gerhard Schrader* and Verlag Chemie deserve our praise and congratulations for producing this excellent volume.

E. Knüsli [NB 216/93 IE]

Einführung in die Arzneibereitung (Introduction to the Preparation of Pharmaceuticals). By *F. Gstirner*. Wissenschaftliche Verlagsgesellschaft mbH., Stuttgart, 2nd revised edit. 1963, XVII, 419 pp., 108 illustrs., cloth, DM 49.50 (about $12.50).

This modernized edition of the original book has erradicated the failings but retained the character of an introduction to methodology despite its extension by 77 pages. This is greatly to the credit of the author, who has at the same time made the terminology used more "scientific" and placed the emphasis on process technology. Naturally, in order to keep the book within reasonable limits, some topics, such as tissue preparations, vaccines, dialysates, and the isolation of active ingredients, are not included.

The book is divided strictly into sections on the preparation of synthetic, natural, and homeopathic drugs. A new appendix deals briefly with sterilization techniques, dressings, and surgical sutures. This last section is, as is emphasised in the text, only a brief resumé. It is clear that the contents in almost

all the chapters have been completely revised, *e.g.* the chapter on emulsions has increased from 30 to 56 pp. and the chapter on ointments includes references to silicone bases, hydrocortisone ointments, *etc.* Modern techniques in such classical fields as the preparation of pastes, powders, soaps, suppositories, pills, syrups, capsules, tablets, and dragees are dealt with. The particularly important practical section on tabletting faults provides an excellent basic introduction to the methodology. Treatments more suitable for a textbook are to be desired in some sections, *e.g.* that on solutions for injection. The sections on the preparation of natural drugs is particularly valuable, since their therapeutic use has been greatly undervalued in face of the abundance of chemical pharmaceuticals. The same applies to the section on homeopathic pharmacy. The completely new illustrations might have been supplemented by technological flow-sheets for the preparation of pharmaceuticals.

This is a book which will be useful not only to the student of pharmacy, but also to practising chemists in the pharmaceutical industry.

S. Balke [NB 219/97 IE]

Fortschritte der Strukturforschung mit Beugungsmethoden (Advances in Structural Analysis using Diffraction Methods). Edited by *R. Brill*. Vol. I. Friedrich Vieweg & Sohn, Braunschweig; Interscience Publishers, a division of John Wiley & Sons, New York-London 1964. 1st Edit., VIII + 221 pp., 102 figs., linen DM 48.– (about $ 12.25).

The appearance of this new series on "advances in structural analysis using diffraction methods" has closed a gap between the numerous original publications in journals and extensive monographs on the subject. In this first volume of the series, individual topics selected from this vast field are discussed by acknowledged experts (*G. E. Bacon*, *B. K. Vainshtein*, *J. Karle*, *W. Hoppe*, *H. Jagodzinski*, and *A. Niggli*). In addition to two articles on the application of neutron and electron diffraction to the determination of structures, particularly the determination of the positions of hydrogen atoms, there is a review of methods for measuring phase angles. Two further sections are devoted to thermal background variations and to the interpretation of the diffuse interferences occurring in crystals with dislocations. Finally, a short discourse on some symmetry problems is given. Every user of this book will be grateful for the instructive examples and mathematical derivations included. The numerous references given will also prove a great aid for the perusal of original publications.

G. Habermehl [NB 245/103 IE]

Chemie und Technologie aliphatischer fluororganischer Verbindungen (The Chemistry and Technology of Aliphatic Organofluorine Compounds). By *D. Osteroth*. Collection of Chemical and Chemical Technological Reviews. New Series 59. Founded by *F. B. Ahrens*, edited by *R. Pummerer*, *L. Birkofer*, and *F. Goubeau*. Ferdinand Enke Verlag, Stuttgart 1964. 1st Edit., VIII, 195 pp., 8 figs., 41 tables, linen DM 58.– (about $15.00).

The author has attempted to provide a survey of the development of the chemistry and technology of aliphatic fluorine compounds up to the year 1961. The book deals with syntheses of fluorinated hydrocarbons, alcohols, ethers, aldehydes, ketones, carboxylic acids, and compounds containing nitrogen and sulfur, as well as with their chemical reactions. In view of the rapid development and vastness of fluorine chemistry, no single author can reasonably be expected to give a complete critical account of the whole field. The reviewer thus looked in vain among the literature cited for numerous references to methods of preparative importance. For example, the synthesis of monofluorocarboxylic acid esters or monofluoroketones is covered better by the publications of *E. D. Bergmann*. Fluorination by perchloryl fluoride is not mentioned, nor are cycloaliphatic fluorine compounds, such as the pharmaceutically important fluoro steroids. Interactions of *N*-bromoacetamide and hydrogen fluoride with olefins, and reactions with difluorocarbene or fluorochlorocarbene have also been overlooked. Reaction mechanisms are hardly touched upon, but patents and technological aspects are more fully covered.

H. Machleidt [NB 233/90 IE]

Mathematik für Naturwissenschaftler und Chemiker (Mathematics for Scientists and Chemists). By *H. Sirk* and *M. Draeger*. Completely revised by *M. Draeger*. Verlag Theodor Steinkopff, Dresden-Leipzig 1963. 9th Edit., xii + 385 pp., 132 figs., linen DM 25.20 (about $6.50)

The value of "Sirk" is demonstrated by its many editions, and now it has appeared in a new edition completely revised by *M. Draeger*. Despite radical alterations, the character of the book has been maintained, and on the whole, the presentation – as well as the typographical appearance – of the volume are clearer. This has been achieved partly by a reorganization of the material. The elementary mathematics hitherto appended at the end now appears together with one section each on combinations and determinants in the new first part of the book. Infinite series and approximation procedures are discussed in a new fifth part. The practical examples in thermodynamics are now gathered together in a single chapter in the third part (functions with several variables). In addition, even more effort has been made here than in previous editions to conveying a lucid and intelligible appreciation of mathematical concepts in order to simplify understanding of the methods described. In this connection, the section on the basic number e, the detailed discussion of the geometrical interpretation of simple, first-order differential equation as a vector field and of its general integral as a one-parameter series of curves, the clear treatment of the method of the integrating factors, and the section applied to differentiating between the concepts of "necessary" and "sufficient" conditions can be cited as examples. Furthermore, the illustrative examples given in the text are supplemented by numerous problems whose solutions are given in the appendix. There is a brief summary at the end of each chapter to assist rapid orientation.

A few sections had to be shortened to make room for these welcome additions and innovations. Thus, treatment of the method for calculating errors by the law of least squares and of Taylor series has been omitted, and elimination of the section on the Schrödinger equation has consequently led to the lack of mention of boundary conditions, eigenvalues, and eigenfunctions of a differential equation. In view of the increasing importance of electronic computers, a somewhat more extensive treatment of iteration procedures would have been desirable.

This new edition of "Sirk/Draeger" is an exceptionally lucid and well-planned introduction to the fundamentals of higher mathematics and can therefore be earnestly recommended to every student of chemistry. Here not only will he find the mathematical basis of classical physical chemistry, but he can also acquire the background which will facilitate his explorations into specialized fields of modern physical and theoretical chemistry.

M. Klessinger [NB 250/108 IE]

Carl Wilhelm Scheele. Apotheker - Chemiker - Entdecker. By *O. Zekert*. Vol. 27 of the series "Grosse Naturforscher" edited by *H. Degen*. Wissenschaftliche Verlagsgesellschaft m.b.H., Stuttgart 1963. 1st Edit., 142 pp., 23 illustrations, linen DM 15.80 (about $4.00).

Carl Wilhelm Scheele (1742–1786) was one of the most prominent chemists during the transition from the phlogistic to the antiphlogistic eras; his biography and achievements are recounted in the present volume. Many of the results of his investigations can be regarded as the beginnings from which organic chemistry developed into an independent science. Even though *Wöhler*'s synthesis of urea is generally accepted as the starting point of synthetic organic chemistry nowadays, it should not be forgotten that, during his investigations of "the coloring material in Berlin blue", *Scheele* prepared hydrogen

cyanide as early as 1782 and even tested its "unusual odor and taste" in complete unawareness of the toxicity of the compound. However, *Scheele*'s name will remain famous mainly because of his discovery of oxygen around 1771, *i.e.* before the work of *Priestley* in 1774, although *Scheele* did not publish his findings until later in his book "Chemische Abhandlung von der Luft und dem Feuer" (Chemical Discourse on Air and Fire) in 1777. According to *J. R. Partington* a report on *Scheele*'s work had actually been published beforehand in 1775 by *Bergman*. "There can hardly be another scientist", writes *Zekert*, "who, within the brief span of only two decades, has created something so meaningful and of lasting value as has *Scheele*", and hence it now seems almost incredible that all his scientific work was carried out within the confines of a laboratory attached to his pharmacy.

The volume closes with a table giving a synopsis of the important dates in *Scheele*'s life in relation to world events of that time. This book will perhaps induce its readers to interest themselves further in this fascinating scientist and in the effects of his work on the development of organic chemistry.

W. Ruske [NB 257/115 IE]

Mass Spectrometry of Organic Ions. Edited by *F. W. McLafferty*. Academic Press Inc., New York-London 1963. 1st Edit., xii + 730 pp., numerous illustrations and tables, linen, $ 24.00.

In recent years mass spectrometry has assumed an important position in chemical research. In this collective volume several authors review their particular fields. The topics dealt with are intended for chemists and physicochemists and include both theoretical and practical aspects of mass spectrometry. The result is a multifarious treatment that will be inspiring and useful to all interested in the subject.

The sections on the quasi-equilibrium theory and appearance potentials are written clearly and with discerning criticism. Several instructive chapters are devoted to the application of mass spectrometry to the study of ion-molecule reactions, free radicals, electrical discharges, and flames, and abundant data are given on experimental techniques, equipment, and previous results. A section on the mass spectra of negative ions is also included.

The second part of the book, which is dedicated to the correlation of mass spectra with molecular structure, will undoubtedly be of greatest interest to the organic chemist. A brief but excellent recapitulation of the general principles involved is followed by chapters in which the techniques and results of mass spectrometry are illustrated by way of examples. Investigations of numerous fatty esters made it possible to detect the fragmentation paths and to elucidate the structures of some natural products. Extensive studies of alkylbenzenes revealed very surprising information about the structures of some ions. Both chapters distinguish in exemplary fashion between proven and postulated fragmentations.

The next section (on the elucidation of the structures of amino acids and alkaloids) illustrates how complicated natural materials can be successfully investigated by combining chemical and mass-spectroscopic results. The success in studying complex mixtures of similar compounds is demonstrated by taking petroleum as an example. A section on high-resolution spectrometers indicates the vast potentials of this method. The chapter on terpenes is unfortunately not satisfactory. In contrast to the rest of the book, here the individual compounds are dealt with too summarily; the fragmentations are few and are all unproved. In addition, there are several errors here, *e.g.* the fragmentation of myrcene on page 653.

On the whole, however, the book is to be highly recommended. Its individual articles are excellent and describe the whole field of mass spectrometry; repetitions have been almost invariably avoided. The literature has generally been evaluated till spring 1962. All results and findings have been critically reviewed; this and the abundant use of tables and illustrations deserve particular praise.

W. Benz [NB 254/112 IE]

Air Chemistry and Radioactivity. By *C. E. Junge*. International Geophysics Series, Vol. 4, edited by *J. van Mieghem*. Academic Press, New York-London 1963. 1st Edit., xii + 382 pp., 83 figs., 66 tables, linen $ 13.50.

Publications on the chemistry of the atmosphere are scattered throughout many scientific journals. The author is therefore to be highly commended for this survey of the present state of research on this subject, which is now developing rapidly. The concentrations of oxygen, nitrogen, and most of the inert gases in the atmosphere can be regarded as being constant with respect to space and time, and hence are not dealt with in the book. The distributions with space and time of the other gaseous components of the atmosphere – over a dozen are known – are described (Chapter 1). These data are important not only because of their influence on organic life (*e.g.* owing to their absorption of sunlight), but also for the investigation of atmospheric circulation and exchange processes. In the second chapter, the physical and chemical properties of aerosols are discussed, together with their distribution in the troposphere and stratosphere. Aerosols have the property of concentrating material from their environment in various ways, and so their structure and composition are continuously changing; they are largely responsible for atmospheric static, atmospheric optics, cloud formation, and the chemistry of the atmosphere.

The most important rainfall processes, which are responsible for the clearing of the atmosphere, are nucleation within clouds and scrubbing by rainfall underneath the clouds. There are also numerous other processes by which materials can be removed from the atmosphere: sedimentation, fixation by objects on the earth's surface, adsorption of gases, chemical reactions, and escape into outer space. General rules for these processes are derived here from a large number of observations (Chapter 4). The most important topic in this connection is the chemical composition of rainfall.

Impurities in the air are mainly due to industrial factories and roadway traffic. In the fifth chapter, a general discussion on the composition of these impurities, their distribution, and their removal from the atmosphere is given. Atmospheric radioactivity is discussed in the third chapter; this arises from three sources: the natural radioactivity of the earth's crust, which leads to the emanation of radon and thoron, the radioactive isotopes produced in the upper troposphere and lower stratosphere by cosmic rays (of these, ^{14}C and ^{3}H have acquired particular importance), and the nuclides formed by nuclear explosions, which are now of general interest because of the danger of radiation damage due to radioactive fall-out. Much attention is given to a description of the distribution of these isotopes in the atmosphere and of their importance for studying circulatory and separatory processes.

This book by *Junge* links together chemistry, nuclear chemistry, and meteorology. It will provide a valuable aid to all scientists interested in problems associated in the widest sense with the atmosphere.

W. Groth [NB 260/118 IE]

Anorganische Chemie (Inorganic Chemistry), Volume III. By *I. Náray-Szabó*. Akademie-Verlag, Berlin and Verlag der Ungarischen Akademie der Wissenschaften, Budapest 1963. 1st Edit., pp. 669, 21 illustr., 4 tabl., linen DM 48.– (about $12.00).

With this third and last volume, the German edition of "Anorganische Chemie" is now completed. The first three chapters deal with the metals and compounds of the copper, zinc, and gallium groups and the fourth, very extensive chapter is devoted to the chemistry of the iron and platinum groups of metals. In addition, the rare gases are discussed, and the rare gas fluorides and oxygen-containing xenon compounds discovered during the last two years are mentioned. A comprehensive account of the properties of the elements and a short section on geochemistry and cosmic chemistry complete this volume.

As in the preceding volumes [1] the author has compiled with remarkable care much physical data and extensive chemical factual material. Unfortunately, especially in the chapter on the metals of group 8 of the periodic system, this is not always up-to-date and outmoded structures and formulae are given, *e.g.* for cyano complexes and halogenocarbonyls. Many new types of compounds of the iron and platinum metals have not been mentioned, *e.g.* the reader will search in vain for a reference to sandwich compounds of the ferrocene type or to the numerous co-ordination compounds of these metals with anomalous oxidation numbers which have been isolated and structurally analysed during the last fifteen years and which are of bonding and sterochemical interest. On the other hand, many a compound stated to be "non-existent" could have been left out. Despite these reservations and certain deficiencies in the coverage of the latest developments, the third volume of *Náray-Szabó* will also serve its purpose as a handbook in many instances. Its carefully compiled subject and formula indices contribute significantly to its efficiency.

R. Nast [NB 218/88 1E]

Friedel-Crafts and Related Reactions. Edited by *G. A. Olah*. Vol. I: General Aspects. Interscience Publishers, a Division of John Wiley & Sons, New York-London 1963. 1st Edit., XXXIV + 1031 pp., numerous illustrs. and tables, linen £ 11.0.0 (about $ 30.50).

Volume I of this series of four volumes (6 books with about 4000 pp.) begins with a survey over the vital, even dramatic period around the discovery of the reaction, which is particularly well illustrated by numerous facsimile reproductions, including extracts from the laboratory notebooks written together by *Friedel* and *Crafts*. (Chapter I: *G. A. Olah* and *R. E. A. Dear*). In Chapter II, *G. A. Olah* defines the range and limitations of the "Friedel-Crafts and Related Reactions" (120 pp.) thereby including any substitution reaction, isomerization, elimination, cracking reaction, polymerization, or addition that is catalysed by Lewis or protonic acids. – This is followed in Chapter III by a short but poignantly lucid discourse by *R. J. Gillespie* on "Brønsted and Lewis Acids" in which the influence of structural parameters upon the acid strength and the importance of strong protonic acids as solvents is stressed. – Under the heading "Catalysts and Solvents" in Chapter IV, *G. A. Olah* no longer describes simply Lewis acids of the metal halide type but includes metal alkyls, metal alkoxides, acidic oxides and sulfides, cation exchangers, and even cation-forming substances such as $AgClO_4$ or $AgBF_4$ in his scheme without constraint. A detailed discussion is given of the part that cocatalysts play in Friedel-Craft reactions; here the importance of small amounts of water or oxygen is given particular attention.

The role of Lewis catalysts in non-aqueous systems is dealt with by *M. Baaz* and *V. Gutmann* in Chapter V. One of the particularly valuable features of this chapter is to be found in its orderly tabular collection of reactions given with the Lewis acid used, the solvent employed, the ionization of the donor-acceptor complex, *etc.*, which is probably unmatched elsewhere. – In Chapters VI and VII, the coordination compounds of boron halides and aluminum halides are discussed respectively by *D. R. Martin* and *J. M. Canon*. Although the authors are to be awarded due commendation for the admittedly arduous task of compiling a summary, for example, of all the boron halogen compounds known (one table contains no less than 464 compounds!), it would probably be more beneficial to the ease of surveyance of the complete work if this chapter (150 pp.) were either radically abbridged or – even better – reorganized to appear as a separate monograph for those interested in this topic.

Chapter VIII by *G. A. Olah* and *M. W. Meyer* again makes good reading, for it records all the intermediates of Friedel-Crafts reactions known to date. The intelligibility of this chapter is aided to no mean extent by the exact definitions given of π-, σ-, and n-complexes, which arise by the interaction of the following coreactants a) catalyst/cocatalyst, b) catalyst/substrate, c) catalyst/reagent, d) catalyst/product, and e) catalyst/solvent. The profound knowledge of the editor in this field in particular makes possible a critical appraisal of chemical and physical methods for detecting such intermediate complexes. In supplementation, Chapter IX by *D. Cook* gives a summary of spectroscopic experiments designed to convey information on the nature of the donor-acceptor complexes occuring as intermediates in Friedel-Crafts reactions. This description includes, for example, the complexes of ketones, which are formed as reaction products, with Lewis acids and the complex formation of Lewis acids with solvents (*e.g.* nitrobenzene). It is understandable that the major accent has been placed upon nitronium and acylium ions and their complexes, for these are relatively easy to secure and are very important. Here again well presented tables enable the reader to obtain a good idea of the current status of knowledge, which, however frequently needs confirmation by other independent methods, particularly X-ray crystallography.

In Chapter X, *R. M. Robert* and *G. J. Fonken* describe vividly how labelled compounds have been applied with great profit in the field of Friedel-Crafts reactions for mechanistic studies, particularly of technically interesting alkylations, dealkylations, rearrangements, and fragmentations. In comparison with the abundance of experimental material, the theoretical evaluation of the results, which is built up on a remarkably critical attitude, is rather scant. – In Chapter XI on "Reactivity and Selectivity", *G. A. Olah* shows that the overall effect of a catalyst/cocatalyst system must always be regarded as the complex result of a number of combining and opposing factors, including the different electronegativities of the halogeno ligands in Lewis acid halides, the dissociation energies of dimeric metal halides, the electronegativities of the molecules acting as donors, the bond lengths and strengths within the donor-acceptor complexes, lattice and solvation energies, and steric effects. This chapter in particular can be consulted by the reader with profit, for it is one of the richest and gives empirical sequences for the relative reactivities of catalysts, cocatalysts, acyl halides, *etc.* in the most important types of reaction. If a compound contains more than a single reactive group, then Friedel-Crafts reactions are subject to considerable limitations on account of the frequently observed lack of specificity of the Lewis acids used. Numerous cleverly selected examples are given to illustrate the various possibilities for procuring a selective course of a Friedel-Crafts reaction on polyfunctional compounds. Both the theorist and experimenting chemist will be interested by the detailed treatment given in this connection to questions of the positional selectivity observed in electrophilic substitutions of aromatic compounds.

A brief introduction to the thermodynamic approach to Friedel-Crafts reactions is given by *D. R. Stull* in Chapter XII. Calculations on the course of ten reactions – mainly alkylations and acylations – are presented and will enable the organic chemist who is not fully competent in this field to find easy access to the subject, especially since complicated reactions have been wittingly avoided and all the thermodynamic constants required for the operations are presented in orderly tables in the appendix. – The carbonium ion mechanism for the Friedel-Crafts reaction, which proabably enjoys general acceptance today, finds additional support in the more or less complete racemization observed when the corresponding optically active alkylating agents are used. The none too numerous findings that have been accumulated to date from stereochemical studies in this field have been admirably collected together by *H. Hart* in the last chapter, which fortunately waives any all too broad theoretical background.

It is certainly to be expected that this first volume of the series, which is so good as to make its user look forward to the coming volumes, will assume its merited and indispensible position in academic and industrial laboratories.

J. Gosselck [NB 298/157 IE]

[1] Cf. review of Vols. I and II in Angew. Chem. *75*, 695 (1963); Angew. Chem. internat. Edit. *2*, 404 (1963).

Friedel-Crafts and Related Reactions. Edited by *G. A. Olah*. Vol. II: Alkylation and Related Reactions. Part I and Part II. Interscience Publishers, a Division of John Wiley & Sons, New York-London-Sydney 1964. 1st Edit., Parts 1 and 2 together, 1362 pp., numerous tables, linen £ 18.18.0 (about $ 52.50).

Volume I of this series placed the general aspects of this subject in the forefront, and now the discussion of "Alkylation and Related Reactions" is continued in greater detail. The intense interest that has been shown by researchers – particularly in industrial laboratories – in the alkylation of aromatics ever since its discovery by *Friedel* and *Crafts* has resulted in such a vast amount of literature reports that the subject can only be covered with great effort. The editor and his co-authors are to be awarded high commendation for undertaking the none too easy task of introducing an orderly principle here. Scientific and patent literature is covered up to 1961 – sometimes up to 1962 – and the references cited are mainly from publications that have appeared within the past 15 years, although frequently (*e.g.* on pp. 2, 475, and 979) references are given to important reviews of earlier investigations.

In Part I, the following topics are discussed in sequence: Methods of alkylating aromatics using alkenes and alkanes (Chapter XIV, *S. H. Patinkin* and *B. S. Friedman*), using dienes and substituted alkenes (Chapter XV, *R. Koncos* and *B. S. Friedman*), using alkynes (Chapter XVI, *V. Franzen*), using halogenated alkanes (Chapter XVII, *F. A. Drahowzal*), using alcohols and ethers (Chapter XVIII, *A. Schriesheim*), with aldehydes and ketones (Chapter XIX, *J. E. Hofman* and *A. Schriesheim*), and finally with inorganic esters and alkylarenesulfonates (Chapter XX, *F. A. Drahowzal*). Part II deals with halogenoalkylation (Chapter XXI, *G. A. Olah* and *W. S. Tolgyesi*), cycloalkylation of aromatics (Chapter XXII, *L. R. C. Barclay*), dehydrogenative condensation (the Scholl reaction, Chapter XXIII, *A. T. Balaban* and *C. D. Nenitzescu*), isomerization of aromatic hydrocarbons (Chapter XXIV, *D. A. McCauley*), alkylation of saturated hydrocarbons (Chapter XXV, *L. Schmerling*), the condensation of halogenoalkanes with alkenes and halogenoalkenes (Chapter XXVI, *L. Schmerling*), the alkylation of alkenes with carbonyl compounds (Chapter XXVII, *C. W. Roberts*), the isomerization of saturated hydrocarbons (Chapter XXVIII, *H. Pines* and *N. E. Hoffman*), hydrogen exchange in aromatic compounds (Chapter XXIX, *V. Gold*), and polymerization (Chapter XXX, *D. C. Pepper*).

Both parts of Volume II are apparently intended for use mainly as handbooks, for it has been attempted to reproduce as much experimental material as possible in tabular form (there are over 320 full-page tables) in order to enable the reader to acquire speedy information on the reaction he is interested in. In general, detailed theoretical considerations such as appeared in large sections in Volume I and conferred upon it the nature of a textbook have been disregarded here; only a few are included, for example in Chapter XXIX (hydrogen exchange) and Chapter XXX (polymerization; here the Ziegler-Natta polymerization has been intentionally excluded).

The outlay and appearance of the two books is good. They are intended primarily for the use of the experimenting chemist, who, the reviewer earnestly believes, will soon find that he would not like to be without them.

J. Gosselck [NB 299/158 IE]

Electronic Charges of Bonds in Organic Compounds. By *G. V. Bykov*, translated from the Russian by *J. T. Greaves*, edited by *R. W. Clarke*. Pergamon Press, Oxford-London-New York-Paris 1964. 1st Edit., viii + 191 pp., 16 figs., 39 tables, linen £3.0.0 (about $8.25).

In this monograph, where a summary of his publications appearing between 1951 and 1960 are presented, *G. V. Bykov* attempts to develop a purely empirical treatment of the electronic structures of organic compounds. The starting point for this approach is the linear relationship between the physical properties of a compound and the charge densities in its bonds. The charge densities evaluated in this manner are used to derive values for the electronegativity of the atoms, this concept being defined in a new way. The author states that the aim of this book is to coordinate the publications in this field and to make them available to all chemists. Unfortunately, this aim is not attained. Instead of relating the various – mostly quantum mechanical – theories of charge density to one another the author's theory is presented in such an unsystematic manner that it is difficult to distinguish between the assumptions and the results of the theory.

The translation does not give an account of the developments that have taken place since the appearance of the Russian edition and does not contribute to an easier understanding of the text. By a slight stretch of imagination, it can be seen from the context that "frequencies of valence fluctuations of the CH-bonds", for example, means C–H valence vibrational frequencies and that "super-conjugation" means hyperconjugation. Since there are about a hundred errors spread out evenly over the text and formulae, it is advisable to check all derivations and formulae carefully. If the reader wishes to peruse some of the original literature cited, he will be surprised to learn that references to Pauling's "Nature of the Chemical Bond" and to Hückel's "Theoretische Grundlagen der organischen Chemie" are based on the Russian editions of these two books.

M. Klessinger [NB 249/107 IE]

Elimination Reactions. By *D. V. Banthorpe*. Vol. 2 of a series: Reaction Mechanisms in Organic Chemistry, edited by *E. D. Hughes*. Elsevier Publishing Co., Amsterdam-London-New York 1963. 1st Edit., viii + 215 pp., 17 tables, linen DM 25.– (about $6.30).

D. V. Banthorpe has investigated elimination reactions, and using his wide experience in this field has written this very readable book. With its 482 references the work reflects the state of this subject at the beginning of 1962. The selection and presentation of the material discussed illustrate the author's subjective approach, stressing the classical examples of β-eliminations from saturated systems. Four sections are devoted to a discussion of the mechanism of olefin formation, the influence of structure on the course of elimination reactions, orientation rules and their interpretation, and eliminations from cyclic systems where base-catalysed reactions are emphasized. Two chapters are devoted to acid-catalysed and pyrolytic eliminations.

It is well-nigh impossible to find a better presentation of this subject matter; however, in the reviewer's opinion, the standpoint adopted in the book is sometimes too "classical", and the chapter on "Less Usual Elimination Reactions" is too short, even though references to reviews by other authors are given. Thus, for example, eliminations from olefins are allowed only three pages and fragmentations receive only two pages of text. A little more space is allotted to α-eliminations, but this certainly does not correspond nowadays to the importance to be attached to the mechanisms pertinent here. An extended treatment of the latter and the inclusion of important results published after completion of the manuscripts would be desirable in any subsequent edition of the work. Nevertheless the book can be highly recommended to advanced students and to anyone interested in reaction mechanisms.

G. Köbrich [NB 255/113 IE]

Technique of Organic Chemistry, edited by *A. Weissberger*. Vol. XI: Elucidation of Structures by Physical and Chemical Methods, Part II. Edited by *K. W. Bentley*. Interscience Publishers, a division of John Wiley & Sons, New York-London 1963. 1st Edit. ix + 537 pp., numerous tables, linen £7.7.0 (about $20.00).

The second part of Vol. XI of this series contains ten interesting articles written by prominent organic chemists. *Z. Valenta* demonstrates in his article that distillation over zinc

dust is still an extremely useful method in structural investigations when known rearrangements are borne in mind. *B. C. L. Weedon* reviews the applications of alkali fusion and the reactions that occur thereby. Relatively unknown reactions, such as the alkyl transfer to ketones, special dehydrogenations of alkoxides, and the demethylation of methoxylated phenols are mentioned. *J. K. N. Jones* and *M. B. Perry* discuss methods for degrading polysaccharides and methylated polysaccharides. *K. W. Bentley* describes the application of conventional methods of cleaving C–O and C–N bonds mainly in the alkaloid series. The reviewer welcomes the inclusion of the little known cleavage of $N-CH_3$ bonds with azodicarboxylic esters discovered by *O. Diels* and of the β-elimination with $LiAlH_4$. *E. Y. Spencer* gives a thirty page review of methods for the hydrolytic degradation and elucidation of the structures of polypeptides and proteins, including a discourse on oxidative procedures. *K. T. Potts* illustrates the application of known methods of cleaving C=C bonds with examples from the chemistry of natural products. The interesting cleavages that occur with alkaline H_2O_2 are relatively unknown. A second article by *K. W. Bentley* on C=C fission reports mainly on common methods; the examples given of abnormal cleavage with ozone are highly instructive. The chapter by *N. Polgar* on methods for shortening side chains and long-chained compounds is also very useful as it describes relatively unfamiliar reactions.

Here brevity does not permit a closer appraisal of the excellent article (150 pages) by *B. Belleau* on the allocation of steric configurations to natural products using chemical methods. This article also describes the latest data on reaction mechanisms and can be recommended as the basis of lectures on stereochemistry. In the final article, *P. de Mayo* writes a most intriguing review of rearrangement reactions that occur with natural products. Only one (see p. 1095) of the few printing and formulae errors is not immediately recognizable: here an attacking proton is drawn directly above an angular methyl group. This volume deserves a hearty recommendation.

H. Plieninger [NB 256/114 IE]

Infrared Band Handbook. Edited by *H. A. Szymanski*. Plenum Press, New York 1963. 1st Edit., xii + 484 pp., linen $7.50.

This book is a catalogue of over 8500 infrared bands in the region between 3610 and 617 cm^{-1}, measured on over a thousand substances. In the main part of the volume, the bands are arranged in order of decreasing wave-number. The information for each band comprises, as far as possible, substance, nature of sample measured, resolution of instrument, type of vibration, band intensity, and reference. The book contains also a substance index and correlation tables for methyl deformation vibrations and C–N valence vibrations, since these vibrations are not included in the main section. The literature references have been restricted to 25 sources covering the period up to 1961. The principal source evaluated is the American Petroleum Research Institute, Project 44 catalogue. Annual supplements costing $7.50 are planned to cover the region down to 250 cm^{-1}. The book is a valuable aid for the identification of unknown substances and for the solution of problems of band assignment.

E. Lippert [NB 261/119 IE]

Oxydation des Métaux (Oxidation of Metals). Vol. I: Processus Fondamentaux (Fundamental Processes). Edited by *J. Bénard*. Gauthiers-Villars et Cie., Paris 1962. 1st Edit., 465 pp., numerous illustrations, linen, NF 55.– (about $11.50).

Over the past few years, experiments on the oxidation of metals have been carried out increasingly under carefully controlled conditions and with highly purified starting materials. The time therefore seemed ripe for reassessment of existing theories and for development of more refined concepts. In this first of two volumes on the "Oxidation of Metals" *J. Bénard* and a number of collaborators have attempted to give a detailed account of the fundamental principles involved, without omitting any relevant material. A brief glance at the contents of the various chapters may serve to illustrate this point. Chapters 1–5: Metal surfaces, adsorption equilibria, the kinetics of adsorption and chemisorption, the structure of chemisorption layers and their influence on the properties of the underlaying metal (*J. Bénard*). Chapters 6–8: Nucleation processes, the growth of thin layers and their orientation (*J. Bénard, J. Bardolle*, and *F. Bouillon*). Chapters 9–11: Thicker layers, methods of investigation and results, diffusion theory of layer formation (*G. Valensi*). Chapters 12–15: Thermodynamics and kinetics of the oxidation of alloys, internal oxidation (*J. Moreau* and *J. Bénard*). Chapter 16: Real structure of oxides, mechanical properties, dislocations, *etc.* (*M. Cagnet*). Tables of crystallographic, thermal, and mechanical properties of metal oxides are also given.

The individual contributors do not always adopt the same approach to their readers. Thus, for example, a detailed derivation of the law of diffusion is given (p. 228), but sometimes simply the results of rather complex theorems are given, *e.g.* for internal oxidation. Nevertheless, the book offers an excellent provocative and modern survey of the subject, and topics that are all too frequently neglected (*e.g.* the morphological and mechanical properties of metal/metal oxide systems) are considered, as is to be expected from this editor and his coworkers. English, French, and German literature has been covered thoroughly and uniformly until 1960 (1052 references).

W. Jaenicke [NB 268/125 IE]

Steroid Reactions: An Outline for Organic Chemists. Edited by *C. Djerassi*. Holden-Day, Inc., San Francisco 1963. 1st Edit., vi + 657 pp., linen $9.75.

C. Djerassi maintains that the increasing profusion of publications connected with the field of steroids has led many chemists who are not familiar with this subject to abandon the practice of reading articles devoted to it. This is regrettable insofar as there is hardly a chemical reaction that has not been applied to steroids. Furthermore the reactions applied have frequently led to particularly lucid results because of the relatively precise knowledge of the structures, conformations, and reactivities of steorid derivatives. In order to break the soil of this fallow field and make it available even to non-steroid chemists, 16 post-graduate students at Stanford University undertook to arrange 14 special aspects of the subject into order in the form of formulae schemes under *Djerassi*'s guidance; the appropriate reaction conditions, yields, and literature references are given for each reaction. The data include the protection of carbonyl and hydroxyl groups, selective oxidation of polyhydroxysteroids, the introduction of fluorine into the steroid system, the production and dehydrohalogenation of α-bromo, α-chloro, and α-iodo ketosteroids, *etc.* Apart from short introductions before the chapters, written text has been completely replaced by formulae and reaction schemes. Thus it is simple for the user of the book to survey the general picture, and this helps him to find any desired reaction rapidly. Since the work done by the students has been checked and supplemented by experienced steroid chemists in large American firms, the result is an excellent review volume which undoubtedly fully achieves its aim of providing a rapid guide to the entire subject and which will therefore soon acquire many friends. The book fills an obvious gap, even though it is not completely free from errors; one must expect this when one considers the abundance of material discussed. However, the reviewer doubts whether it will influence many non-steroid chemists into investigating the ever increasing amount of steroid literature. In any case, it will certainly be often consulted by the specialist in this field.

R. Tschesche [NB 285/143 IE]

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Recent Advances in the Total Synthesis of Steroids

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In the total synthesis of steroids on the industrial scale, three factors are important: stereoselectivity of the reactions used, resolution of racemic intermediates at the earliest possible stage, and convergence of the synthesis. Theoretical advances and wider practical experience in the chemistry of polycyclic compounds have recently led to the development of the first syntheses which are suitable for the industrial production of steroid hormones.

Introduction
I. Theoretical Principles
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a) Steric Factors
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b) Application to Specific Functions
α) Ketones
β) Olefinic Double Bonds
γ) Enol Functions
II. Practical Considerations
a) Formation of a Center of Asymmetry in Positions 13 and 14
b) Formation of a Center of Asymmetry in Position 10
c) Development of Synthetic Routes

Introduction

The object of the total synthesis of steroids is to build up polycyclic compounds containing several centers of asymmetry. If the molecule contains n asymmetric centers, it is possible to obtain 2^n isomers; in the case of steroids, only one of these is of biological importance. Consequently, the reactions used in the total synthesis of steroids must be highly stereoselective. The starting materials for these reactions are unsaturated cyclic compounds containing C=C double bonds, a keto group, or an enol function, *i. e.* compounds with one or more trigonal carbon atoms. The stereochemical problem of the total synthesis of steroids therefore consists in the stereoselective conversion of trigonal carbon atoms belonging to five- or six-membered rings.

In addition to this chemical problem, there is an economic problem: The production of an optically active steroid in high yield by a total synthesis involving a large number of steps requires early resolution of racemic intermediates and convergence of the stepwise synthesis of the ring system [*].

All of these requirements present obstacles to the development of a total steroid synthesis suitable for large-scale production. Following the first total syntheses by *Bachmann* (1939), no solution to the problem was found for a long time, in spite of many, often extremely elegant attempts. Recently, however, the advance of conformational analysis and new findings in the chemistry of polycyclic compounds have led to new solutions.

As a basis for a review of the developments of the past 10 years, we shall first consider the theoretical principles involved in the stepwise synthesis of the steroid skeleton.

I. Theoretical Principles

1. Reactivity and Stability

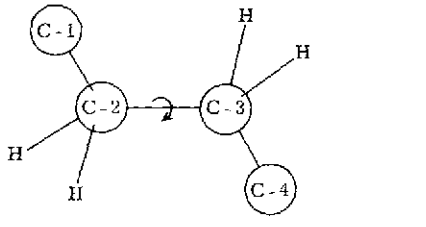
Since the elucidation of the geometry of the cyclohexane ring by *Hassel* in 1943, our knowledge of the reactivities of the ring systems occurring in steroids has greatly in-

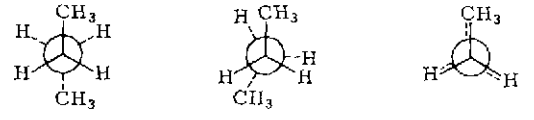
[*] A converging synthesis is one in which several parts of the molecule are prepared first, and these are then joined together to form a single intermediate.

creased, particularly as a result of the development of conformational analysis.

Cyclohexane

According to *Klyne* and *Prelog* [1], the conformations resulting from rotation about a single bond can be described by the magnitude of the dihedral angles. Thus the conformations of butane are staggered *(1)*, skew *(2)*, or eclipsed *(3)*, depending on the dihedral angles $\alpha = \sphericalangle$ C(1)-C(2)-C(3)-C(4). These conformations give rise to the interactions and strains which determine the energy content of a structure. Conformation *(1)* corresponds to the minimum potential energy, and *(3)* to the maximum.



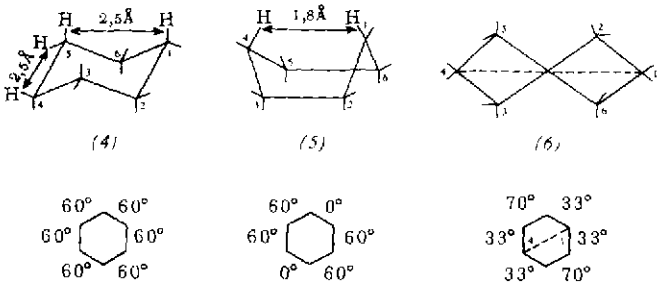


(1), $\alpha = 180°$ *(2)*, $0° < \alpha < 180°$ *(3)*, $\alpha = 0°$

The cyclohexane ring can to some extent be regarded as a cyclic combination of butane units, each of which contributes its own conformational problem. The conformation of cyclohexane is therefore defined by the six dihedral angles in the ring. The potential energy is determined by the steric interactions of atoms which are not directly bonded to one another, and by strains resulting from these interactions.

The chair conformation *(4)*, with its three-fold axis of symmetry, has six equal dihedral angles of 60° each, and steric interactions within the molecule are reduced to a minimum. This is the reason for the great stability of this conformation.

The boat form *(5)*, with two dihedral angles of 0° and four of 60°, contains two pairs of eclipsed interactions and a 1,4-bow-stern interaction. Consequently, this form is less stable by about 6.5 kcal/mole than the chair conformation.



(4) *(5)* *(6)*

The potential energy of the twist conformations, *e. g. (6)*, is somewhat lower than that of the boat form *(5)* [2].

Among the non-bonded interactions in the chair form of cyclohexane, the 1,3-interactions between axial substituents and the 1,2-interactions between equatorial substituents are particularly important. Conformational analysis shows that the distance between two axial hydrogen atoms or between two adjacent equatorial hydrogen atoms in the chair conformation *(4)* is about 2.5 Å.

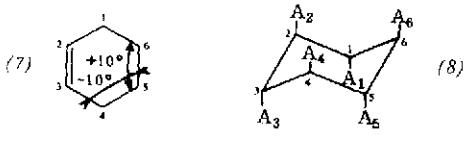
Slight changes in the distances between axial hydrogens have no appreciable effect on the interactions. This is not the case, however, with substituents larger than hydrogen. Thus the energy of interaction between 1,3-diaxial methyl groups is about 5.5 kcal/mole greater than that for two equatorial methyl groups. An example of this is the reflex effect described by *Ourisson* [3].

The eclipsed interactions are also appreciable, and may result in conformational changes (*e. g.* the *gem*-dimethyl effect [4]) or affect the intermediate states of various reactions (see p. 191).

In all cyclohexanes, steric interactions lead to deformation of the ring. Conversely, changes in the dihedral angle affect the distance between atoms which are not directly linked together, *i. e.* steric interactions and conformational changes are closely related.

Little systematic study has so far been devoted to conformational changes in cyclohexane rings. Exceptions, however, are vectorial investigations, particularly those by *Corey* and *Sneen* [5, 6]. Their methods have recently been improved by *Bucourt* [7, 8], working in our laboratory.

Deformations of the cyclohexane ring can be analyzed by determining the deviations of the dihedral angle from an assumed normal value of 60° [7, 8]. Thus on comparison of the half-chair form of cyclohexane *(7)* with the chair form, we find that the "*para*" dihedral angle C(4)-C(5)-C(6)-C(7) has been opened up [*], while the "*meta*" dihedral angle C(3)-C(4)-C(5)-C(6) has been closed, the difference from the normal angle being of the order of 10° in each case [7, 8].



(7) *(8)*

Conversely, deformation of a dihedral angle alters the geometry of a chair cyclohexane, and hence also the distances between axial substituents. The axial substituents A_2, A_4 and A_3, A_1 *(8)* on the C-atoms of the deformed dihedral angle C(1)-C(2)-C(3)-C(4) approach one another when this angle opens up, and move apart when the angle closes.

[1] *W. Klyne* and *V. Prelog*, Experientia *16*, 521 (1960).

[2] *H. H. Lau*, Angew. Chem. *73*, 423 (1961).

[3] *C. Sandris* and *G. Ourisson*, Bull. Soc. Chim. France *1958*, 1524.

[4] *W. Klyne*, Adv. Org. Chemistry *1*, 320 (1960).

[5] *E. J. Corey* and *R. A. Sneen*, J. Amer. chem. Soc. *77*, 2505 (1955).

[6] *L. C. G. Goaman* and *D. F. Grant*, Tetrahedron *19*, 1531 (1963).

[7] *R. Bucourt*, Bull. Soc. Chim. France *1962*, 1983.

[8] *R. Bucourt*, Bull. Soc. Chim. France *1963*, 1262; *1964*, 2080.

[*] The expressions "opening" and "closing" refer to the widening or narrowing of the dihedral angle from a standard value of 60 °C.

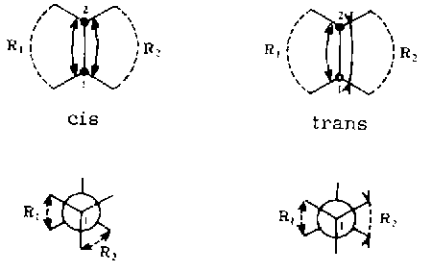
If all carbon atoms of the ring carry only hydrogen atoms, the deformation energy is about 1 kcal/mole for 10° and is practically independent of the sign of the deformation, provided that the magnitude of the latter is small. If, on the other hand, the molecule contains a bulky axial substituent, such as a methyl or methylene group, the change in the interaction energies is no longer negligible.

The effect is greatest when a substituent is attached to one of the carbon atoms which form the vertex of the dihedral angle, *i. e.* attached to C-2 or C-3 in the case of the angle C(1)-C(2)-C(3)-C(4). Opening of the dihedral angle then causes an increase in the energy of interaction, while closing causes a decrease.

b) Polycyclic Compounds

If several rings are fused together as in the steroids, additional interactions arise, depending on the structural elements of the rings and on the type of ring fusion *(cis* or *trans)*. The polycyclic skeleton is fairly rigid, *i. e.* the fusion of the rings results in a mutual interdependence of all steric and conformational effects. Any analysis of the behavior of polycyclic compounds must take into account the transmission of steric and conformational interactions over the entire structure ("conformational transmission" [9]) and should not overlook the stability of the *cis*- or *trans*-fusion of the rings.

Bucourt's analysis [7, 8] of conformational deformations on the basis of changes in the dihedral angles permits to study how deformations are transmitted between two *ortho*-fused rings. Consider two rings R_1 and R_2 (Scheme 1) with a common bond. If the dihedral angle about



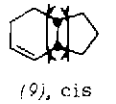
Scheme 1. Behavior of the dihedral angle about the common bond of two *cis*- or *trans*-fused rings R_1 and R_2. In the lower figures the upper figures are viewed along their axes (C-1)—(C-2). The arrow ↔ denotes opening, and › ‹ denotes closing of the dihedral angle.

the common bond is deformed in R_1, the dihedral angle in R_2 also suffers a deformation of the same magnitude. The two deformations have the same sign when the rings are *cis*-fused and opposite signs when the rings are *trans*-fused. In other words, if the dihedral angle about the common bond of two *cis*-fused rings opens in one of the rings, it will also open in the other. If the rings are *trans*-fused, on the other hand, opening of the angle in one ring results in closing of the corresponding angle in the other.

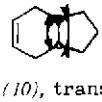
[9] *D. H. R. Barton, A. J. Head*, and *P. J. May*, J. chem. Soc. (London) *1957*, 935.

α) *Tetrahydroindanes*

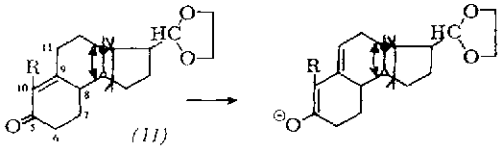
In the tetrahydroindanes *(9)* and *(10)* the deformations at the common bond, which are produced by the five-membered ring and the double bond, lead to *cis*-fusion in *(9)* and to *trans*-fusion in *(10)*. The structures *9* and *10* are the most stable, both theoretically and experimentally. This could explain, for example, the observation that alkylation on C-10 of the tricyclic C/D *trans*-compound *(11)* does not require preliminary blocking of position 6, although this is necessary if ring D is six-membered [10].



(9), cis



(10), trans

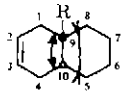


(11)

β) *Octalins*

The Δ^2- and Δ^3-isomers *(12)* and *(13)* of *trans*-octalin with no substituent on C-9 (R = H) exhibit practically no difference in stability, since there are no axial substituents other than hydrogen. A marked difference is observed, on the other hand, if C-9 carries an angular methyl group ($R = CH_3$). Analysis by *Bucourt*'s method shows that the steric pressure exerted by the methyl group on the axial hydrogen atoms of ring B (H-atoms on C-5 and C-7) is greater in the presence of a 3,4-double bond *(12)* than with a 2,3-double bond *(13)*. Thus when $R = CH_3$, *(13)* is more stable than *(12)*.

(12)



(13)

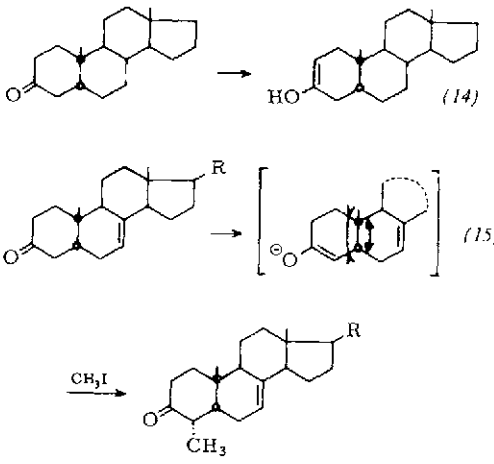
These facts are in excellent agreement with *Corey* and *Sneen*'s theory [5] and with *Djerassi*'s observation [11] that for steric reasons 3-oxo-A/B-*trans* steroids preferentially form Δ^2-enols *(14)*. An additional 7,8-double bond, on the other hand, leads to the formation of a Δ^3-enol *(15)*, since only this structure is compatible with the deformation of the dihedral angle caused by the 7,8-double bond [12].

The fact that a 3,4-double bond in *cis*-octalin *(17)* is more stable than a 2,3-double bond *(16)* is also explained by a decrease in the steric pressure. This decrease is greater for removal of the axial hydrogen atom on C-4 [which interacts with the axial hydrogens on C-6 and C-8, cf. *(19)*] than for removal of the axial hydrogen on C-2 (which interacts only with the axial hydrogen on C-8). However, a conformational effect also contributes

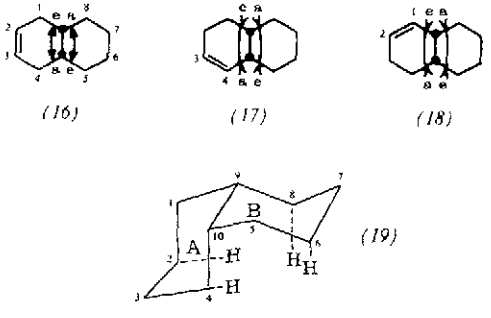
[10] *L. B. Barkley, W. S. Knowles, H. Raffelson*, and *Q. E. Thompson*, J. Amer. chem. Soc. *78*, 4111 (1956).

[11] *B. Berkoz, E. P. Chavez*, and *C. Djerassi*, J. chem. Soc. (London) *1962*, 1323.

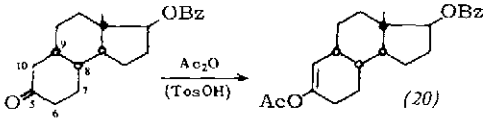
[12] *Y. Mazur* and *F. Sondheimer*, J. Amer. chem. Soc. *80*, 6296 (1958).



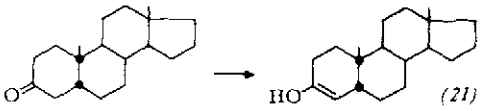
to the lower stability of the 2,3-double bond: in ring B this double bond causes opening of the dihedral angle at the ring junction, and so increases the interactions between the C-4 methylene group [C-4 is axial with respect to ring B, cf. *(19)*] and the two axial hydrogen atoms on C-6 and C-8. For the same reason, the 2,3-double bond *(16)* should be less stable than a 1,2-double bond *(18)*: by closing the dihedral angle at the ring junction in ring B, a 1,2-double bond reduces the interactions between the C-4 methylene group and the axial hydrogen atoms on C-6 and C-8. Thus the difference in the stabilities of the structures *(16)* and *(18)* is entirely due to the conformational effect of ring B, and the stabilities of the three compounds decrease in the order *(17)* > *(18)* > *(16)*. It should be pointed out, however, that the difference in stability between *(17)* and *(18)* becomes appreciable only when the *cis*-octalin is part of a polycyclic system which prevents conversion to the other conformation.



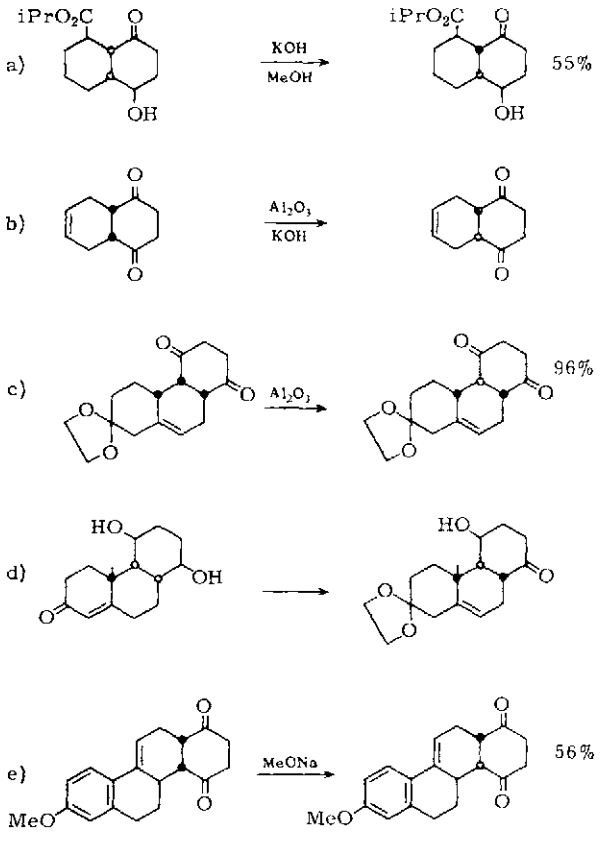
The difference in the stabilities of structures *(16)* and *(18)* manifests itself in the acetylation of 17 β-benzoyloxy-5-oxo-des-A-8α-estrane, which leads exclusively to the $\Delta^{5(10)}$-enol acetate *(20)* [13].



The competition between structures *(16)* and *(17)* may be compared to the enolization of the 3-oxo-A/B-*cis* steroids, in which the angular methyl group (which is axial with respect to ring B) reinforces the conformational effect. These 3-oxo steroids form Δ^4-enols *(21)* in preference to Δ^2-enols.



It is not possible in the present paper to review the whole of our knowledge regarding the relative stabilities of polycyclic systems (cf. [14]). We shall therefore confine ourselves to a few examples which show that differences in stability arising from the ring fusion in a polycyclic system have been utilized in the total synthesis of steroids to effect the epimerization of asymmetric centers adjacent to carbonyl functions. Thus the greater stability of the *trans*-1-decalone and the *trans*-1,4-dioxo-$\Delta^{6(7)}$-octahydronaphthalene made possible the inversions shown in Equations (a) to (e) [15–19].



In his synthesis of epiandrosterone [20, 21] from hydrochrysene, *Johnson* made use of the stability of the *trans-anti-trans* system *(22)* for the isomerization at C-13. Owing to the greater stability of the 2,3-double bond in *trans*-octalins (cf.

[13] *G. Nominé* and *R. Bucourt*, unpublished work.

[14] *E. L. Eliel*: Stereochemistry of Carbon Compounds. McGraw-Hill, New York 1962.

[15] *J. O. Jilek, B. Kakáč*, and *M. Protiva*, Coll. czech. chem. Commun. *256*, 2229 (1961).

[16] *I.N.Nazarov* and *L.D.Bergelson*, Izv. Akad. Nauk U.S.S.R., Otdel. khim. Nauk *1959*, 1961; Chem. Abstr. *55*, 10980 (1960).

[17] *K. K. Pivnitskii* and *I. V. Torgov*, Izv. Akad. Nauk U.S.S.R., Otdel. khim. Nauk *1961*, 1080; Chem. Abstr. *55*, 27238 (1960).

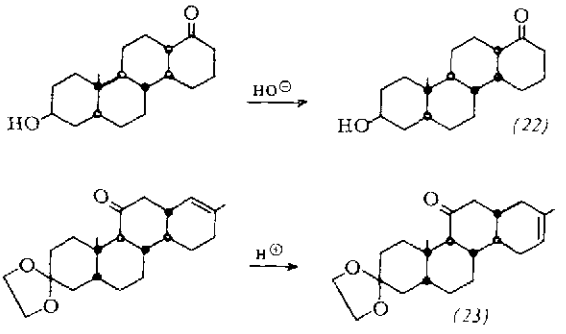
[18] *G. I. Poos, G. E. Arth, R. E. Beyler*, and *L. H. Sarett*, J. Amer. chem. Soc. *75*, 422 (1953).

[19] *G. P. Verkholetova* and *I. V. Torgov*, Izv. Akad. Nauk U.S.S.R., Otdel. khim. Nauk *1962*, 861.

[20] *W. S. Johnson, B. Bannister*, and *R. Pappo*, J. Amer. chem. Soc. *78*, 6331 (1956).

[21] *J. E. Cole, W. S. Johnson, P. A. Robins*, and *J. Walker*, J. chem. Soc. (London) *1962*, 244.

p. 193), it was possible to isomerize a 17,17a- to a 16,17-double bond *(23)* [22].



2. Attack at Trigonal Carbon Atoms

In steroid chemistry, asymmetric centers are generally formed by additions to carbonyl groups or olefinic double bonds and by attack on enol functions, *i. e.* by reactions with unsaturated groups containing one or more trigonal carbon atoms. They result in the conversion of trigonal sp^2 carbon to the tetragonal sp^3 state. Owing to the unsaturated character of these groups and the fact that they form part of a six-membered ring structure, these transitions depend on the following steric factors:

α) perpendicularity of the attack,

β) accessibility of the reaction center,

γ) energy of the intermediate states.

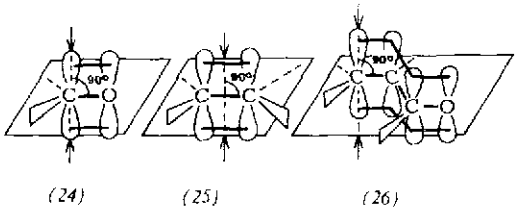
a) Steric Factors

α) *Perpendicularity of the Attack*

Any transformation which permits delocalization of electrons is favored by the gain in energy associated with delocalization. Application of this fact to the transition state of a reaction leads to the principle of maximum overlap of reacting orbitals. According to this principle, a reagent attacks an unsaturated function in such a way as to give the maximum possible overlap between the reacting orbital of the reagent and the π-orbital of the unsaturated function [23]. The electron density of the π-orbital is greatest in the direction perpendicular to the plane which contains the atoms involved in the double bond. The reactant must therefore approach the reaction center from this direction. If the reaction is reversed, the reactant will depart in the same direction, in accordance with the principle of microreversibility.

Toromanoff [24,25], in his contribution to our investigations, stressed that the stereoelectronic principle of perpendicular attack and departure is a very general one and is applicable to a wide variety of unsaturated groups: carbonyl functions *(24)*, olefinic and enolic double bonds *(25)*, α,β-unsaturated carbonyl functions *(26)*, allylic and homoallylic structures, *etc.*

The principle of perpendicular attack and departure is referred to as a stereoelectronic principle [23], since it describes both the electronic (delocalization of the electrons) and steric (orthogonality) features of the reaction. It stipulates a certain orientation of the attacking species



(24) *(25)* *(26)*

as the latter approaches the substrate, and so introduces steric limitations which define the accessibility of the reaction center. It also places restrictions on the geometry of the transition state, which will be discussed later (see Section γ).

β) *Accessibility of the Reaction Center*

The reactant may approach the plane containing the atoms involved in the double bond perpendicularly either from above or form below. Which side is preferred depends on the accessibility, *i. e.* on steric and polar peculiarities of both the cyclohexane structure and the reactant. Steric hindrance by the cyclohexane structure may arise from various causes, an important factor being the presence of axial substituents in the *meta* position relative to the attacked carbon atom.

The concept of accessibility is extremely important. It was developed by *Dauben* [26] under the name "steric approach control" for attack at ring carbonyl groups, and has subsequently been applied or criticized by numerous authors [27–33]. In steroid chemistry, the reaction of carbonyl or enol functions in cyclohexane systems may be greatly influenced by the accessibility of these groups. It should be noted that the accessibility of the reaction center favors the formation of the kinetically controlled product, and can therefore have a decisive effect on the stereochemical result of a reaction only under non-equilibrating conditions.

γ) *Energy of Intermediate States*

The steric course of a reaction also depends on thermodynamic factors, *i. e.* on the energies of the intermediate states through which the ring passes in the course of the reaction. One of these states, namely the transition state, determines the energy barrier which the system must surmount for the reaction to take place. The energy of a transition state is governed primarily by the structures of

[22] *L. Velluz, G. Amiard, R. Heymès,* and *B. Goffinet,* Bull. Soc. Chim. France *1961*, 2166.

[23] *E. J. Corey* and *R. A. Sneen,* J. Amer. chem. Soc. *78*, 6269 (1956).

[24] *E. Toromanoff,* Bull. Soc. Chim. France *1962*, 1190.

[25] *E. Toromanoff,* Bull. Soc. Chim. France *1962*, 708.

[26] *W. G. Dauben, G. J. Fonken,* and *D. S. Noyce,* J. Amer. chem. Soc. *78*, 2579 (1956).

[27] *J. Valls* and *E. Toromanoff,* Bull. Soc. Chim. France *1961*, 758.

[28] *H. E. Zimmerman,* J. Amer. chem. Soc. *78*, 1168 (1956).

[29] *H. E. Zimmerman* and *T. W. Cutshall,* J. Amer. chem. Soc. *81*, 4305 (1959).

[30] *H. E. Zimmerman* and *A. Mais,* J. Amer. chem. Soc. *81*, 3644 (1959).

[31] *H. E. Zimmerman,* J. org. Chemistry *20*, 549 (1955).

[32] *A. V. Kamernitzky* and *A. A. Akhrem,* Tetrahedron *18*, 705 (1962).

[33] *D. H. R. Barton,* J. chem. Soc. (London) *1953*, 1027.

the reactants. The transition state may resemble either the starting material (where the carbon atom under attack is trigonal in reactions involving doubly bonded C-atoms) or the end product (where the carbon atom under attack is tetragonal). It is practically impossible, however, at least in the case of cyclohexanes, to describe accurately the degree of rehybridization of the attacked carbon atom in the transition state.

In keto-enol reactions which have been studied in detail, both theoretical [34, 35] and experimental [36, 37] findings indicate that the transition states closely resemble the enol forms. For other reactions of enols or enoxides, it is assumed, explicitly or implicitly, that the transition state lies closer to the enol form than to the keto form. However, it is not purely enolic, *i. e.* the carbon atom under attack already possesses some tetragonal character. The extent of this rehybridization depends on several factors, including the nature of the carbonyl derivative and the electrophilic character of the reagent attacking the enol [23].

The course of the *C*-alkylation of cyclohexenoxides is the subject of controversy. From theoretical considerations, it seems that the transition state should be similar to the ketone formed (tetragonal carbon) [38–40], whereas experimental results are generally interpreted as indicating a similarity between the transition state and the enolic starting material (trigonal carbon). We have therefore attempted to analyse transformations of trigonal carbon atoms by assuming that the intermediate states are rings in which the reacting carbon atom already has appreciable tetragonal character, *i.e.* in which the end products are preformed. (Naturally these intermediate states do not necessarily correspond to true transition states.) The energy of an intermediate state is governed by geometrical factors. These, in turn, are the result of stereoelectronic, steric, conformational, and polar factors, *i.e.* of specific properties of the ring which is being attacked. The reaction will proceed only if, during its course, the ring can assume a conformation which satisfies the various structural requirements. The direction of attachment of the reagent will correspond to this conformation.

These considerations by no means disregard the energies of the more trigonal intermediate states; in fact, the analysis of the accessibility is nothing else than the investigation of the factors which determine the energy levels of more trigonal intermediate states.

It can be seen, therefore, that in analysing the stereochemistry of an attack the two parameters "accessibility" and "energy of the tetragonal intermediate states" must be taken into account. Each of these parameters defines a steric orientation of the substituent being introduced. If both orientations are similar, or even equal, then the stereochemistry of the attack is unambiguously defined. If, on the other hand, they are different, it is necessary to estimate the importance of mutually opposing effects in order to establish the stereochemistry of the reaction.

[34] *C. G. Swain* and *E. R. Thornton*, J. Amer. chem. Soc. *84*, 817 (1962).

[35] *J. L. Kurz*, J. Amer. chem. Soc. *85*, 987 (1963).

[36] *C. G. Swain* and *E. R. Thornton*, J. Amer. chem. Soc. *83*, 3884 (1961).

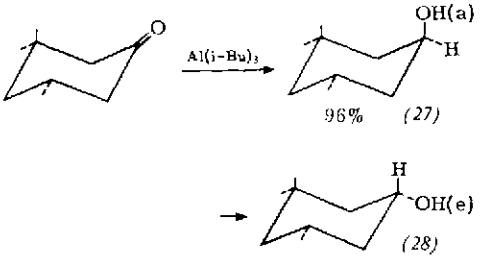
[37] *C. G. Swain, E. C. Stiwers, J. F. Reuwer*, and *L. J. Schaad*, J. Amer. chem. Soc. *80*, 5885 (1958).

[38] *W. S. Johnson, D. S. Allen, R. R. Hindersinn, G. N. Sausen*, and *R. Pappo*, J. Amer. chem. Soc. *84*, 2181 (1962).

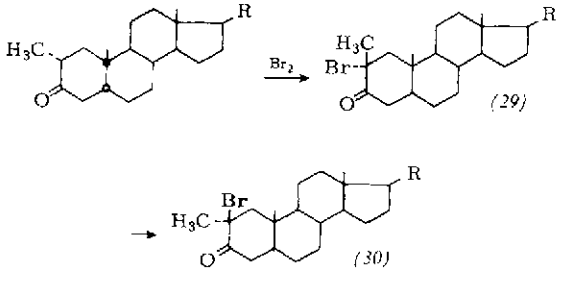
[39] *D. S. Allen*, Ph. D. Thesis, University of Wisconsin 1960, University Microfilm Mic 60–5813.

[40] *J. H. Fried, G. E. Warth*, and *L. H. Sarett*, J. Amer. chem. Soc. *82*, 1684 (1960).

The various factors influencing the stereochemistry of attachment to a trigonal carbon atom may cause the substituent introduced to assume a position which is not the most stable one thermodynamically. The attachment may then lead initially to an unstable product, which under equilibrating conditions is converted to a thermodynamically more stable isomer. This observation can be made in the case of reversible non-equilibrating reactions, in which the substituent is intially fixed, but then detaches itself from the molecule, to form another bond which yields a stable isomer. For example, the kinetically controlled reduction of 3,3,5-trimethylcyclohexanone leads to an axial alcohol *(27)*, which in the presence of excess ketone is converted to the thermodynamically more stable equatorial isomer *(28)* [41].

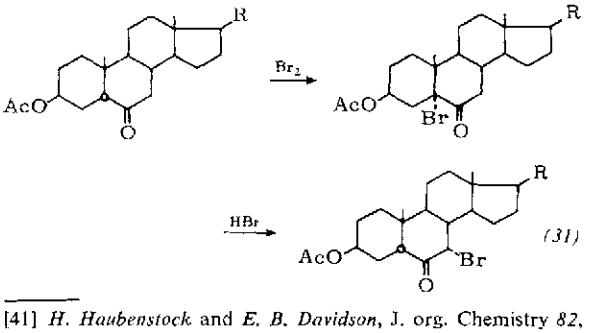


The bromination of a 2-methyl-3-oxo steroid first yields a 2α-bromide *(29)*, which then isomerizes to the 2β-bromide *(30)* [42, 43].



These two examples illustrate the effects of accessibility and of thermodynamic stability. The thermodynamic factor plays a role only in reversible reactions under equilibrating conditions.

Another example is the migration of a 5α-halogen to the 7α-position in 6-oxo steroids *(31)* [44].



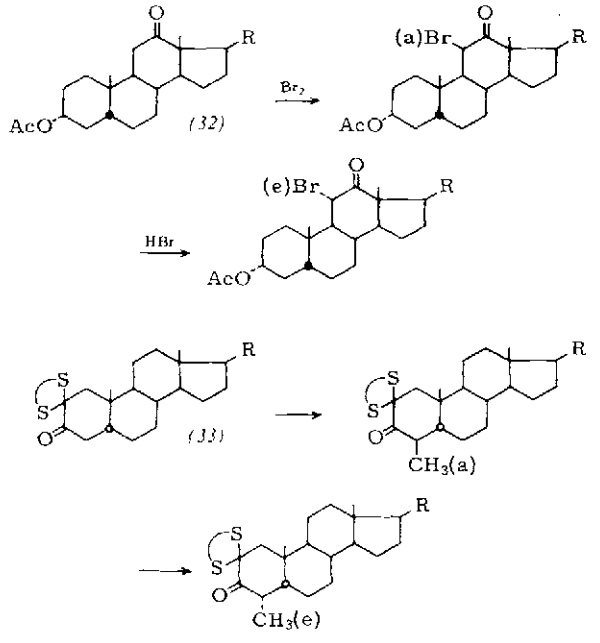
[41] *H. Haubenstock* and *E. B. Davidson*, J. org. Chemistry *82*, 2772 (1963).

[42] *C. Djerassi, N. Finch, R. C. Cookson*, and *C. W. Bird*, J. Amer. chem. Soc. *82*, 5488 (1962).

[43] *R. Vilotti, H. J. Ringold*, and *C. Djerassi*, J. Amer. chem. Soc. *82*, 5693 (1960).

[44] *E. J. Corey*, J. Amer. chem. Soc. *76*, 175 (1954).

Equilibrations may also result from epimerization *via* enol functions, *e. g.* in the bromination of 12-oxo steroids *(32)* [44] or in the methylation of 3-oxo steroids *(33)* [45].

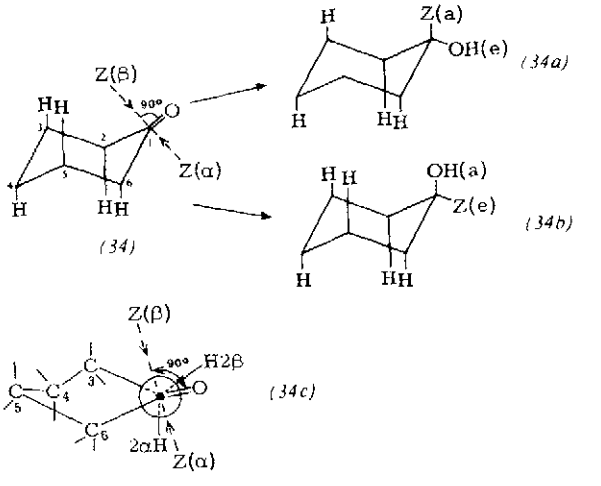


b) Application to Specific Functions

α) *Ketones* ($sp^2 \rightarrow sp^3$)

When applied to reactions of the carbonyl group [24], the principle of perpendicular attack expresses *Cram*'s rule in electronic terms. This rule was originally derived for linear carbonyl derivatives from purely steric considerations [46, 47].

In the case of a chair cyclohexanone *(34)*, perpendicular attack of a reagent Z can take place from either side of the plane C(2)-C(1)-C(6). Accordingly, the resulting hydroxyl group will occupy either an equatorial [β-attack *(34a)*] or an axial [α-attack *(34b)*] position.

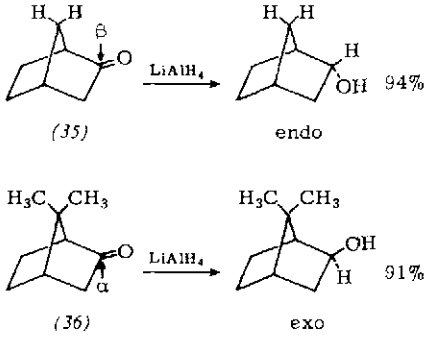


[45] *J. L. Beton, T. G. Halsall, E. R. H. Jones*, and *P. C. Phillips*, J. chem. Soc. (London) *1957*, 753.

[46] *D. J. Cram* and *F. A. A. Elhafez*, J. Amer. chem. Soc. *74*, 5828 (1952).

[47] *J. L. Mateos* and *D. J. Cram*, J. Amer. chem. Soc. *81*, 2756 (1959).

The side from which attack takes place depends primarily on the accessibility of the carbonyl group [cf. formula *(34c)* in which *(34)* is viewed along the axis (C-1)-(C-2)]. Reactions of a carbonyl which is shielded on one side have been studied by *Dauben* [26]. For example, the stereochemistry of the reduction of bicyclo[2,2,1]heptanone *(35)* with complex hydrides is reversed by the introduction of two methyl groups at C-7 *(36)*.



The accessibility of a carbonyl group is particularly affected by axial substituents on the two β-C-atoms [26]. Thus the reduction of 11-oxo steroids with complex hydrides leads exclusively to the 11β-alcohols, *i. e.* attack from the β-side is prevented by the two angular 1,3-diaxial methyl groups. The introduction of a 13β-methyl group into a 17-oxo steroid also causes formation of the 17β-alcohol on reduction.

However, the accessibility of the carbonyl group also depends on the reactant used, and in particular on its bulk, which is often difficult to define owing to solvation [32, 49].

In addition, carbonyl reactions of the type $sp^2 \rightarrow sp^3$ are controlled by the nature of the transition states, about which little is known at present. According to *Dauben*, the transition states in the reduction of cyclohexanones with complex hydrides are assumed to have a hybridization between sp^2 and sp^3. The partly tetragonal character of the carbon atom under attack brings into play those factors which determine the stability of the final product. This leads to a rule formulated by *Barton* [50], according to which an unhindered ketone will yield the thermodynamically more stable epimer (*Dauben*'s "product development control").

This view has been criticized in particular by *Kamernitzky* and *Akhrem* [32]. According to these authors, reactions of the carbonyl group are controlled not only by the accessibility but also by a polar orientation factor, which leads to axial attachment of the reactant. This attachment is claimed to be much more strongly influenced by the kinetics of the reaction than by the thermodynamic stability of the product. *Kamernitzky* and *Akhrem* base their arguments on the relative volumes of the substituents. However, this theory is to be regarded with certain reservations, since the true volume of the hydroxyl functions, which may be solvated or complexed, is unknown [48].

This lack of accuracy is not the only complication in the problem of carbonyl reactions; there is also some uncertainty regarding the active part of the reactant which attacks the carbonyl group, and as to whether or not the reaction proceeds by a concerted mechanism. Further discussion of this subject [32, 51] is beyond the scope of the present paper.

[48] *O. H. Wheeler* and *J. L. Mateos*, Canad. J. Chem. *36*, 1431 (1958).

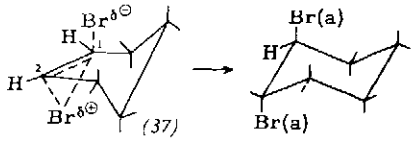
[49] *D. M. S. Wheeler* and *J. W. Huffman*, Experientia *16*, 516 (1960).

[50] *D. H. R. Barton*, J. chem. Soc. (London) *1953*, 1027.

[51] *H. J. E. Loewenthal*, Tetrahedron 6, 269 (1959).

β) *Olefinic Double Bonds* (2 $sp^2 \rightarrow 2\ sp^3$)

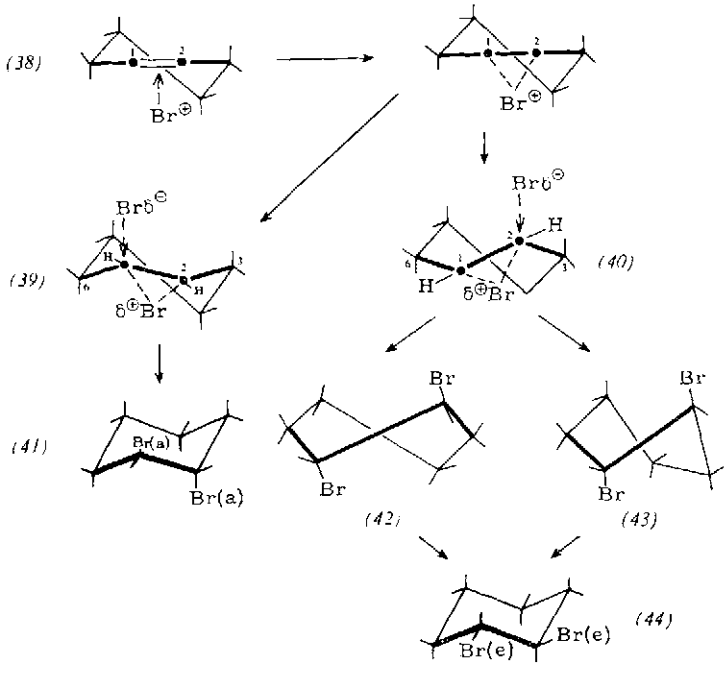
Perpendicular attack of an electrophilic reagent (*e. g.* Br_2) on a cyclic olefin leads to *trans*-diaxial attachment of the new substituents [52, 53]. The electrophilic portion (Br^+) and the anion (Br^-) must lie in the plane of maximum electron density and on opposite sides of the double bond. This is illustrated by the bromination of a cyclohexane in the half-chair form *(37)*.



(37)

The intermediate formation of a bridged bromonium ion demonstrates the analogy between the *trans*-diaxial addition and the diaxial cleavage of epoxides, which forms the basis of *Fürst* and *Plattner*'s rule.

Whether the electrophilic portion (Br^+) attacks from the β- or the α-side is mainly determined by the accessibility of the double bond. In the absence of electronic effects, the anionoid portion of the reactant (Br^-) may become attached to either of the two doubly bonded carbon atoms. To satisfy the principle of perpendicular attack, and in accordance with an analysis applied to the half-chair form *(38)* by *Valls* and *Toromanoff* [27], these two modes of attachment may be regarded as "pre-chair" *(39)* and "pre-twist" *(40)* forms [*]. Chair *(41)* and twist *(42)* conformations are already preformed in these intermediate states, and under certain circumstances the twist form can be converted to the chair form *(44)*.



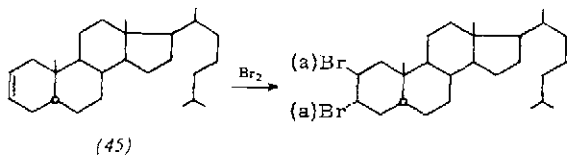
[52] *G. H. Alt* and *D. H. R. Barton*, J. chem. Soc. (London) *1954*, 4234.

[53] *D. H. R. Barton* and *R. C. Cookson*, Quart. Reviews (Chem. Soc. London) *10*, 44 (1956).

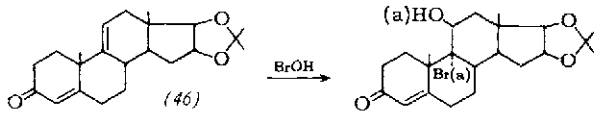
[*] The intermediate state *(40)*, which we originally called the "pre-boat" form [27], is in fact a flexible "pre-twist" conformation. Analysis of the dihedral angles shows that it is a "twisted" conformation with the axis of symmetry passing through the C-3 and C-6 vertices, which leads to the least possible distortion of the original structure.

Whether the Br^- will become attached to C-1 or to C-2 will depend on the relative energies of the two intermediate states. In general, energy factors favor the "pre-chair" form in preference to the "pre-twist" form.

Although a few exceptions are known (particulary in the case of the hydrogen halides), the principle of *trans*-diaxial addition has been shown to be of wide applicability particularly in the steroid series, both with symmetrical (Br_2) and with unsymmetrical (HOBr) reagents, as is shown by examples *(45)* and *(46)*.



(45)



(46)

In the addition of HOBr to *(46)*, accessibility permits attack of the electrophilic Br^+ ion only from the α-side. Attachment of this ion in the 11α-position would require a flexible intermediate state of very high energy; attachment in the 9α-position, on the other hand, passes through the much more favorable "pre-chair" form. It is interesting to note that the 9α-Br,10β-OH addition of HOBr proceeds in opposition to the inductive and electromeric effects (Markownikoff's rule).

In addition to accessibility, a polar substituent in the neighborhood of the double bond can determine the direction of attack. This is true for reactions of carbenes with cyclopentenols [54] and cyclohexenols [55], and for the epoxidation of cyclohexenes, which has been investigated by *Henbest* [56] and *Takeda* [57]. According to these authors, hydroxyl or nitrile groups can affect the stereochemistry of epoxydation in two ways: by binding the reactant in the transition state, or simply by dipole interactions.

One particular aspect of accessibility manifests itself in the catalytic hydrogenation of cyclohexene derivatives, which corresponds to the *cis*-addition of two hydrogen atoms. The molecule must be fixed at the surface of the catalyst with the least hindered side of its double bond. The steric orientation of the two hydrogen atoms to be added is then governed principally by 1,3-diaxial interactions in the unsaturated molecule. *Hadler* [58] has referred to these as "primary steric factors"; they are thought to be responsible for the stereochemistry of the catalytic hydrogenation of Δ^4- and Δ^5-steroids.

Here again, the experimental results cannot be explained by differences in accessibility alone, but intermediate states with almost tetrahedral carbon atoms must also be considered. For example, hydrogenation of the 1-methyl derivatives of *(47)* and *(48)* proceeds three times as slow as hydrogenation of the unsubstituted compounds, al-

[54] *S. Winstein* and *J. Sonnenberg*, J. Amer. chem. Soc. *83*, 3235 (1961).

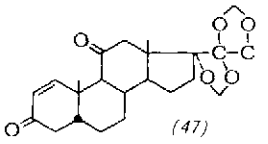
[55] *W. G. Dauben* and *G. H. Berezin*, J. Amer. chem. Soc. *85*, 468 (1963).

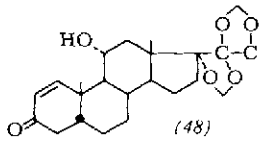
[56] *H. B. Henbest*, Proc. chem. Soc. (London) *1963*, 159.

[57] *K. Takeda*, *K. Hamamoto*, *K. Sasaki*, *N. Maezono*, and *A. Murabayashi*, Steroids *2*, 27 (1963).

[58] *H. I. Hadler*, Experientia *11*, 175 (1955).

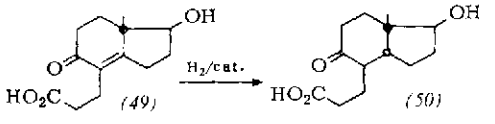
though the extra substituent does not alter the accessibility of the β-side [59].

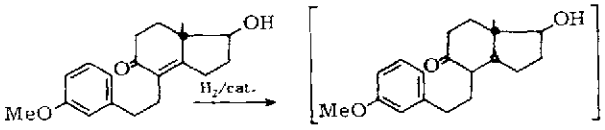

(47)


(48)

Polar substituents can also exert a directing influence on catalytic hydrogenation [60]. Catalytic *cis*-hydrogenations are extremely important in the total synthesis of steroids for the formation of asymmetric centers, particularly that in position 14 (cf. p. 195) [51]. $\Delta^{14(15)}$-Steroids are mainly hydrogenated from the α-side, since the β-side is shielded by the C-18 methyl group. The yield is greater in the hydrogenation of a 17β-hydroxy-$\Delta^{14(15)}$-steroid than for a 17-ketone [61] (cf. p. 196).

A difficult stereochemical problem is encountered in the catalytic hydrogenation of bicyclic intermediates with an 8,14-double bond (cf. p. 195). *Velluz*, *Nomine* et al. [62] solved this problem by using a bicyclic derivative *(49)* with an alkyl side-chain on C-8. They obtained mainly the product of α-hydrogenation, *i. e.* the *trans*-hydrindane structure *(5)*. An analogous reaction [*(51)* → *(52)*] has been described by other authors [136].


(49) (50)

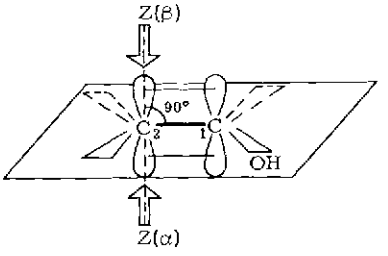

(51) (52)

γ) *Enol Functions* (2 $sp^2 \rightarrow sp^3 + sp^2$)

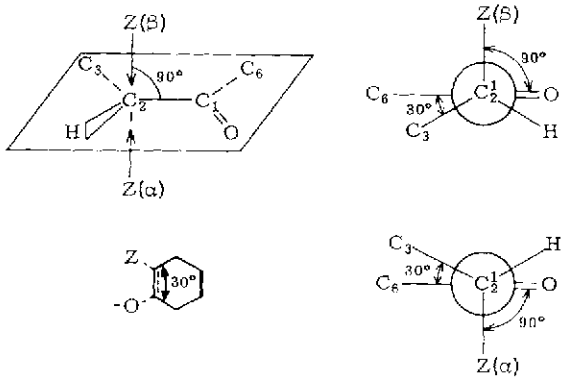
Reactions, such as halogenation or alkylation of a carbon atom adjacent to a carbonyl group, require preliminary enolization, and so correspond to reactions with enol functions. They are greatly different from the reactions of cyclohexenes in which attack can take place on either of the doubly bonded carbon atoms. In the case of enols, the positive electromeric effect (+E) directs the reaction completely towards the carbon atom which does not carry the OH group *(53)*.

Viewed from another angle, addition to an olefin requires the conversion of two trigonal into two tetragonal carbon atoms (2 $sp^2 \rightarrow 2\ sp^3$), whereas attack at an enol function requires rehybridization of only one trigonal carbon atom, the other remaining trigonal as part of the carbonyl group (2 $sp^2 \rightarrow sp^3 + sp^2$). As a result, the stereoelectronic factor becomes particularly important in reactions involving cyclohexenols.

The attacking reagent obeys the principle of maximum overlap of the participating orbitals by perpendicularly approaching the plane of the atoms which constitute the enol function *(53)*.


(53)

The steric course of the reaction is largely determined by the accessibility of the molecule from the α- and from the β-side. Another important factor is the energy of the transition state. For reasons mentioned on p. 186, we shall assume that the transition state resembles the ketonic product ($sp^3 + sp^2$). In an intermediate state of this type, the bond which is being formed is perpendicular to the plane defined by the carbonyl function and the adjacent C-atoms. Consequently the dihedral angle O-C(1)-C(2)-Z must be 90° and the dihedral angle C(6)-C(1)-C(2)-C(3) becomes 30° (Scheme 2). Thus the stereoelectronic factor leads to a new restriction on the geometry of the transition state, and may strongly affect the steric course of the reaction [*].



Scheme 2. Attack of a reagent Z at a carbon atom adjacent to a carbonyl group. The figure on the upper right shows the attack from the β-side, the figure on the lower right that from the α-side. In both cases the molecule is viewed along its (C-2)–(C-1) axis.

In accordance with the principle of micro-reversibility, the discussion of the attack of Z also applies to the reverse process.

It follows directly from the principle of perpendicular attack that attack and departure will be axial in the chair form of cyclohexanone: the geometry of a chair cyclohexanone *(54)*, as viewed along the C(1)-C(2) bond *(55)*, is defined by the dihedral angles O-C(1)-C(2)-H(2β) = 117°, O-C(1)-C(2)-H(2α) = 3°, and C(6)-C(1)-C(2)-

[59] *D. Bertin* and *J. Perronnet*, unpublished work.

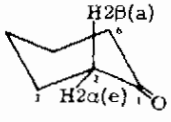
[60] *T. J. Howard*, Chem. and Ind. *1963*, 1899.

[61] *D. K. Banerjee*, *S. Chatterjee*, *C. N. Pillai*, and *M. V. Bhatt*, J. Amer. chem. Soc. *78*, 3769 (1956).

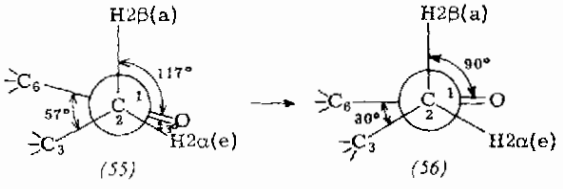
[62] *L. Velluz*, *G. Nominé*, *G. Amiard*, *V. Torelli*, and *J. Cérede*, C. R. hebd. Séances Acad. Sci. *257*, 3086 (1963); see also *P. Wieland*, *H. Überwasser*, *G. Anner*, and *K. Miescher*, Helv. chim. Acta *36*, 376, 646, 1231 (1953).

[*] We have assumed, for simplicity, that while the reactant is being attached to C-2, it is not also bonded to the oxygen of the carbonyl group which is being formed; in fact, however, both steps may proceed simultaneously [24].

C(3) – 57° [*]. Now enolization of the carbonyl function requires a hydrogen atom at C-2 to assume a position perpendicular to the plane C(6)-C(1)-C(2). This change must take place with the least possible distortion of the cyclohexane structure. It is obvious [*(55)* → *(56)*] that the axial 2β-hydrogen atom can assume the perpendicular position (117° → 90°) more readily than the equatorial 2α-hydrogen (3° → 90°). The enol is therefore formed preferentially by migration of the 2β-hydrogen atom. In the reverse process (formation of the ketone), the proton becomes attached to C-2 of the enol in such a way that it finally occupies an axial (2β) position [23].



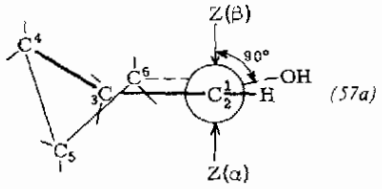
(54)



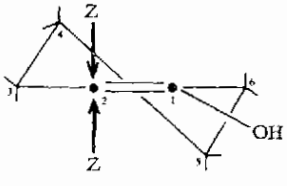
(55) *(56)*

This axial attachment, which is encountered in many reactions of enols (protonation, halogenation, alkylation), has been theoretically interpreted by *Corey*, and is in fact simply a result of the principle of perpendicular attack.

Generalization of the rule of axial attack [27] leads to two possible courses for the perpendicular attack on a cyclohexenol in the half-chair conformation *(57a, b)*. Attack from the β-side leads to a "pre-chair" intermediate, and then to a chair form with Z in an axial (2β) position. Attack from the α-side, on the other hand, gives a "pre-twist" conformation; this in turn yields a flexible ring, with Z in the axial (2a) position, which can finally go over to a chair form with an equatorial (2α) Z. In general, the "pre-chair" form (*i. e.* β-attack) is energetically more favorable than the "pre-twist" form (the formation of which requires greater deformation of the ring) [**].



(57a)



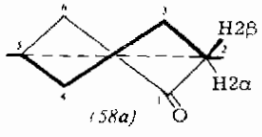
(57b)

[*] The geometry of cyclohexanone is reported to be very similar to that of cyclohexane [64].

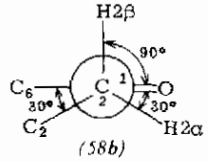
[**] Another interpretation assumes an axial α-attack on the half-boat form of the enol (whereas β-attack would have to occur on the half-chair form) [43].

It follows from the foregoing discussion that equatorial attacks are unlikely from the stereoelectronic standpoint and therefore need no longer be considered [42,43].

It must be emphasized that the rule of axial attack is valid only in the case of the chair form. The principle of perpendicular attack, on the other hand, is far more general and is valid for all possible forms of cyclohexane, including the flexible forms for which the term "axial orientation" may be meaningless. For example, in the twist form *(58a)* with C(2)-C(5) as the axis the 2β-hydrogen atom is in a position favorable for departure, *i. e.* it is perpendicular to the carbonyl group *(58b)*, while it forms an angle of only about 45° with the mean plane of the ring.



(58a)

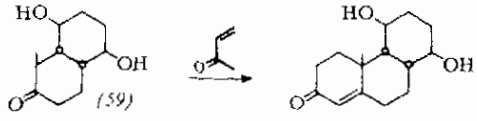


(58b)

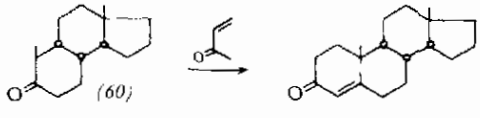
Thus, for conformational analysis of the intermediate states the principle of perpendicular attack is most important. The angle which has as its "hinge" the C-C bond involed in enolization is the corresponding dihedral angle (Scheme 2). The other dihedral angles then must be such as to minimize ring deformation. The potential energy of such a conformation will depend on the deformations of all the dihedral angles and on the steric interactions between atoms which are not directly linked together.

The following examples illustrate the effects of these factors on the stereochemical results of enol reactions:

1. If the accessibility of the enol function and the energy level of the intermediate state favor attack from the same side, the reaction will be highly stereoselective. A good example are the "folded", *i. e. cis*-fused, polycyclic structures *(59)* and *(60)*, which are particularly accessible



(59)



(60)

from the convex α-side. An alkylating agent may enter axially in to a "pre-chair" form, so leading to an intermediate state of low energy (as compared with the "pre-twist" form which would result from β-attack) [18,65,66].

A methyl group makes the "pre-twist" conformation more stable than the "pre-chair" form, and favors attack

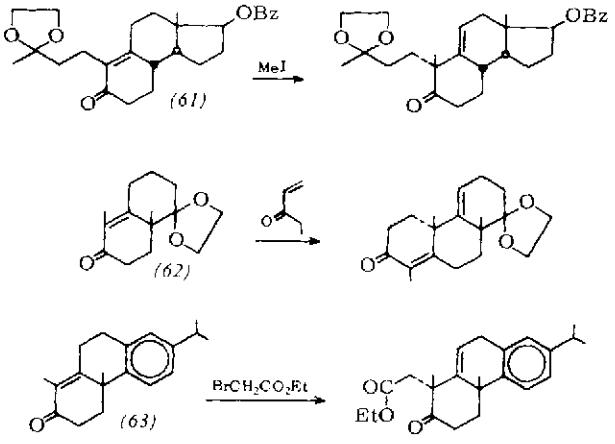
[63] *D. J. Crispin* and *J. S. Whitehurst*, Proc. chem. Soc. (London) *1962*, 356.

[64] *W. Moffit, R. B. Woodward, A. Moscowitz, W. Klyne*, and *C. Djerassi*, J. Amer. chem. Soc. *83*, 4013 (1961).

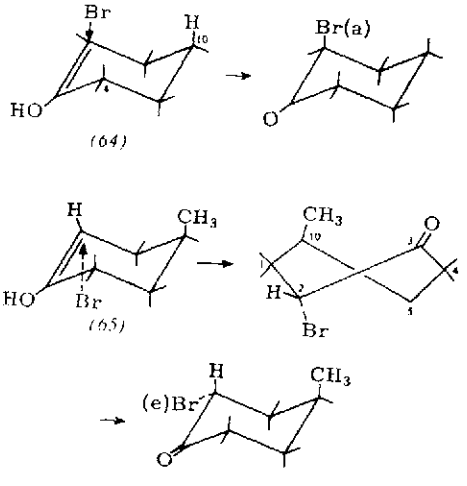
[65] *L. H. Sarett, G. E. Arth, R. M. Lukes, R. E. Beylor, G. I. Poos, W. F. Johns*, and *J. M. Constantin*, J. Amer. chem. Soc. *74*, 4974 (1952).

[66] *D. K. Banerjee, V. Paul*, and *S. K. Balasubramanian*, Tetrahedron Letters 1960, No. 12, p. 123.

from the remote side. Whereas on alkylation of *(61)* the main product results from β-attack ("pre-chair" intermediate) [67], an 8β-methyl group [compounds *(62)* and *(63)*, steroid numbering!] permits alkylation from the α-side ("pre-twist" intermediate) [68, 69]. This 8β-methyl group plays a double part: it favors approach from the α-side, and destabilizes the "pre-chair" intermediate resulting from β-attack.



2. If the accessibility of the enol function and the energy level of the intermediate state oppose each other, the product is frequently a mixture of epimers (unless one of the two factors predominates). Examples are found in the bromination of A/B-*trans*-3-oxo steroids: 19-nor derivatives *(64)* take up bromine in the 2β-position ("pre-chair" intermediate), although β-attack is hindered by the axial hydrogen atoms on C-4 and C-10. In *(65)*, on the other hand, β-attack is further hindered by the methyl group on C-10. The bromine cation must therefore approach from the α-side, leading *via* a "pre-twist" intermediate to a chair form with an equatorial 2α-bromine. It should be pointed out that the flexible intermediate can be isolated in the bromination of the 2-methyl derivative of *(65)* [42, 43].

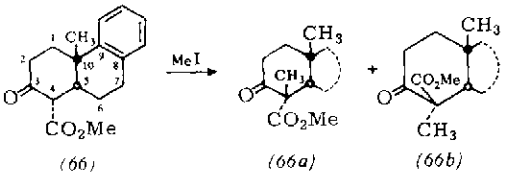


[67] *L. Velluz, G. Nominé,* and *J. Mathieu,* Angew. Chem. *72,* 725 (1960).

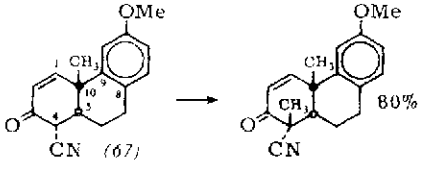
[68] *M. Brown,* Dissertation Abstracts *23,* 4107 (1963).

[69] *G. Stork* and *J. W. Schulenburg,* J. Amer. chem. Soc. *84,* 284 (1962).

Similar observations have been made in the alkylation of enoxides. Thus, methylation of the keto ester *(66)* yields a mixture of the epimeric 4-methyl derivatives *(66a)* and *(66b)* in the ratio 2.4:1 [70]. This result can be explained by considering the opposing effects of the angular 10β-methyl group (which favors accessibility of the α-side) and of the ester function on C-4 (which, owing to its eclipsed interaction with the methylene group on C-6, destabilizes the flexible conformations which would be compatible with the opening of the dihedral angle C(4)-C(5)-C(10)-C(1) caused by the 8,9-double bond).



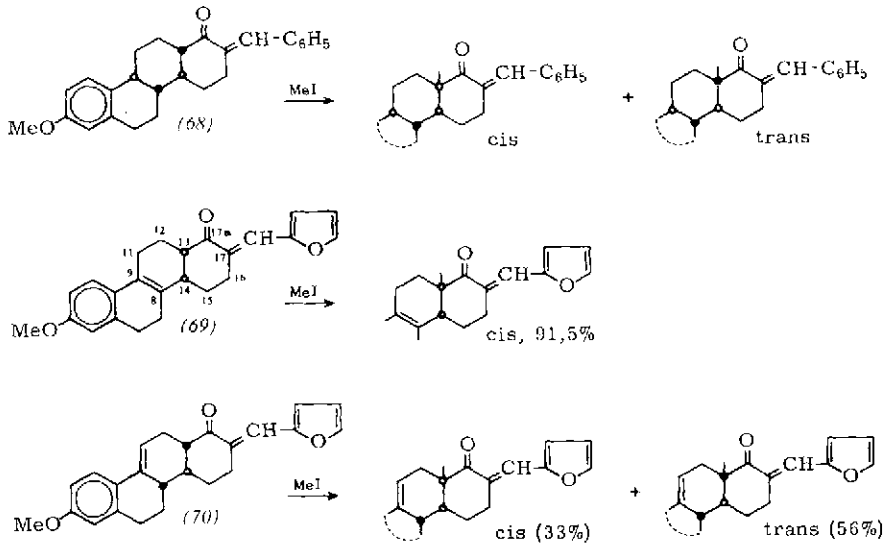
It is interesting to note that the analogous structure *(67)*, which contains a 1,2-double bond, gives only the 4β-methyl derivative, although here β-attack is more strongly hindered [71]. *Stork* [69] has pointed out that the 1,2-double bond in *(67)* is coplanar with the carbonyl function in position 3 only in the chair form of the ring, so that a "pre-chair" intermediate is favored. We believe that, in addition, the conformations resulting from α-attack would be incompatible with the opening of the dihedral angle C(4)-C(5)-C(10)-C(1) caused by the 8,9-double bond.



The above examples, particularly *(66)* and *(67)*, show the importance of the number of double bonds present in the molecule. They affect the dihedral angle at the ring junction and force the reacting ring to assume flexible forms in which the interactions of 1,3-diaxial substituents at the "ring hinge" are modified. A particularly good example of these effects is provided by the work of *Johnson* et al. While the alkylation of compound *(68)* yields a mixture of epimers in which the *cis*-isomer predominates (*cis*:*trans* = 3:1), the introduction of a double bond *(69)* in the *meta*-position relative to the junction dihedron leads to exclusive formation of the *cis*-isomer. After introduction of a double bond in the *para*-position *(70)*, on the other hand, the principal product is the *trans*-isomer.

These results cannot be explained simply by the effect of accessibility [21, 39]. Rather the influence of trigonal carbon atoms on the energy levels of the transition states must also be taken into account. Analysis by *Bucourt*'s method [8] (see p. 182) shows that, in the case of the hexahydronaphthalenes, *cis*-fusion is favored if the two dihedral angles of 0° occupy equivalent positions *(e.g. meta, meta)*. Consider compounds *(69)* and *(70)*: if the 17a-carbonyl function and the double bond at C-17 are

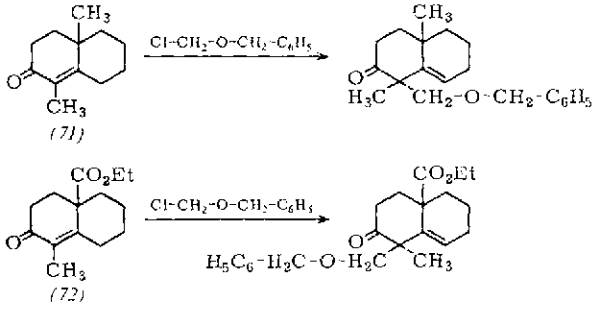
[70] *E. Wenkert* and *A. Tahara,* J. Amer. chem. Soc. *82,* 3229 (1960).



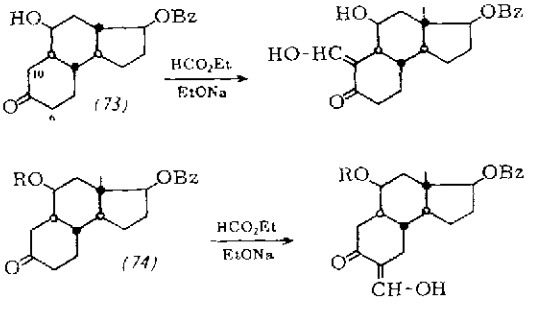
coplanar, the dihedral angles C(13)-C(17a)-C(17)-C(16) and C(14)-C(8)-C(9)-C(11), which are in *meta*-positions relative to the ring junction and which are 0° each, favor the *cis*-product, while in *(70)* the dehedral angles of 0°, *viz.* C(13)-C(17a)-C(17)-C(16) and C(8)-C(9)-C(11)-C(12), are in the *meta*- and *para*-positions, respectively, and thus favor the *trans*-isomer.

3. Finally, there are cases in which the accessibility requires attack from one side, while the energy level of the corresponding intermediate states is so high that the reaction cannot proceed [72, 73] or takes place at another site. This would explain, for example, the bromination of a 3-oxo-5β-methyl steroid at C-2 [40].

Polar factors frequently affect the approach of a reactant and/or the stability of an intermediate state. It has been suggested [74] that effects of this type may be caused by dipole pairing or by solvation of the nascent carbonium ion. In *(72)*, for example, the angular ethoxycarbonyl group reverses the stereochemistry of the alkylation of the enol *(71)* [75].



Similarly, an 11β-hydroxyl group directs the hydroxymethylation of the tricyclic compound *(73)* towards C-10, whereas the reaction occurs at C-6 in the absence or on blockage of the hydroxyl group [76].



II. Practical Considerations

One of the main difficulties in the total synthesis of steroids is the stereoselective introduction of centers of asymmetry by conversion of carbon atoms from the trigonal to the tetragonal state (alkylation of enoxides, hydrogenation of double bonds, epimerization of carbon atoms adjacent to carbonyl groups, *etc.*). In this paper, we shall deal only with the formation asymmetric centers in the angular positions 10 and 13, and in position 14.

a) Formation of a Center of Asymmetry in Positions 13 and 14

The stereoselective synthesis of the 13-alkyl-*trans*-hydrindane *(75)*, corresponding to rings C and D of a steroid, has long been a difficult problem. In fact, most attempts to synthesize *(75)* directly were defeated by the greater stability of the *cis*-hydrindane structure *(76)*.

(75), trans *(76)*, cis

[71] *M. E. Kuehne*, J. Amer. chem. Soc. *83*, 1492 (1961).

[72] *H. J. Ringold* and *G. Rosenkranz*, J. org. Chemistry *21*, 1333 (1956).

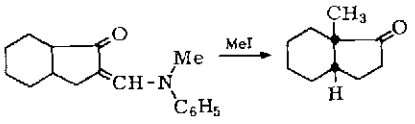
[73] *A. Bowers* and *H. J. Ringold*, J. Amer. chem. Soc. *81*, 424 (1959).

[74] *F. J. McQuillin* and *P. L. Simpson*, J. chem. Soc. (London) *1963*, 4726.

[75] *C. L. Graham*, *F. J. McQuillin*, and *P. L. Simpson*, Proc. chem. Soc. (London) *1963*, 136.

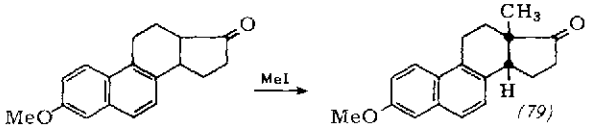
[76] *L. Velluz*, *R. Bucourt*, *M. Vignau*, *E. Toromanoff*, and *G. Nominé*, Liebigs Ann. Chem. *669*, 153 (1963).

One of the unsuccessful methods was the angular alkylation of hydrindane derivatives. This reaction, which in the case of compound *(77)* yields the cis-isomer *(78)*, had been tried



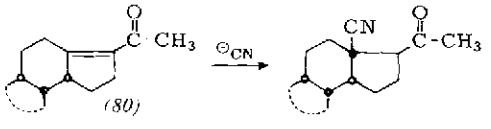
(77) *(78)*, cis

in the tetracyclic series as early as 1938 [77,78]. When applied to the methyl ether of 18-norequilenin (with the 16 position blocked), it gave the *cis*-derivative *(79)* [(±)-iso-equilenin].



(79)

The preferential formation of the *cis*-isomer renders difficult any synthesis which proceeds *via* a hydrindane with no substituent at C-13 [79, 80]. Nevertheless, *Nagata* has recently re-examined this question: under favorable conditions [81] the 1,4-addition of a cyanide ion to an α,β-unsaturated ketone *(80)* leads predominantly to the C/D-*trans*-isomer. This addition is suitable for certain syntheses (aldosterone, conessine), but is too complicated for the introduction of an angular methyl group.



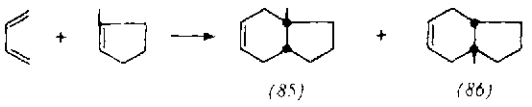
(80)

An attempt has been made to use the Diels-Alder reaction for the direct synthesis of the hydrindane system corresponding to rings C and D. Ring C was prepared by addition of a diene to a cyclopentene, *e.g.* *(81)*–*(84)*, which already contained a methyl group in what was to become the angular position.

(81), R = H *(83)*, R = H

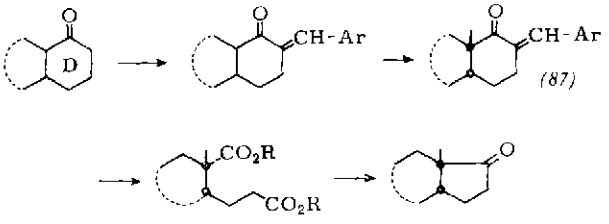
(82), R = CH_3 *(84)*, R = CH_3

The results were not very encouraging, however, since the diene synthesis gave *cis*-fused rings *(85)*, and the changing direction of addition of the diene also led to products with angular methyl groups on C-14 *(86)*. Although this method has been studied very intensively [82–84], it has now been abandoned, except for a few special cases such as the 18-nor-steroids and the D-homosteroids.



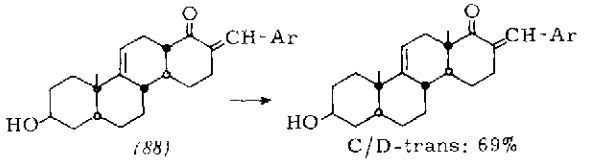
(85) *(86)*

These difficulties led to an investigation of the angular alkylation of decalin structures, which should be more stable in the *trans*-form than the hydrindane structures. The synthesis of rings C and D *via* a D-homosteroid intermediate *(87)* was suggested by *Johnson* and *Allen* ("hydrochrysene syntheses").

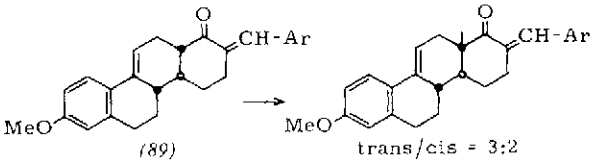


(87)

The stereoselectivity of this reaction was found to be poor. However, *Johnson* et al. [38, 39] observed that the unfavorable *cis*/*trans*-ratio [85, 88, 89] could be reversed by the introduction of a 9,11-double bond *(88)*, *(89)*. The theory underlying this phenomenon has been discussed above (cf. p. 191). The method so modified was used for the synthesis of estrone [86, 87]. However, its value is still limited by the fact that it is not completely stereospecific, and that the final contraction of the six-membered ring D to a five-membered ring proceeds only with low yields.



(88) C/D-trans: 69%



(89) trans/cis = 3:2

[77] *A. J. Birch, R. Jaeger*, and *R. Robinson*, J. chem. Soc. (London) *1945*, 582.

[78] *A. Koebner* and *R. Robinson*, J. chem. Soc. (London) *1938*, 1994.

[79] *N. A. Nelson* and *R. B. Garland*, J. Amer. chem. Soc. *79*, 6313 (1957).

[80] *R. B. Woodward, H. H. Inhoffen, H. O. Larson*, and *K. H. Menzel*, Chem. Ber. *86*, 594 (1953).

[81] *W. Nagata, T. Teresawa*, and *T. Aoki*, Tetrahedron Letters *1963*, 865.

[82] *E. Dane* and *J. Schmitt*, Liebigs Ann. Chem. *536*, 196 (1938).

[83] *T. I. Sorkina, I. I. Zaretskaya*, and *I. V. Torgov*, Dokl. Akad. Nauk U.S.S.R. *129*, 345 (1959); Chem. Abstr. *54*, 7659 (1960).

[84] *I. N. Nazarov* and *I. L. Kotlyarevskii*, Izv. Akad. Nauk U.S.S.R., Otdel. khim. Nauk *1953*, 1100; Chem. Abstr. *49*, 2458 (1955).

[85] *W. S. Johnson, D. K. Banerjee, W. P. Schneider, C. D. Gutsche, W. E. Shelberg*, and *L. J. Chinn*, J. Amer. chem. Soc. *74*, 2832 (1952).

[86] *J. E. Cole, W. S. Johnson, P. A. Robins*, and *J. Walker*, J. chem. Soc. (London) *1962*, 244.

[87] *J. E. Cole*, Dissertation Abstracts *21*, 51 (1960).

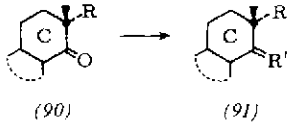
[88] *W. S. Johnson, B. Bannister*, and *R. Pappo*, J. Amer. chem. Soc. *78*, 6331 (1956).

[89] *W. S. Johnson, B. Bannister, R. Pappo*, and *J. E. Pike*, J. Amer. chem. Soc. *78*, 6354 (1956).

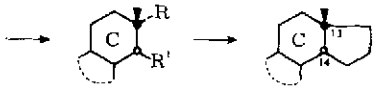
Johnson [90], in his synthesis of aldosterone [91], made use of the fact that the principal product of this method in its original form is the 9-alkyl-*cis*-decalin. The alkyl group introduced at C-13 during formation of the *cis*-decalin system was so chosen that it contained the elements of the future five-membered ring D.

Since no method could be found for the direct synthesis of the 13-alkylhydrindane structure with its two centers of asymmetry (C-13 and C-14), the problem was divided (1) creation of the asymmetric center C-13, and (2) subsequent creation of the asymmetric center C-14.

The asymmetric center C-13 can be formed by either of two routes: by joining ring D onto ring C, which already contains the future angular methyl group *(90)*,

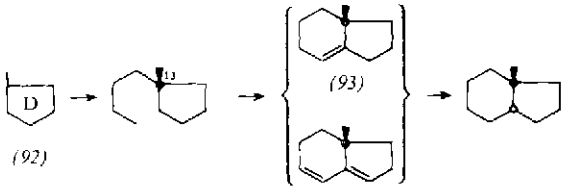


(90) *(91)*



(91a)

or by joining ring C onto a pre-methylated ring D *(92)*.

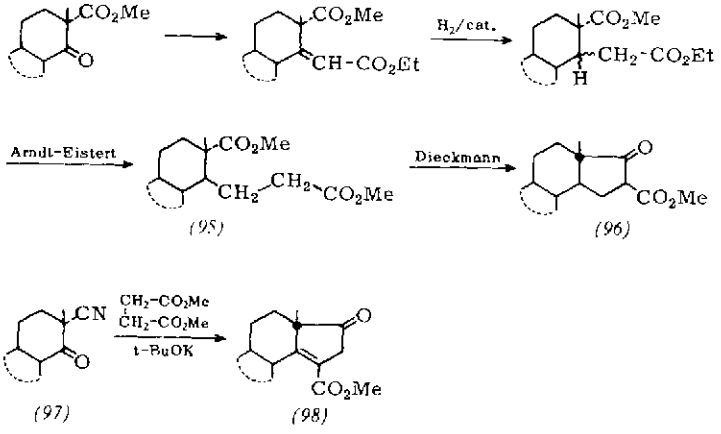


(92) *(93)* *(94)*

The asymmetric center C-14 must then be formed by reduction of a double bond, which may be exocyclic with respect to ring C *(91)*, or endocyclic in ring C *(93)* or ring D *(94)*.

The first of these schemes has been widely used. Ring C of the starting material *(90)* was a cyclohexanone derivative with a center of asymmetry in position 13. One of the substituents on C-13 was a carboxyl or cyanide group, which provided a point of attachment for the synthesis of ring D. The remaining elements of ring D were attached to C-14 by alkylidenation *(91)*. After reduction of the resulting exocyclic double bond, the five-membered ring D was closed by joining the chains attached to C-13 and C-14, using one of the following reactions:

Dieckmann reaction [*(95)* – *(96)*] *(Bachmann, Anner* and *Miescher, Robinson)*, acyloin condensation *(Sheehan)* [92], Stobbe condensation [*(97* – *(98)*] [93, 94], Alkylation *(Sarett)*, alkylidenation *(Wilds, Johnson,* and *Christiansen)*.



(95) *(96)* *(97)* *(98)*

After the desired configuration of the asymmetric center C-13 had been secured in the intermediate *(91)*, the stereochemical problem was to create the asymmetric center C-14. In principle there was no obstacle to the formation of a cyclohexane derivative *(91a)* with *trans*-diequatorial side chains on C-13 and C-14. *Johnson* (catalytic hydrogenation) [95] and *Sarett* (alkali metals/NH_3) [96] investigated the stereochemistry of the reduction *(91)* -> *(91a)*, and found that it was dependent on both the unsaturated compound and the reducing agent. High stereoselectivity can be achieved by correct choice of the reduction conditions.

In the second of the synthetic schemes mentioned above, in which a methylated cyclopentane derivative *(92)* (or its precursor) is used as the starting material [97], ring C is built up in two steps: introduction of a carbon chain at C-13, followed by ring closure to C-14. This scheme, which had been considered as early as 1935 [98], has been frequently used in recent syntheses. There are a number

[90] *W. S. Johnson, D. G. Martin, R. Pappo, S. D. Darling,* and *R. A. Clement*, Proc. chem. Soc. (London) *1957*, 58.

[91] *W. S. Johnson, J. C. Collins, R. Pappo,* and *M. B. Rubin*, J. Amer. chem. Soc. *80*, 2585 (1958).

[92] *J. C. Sheehan, R. A. Coderre,* and *P. A. Cruickshank*, J. Amer. chem. Soc. *75*, 6231 (1953).

[93] *W. S. Johnson, J. W. Petersen,* and *C. D. Gutsche*, J. Amer. chem. Soc. *67*, 2274 (1945).

[94] *W. S. Johnson, J. W. Petersen,* and *C. D. Gutsche*, J. Amer. chem. Soc. *69*, 2942 (1947).

[95] *W. S. Johnson, R. G. Christiansen,* and *R. E. Ireland*, J. Amer. chem. Soc. *79*, 1995 (1957).

[96] *G. E. Arth, G. I. Poos, R. M. Lukes, F. M. Robinson, W. F. Johns, M. Feurer,* and *L. H. Sarett*, J. Amer. chem. Soc. *76*, 1715 (1954).

[97] *J. J. Panouse* and *C. Sannié*, Bull. Soc. Chim. France *1955*, 1036.

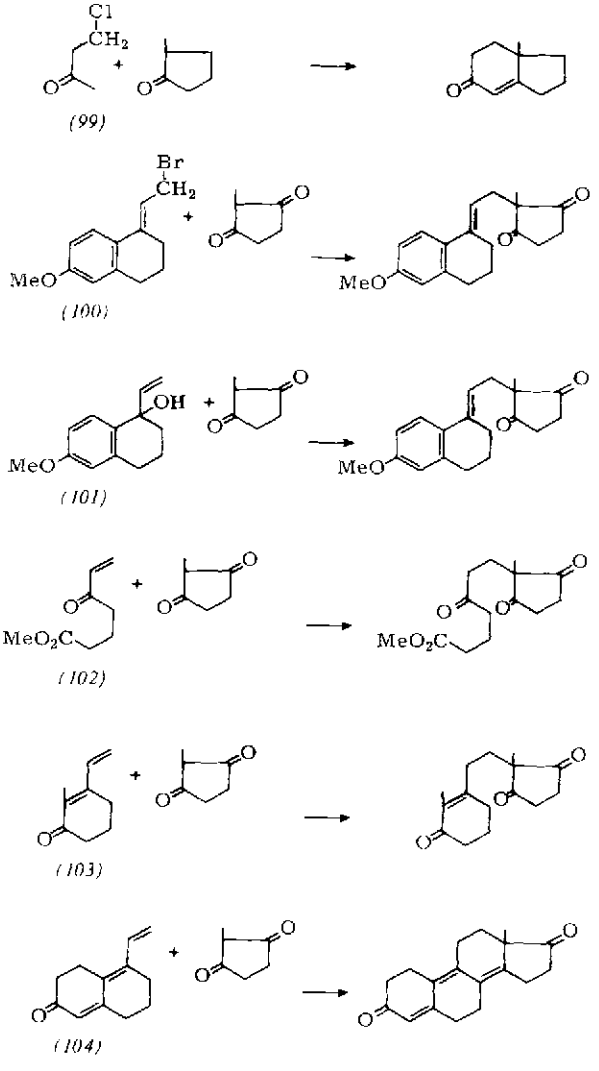
[98] *A. Cohen, J. W. Cook,* and *C. L. Hewett*, J. chem. Soc. (London) *1935*, 445.

of variants, in which alkylation is achieved with one of the following reagents:

saturated alkyl halides *(99)* [99, 100],

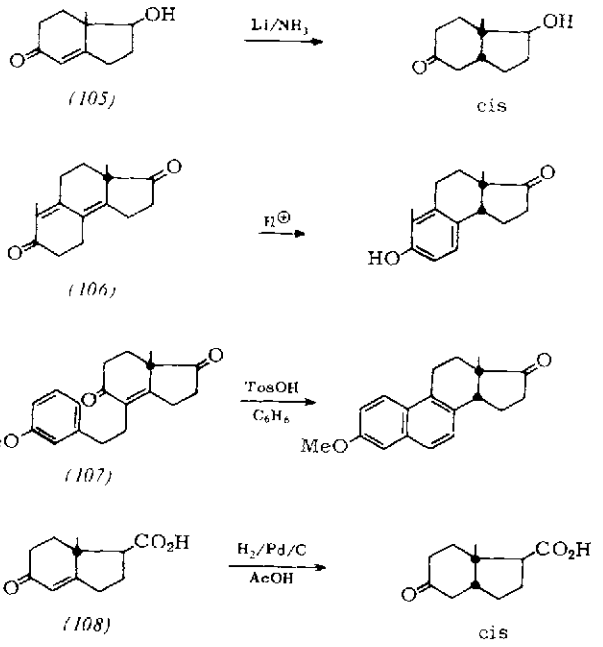
allyl halides *(100)* [101] or allyl alcohols *(101)* [102 to 105],

unsaturated ketones (or their precursors), by 1,4-addition *(102)* [106, 62], 1,6-addition *(103)* [107], or 1,8-addition *(104)* [108].



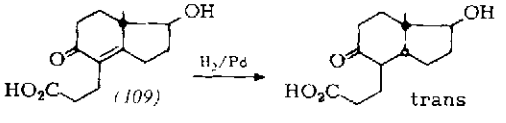
Ring closure is generally effected by alkylidenation, giving rise to an 8,14-double bond *(93)* or a 14,15-double bond *(94)*.

The formation of the asymmetric center C-14 by the reduction of structures *(93)* or *(94)* is stereochemically more difficult than in the case of the exocyclic derivative



(91). Any change allowing the carbon atom to appear temporarily in a form in which it is unable to retain its configuration (*e. g.* as a carbanion, a free radical, or a carbonium ion) may lead to the more stable *cis*-hydrindane system. This is precisely what happens during the reduction of the bicyclic derivative *(105)* [109, 110]. For similar reasons, isomerization of the 8,14-double bond in *(106)* and *(107)* leads to a C/D-*cis*-system [63, 107a]. The same result is obtained on catalytic hydrogenation of *(108)* [109, 110].

Velluz, *Nomine*, and *Amiard* [62] succeeded in solving this problem by using a bicyclic derivative *(109)* with a side chain on C-8. Hydrogenation of this compound is satisfactorily stereoselective and yields the *trans*-hydrindane (cf. p. 189 and [63]).



The presence of an alkyl substituent on C-8 is not the only reason for the stereospecificity of this reduction; the nature of the substituent on C-17 also plays an important part. It was shown that replacement of the 17β-hydroxyl group by a carbonyl group jeopardizes the stereospecificity of the hydrogenation.

If, in the creation of the center of asymmetry in position 14, the starting material has a 14,15-double bond *(110a,b)* or two double bonds in the 8,9- and 14,15-posi-

[99] *R. Miller*, Ph. D. Thesis, Rutgers University 1956, University Microfilm 22536.

[100] *S. C. Ray* and *U. R. Ghatak*, J. indian chem. Soc. *36*, 137 (1959).

[101] *D. J. Crispin* and *J. S. Whitehurst*, Proc. chem. Soc. (London) *1963*, 22.

[102] *T. B. Windholz*, *J. H. Fried*, and *A. A. Patchett*, J. org. Chemistry *28*, 1092 (1963).

[103] *T. Miki*, *K. Hiraga*, and *T. Asako*, Proc. chem. Soc. (London) *1963*, 139.

[104] *A. V. Zakharychev*, *V. E. Limanov*, *S. N. Ananchenko*, *A. V. Platonova*, and *I. V. Torgov*, Izv. Akad. Nauk U.S.S.R., Otdel. khim. Nauk *1963*, 1701.

[105] *S. N. Ananchenko* and *I. V. Torgov*, Tetrahedron Letters *1963*, 1553.

[106] *G. A. Hughes* and *H. Smith*, Chem. and Ind. *1960*, 1022.

[107] *J. J. Panouse* and *C. Sannié*, Bull. Soc. Chim. France *1956*, 1429.

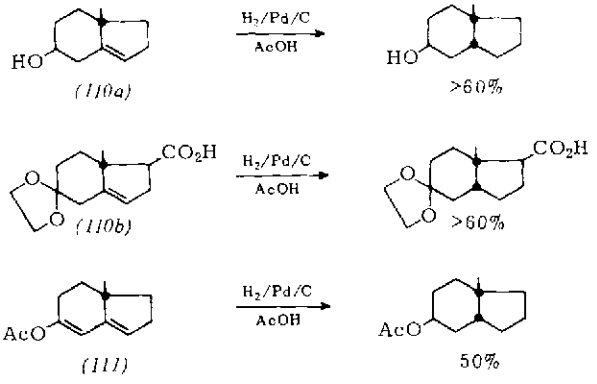
[107a] *C. Sannié*, *C. Neuville*, and *J. J. Panouse*, Bull. Soc. Chim. France *1958*, 635.

[108] *T. B. Windholz*, *J. H. Fried*, *H. Schwam*, and *A. A. Patchett*, J. Amer. chem. Soc. *85*, 1707 (1963).

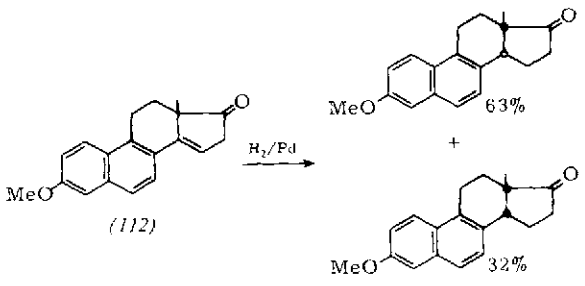
[109] *M. Chaykovsky*, Ph. D. Thesis, University of Michigan 1961, University Microfilm 61–6328.

[110] *C. B. C. Boyce* and *J. S. Whitehurst*, J. chem. Soc. (London) *1960*, 4547.

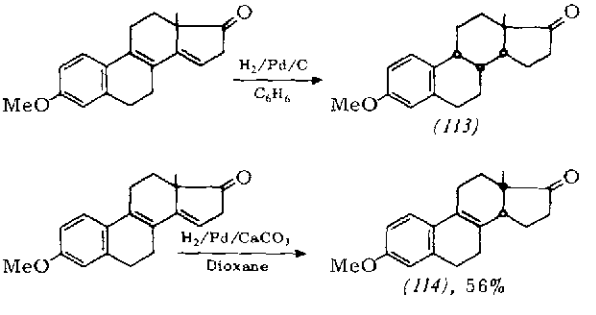
tions *(111)*, the same stereochemical difficulties are encountered as with *(93)*, *i. e.* the reaction leads preferentially to the *cis*-hydrindane derivative [109].



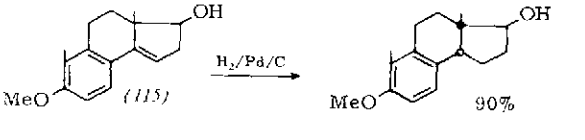
The stereochemistry of these reductions is more complex in the case of tri- and tetracyclic systems. It depends on the reducing agent used, and above all on the nature of the substituent on C-17. For example, the catalytic hydrogenation of the 17-oxo compounds *(112)* leads to mixtures of products [94] (cf. also p. 189).



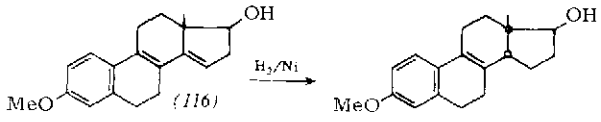
Moreover, the reactant must be sufficiently mild (Raney nickel [106] or $Pd/CaCO_3$ [102]) *(114)* in order to avoid the formation of an 8-iso-center as in *(113)*.



The yield of the reduction is improved if the 17-carbonyl group is converted into a 17β-hydroxyl group *(115)* [61]. This prevents migration of the 14,15-double bond into the 15,16-position to form the more stable *cis*-hydrindane derivative.

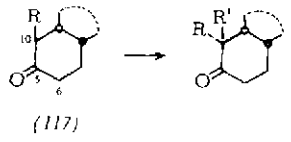


The high stereospecificity of this reaction has been utilized in a number of total syntheses [67, 103], another example being *(116)*.



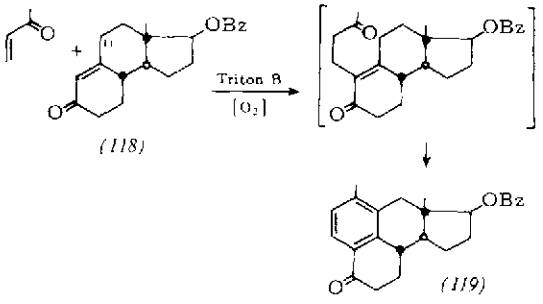
b) Formation of a Center of Asymmetry in Position 10

The center of asymmetry at C-10 is generally formed by alkylation of a cyclohexanone *(117)* which already carries an alkyl group on C-10 (steroid numbering).

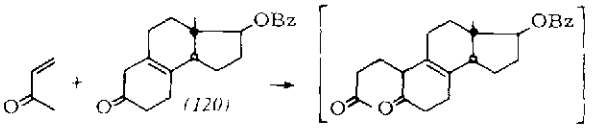


This alkylation can take place on either C-10 or C-6. It is not necessary to block C-6, however, if ring D is five-membered (cf. p. 183).

In cyclohexenones of the type *(118)*, alkylation is also subject to interference from C-11. Thus methyl vinyl ketone condenses with C-11 *(119)* in the presence of Triton B [67] or sodium ethoxide [111].



We were able to avoid this reaction [67] by starting with an unconjugated ketone *(120)*, in which position 11 is no longer activated by a vinylogous double bond, as it is in *(118)*.



A satisfactory alkylation of C-10 can also be achieved by the method recommended by *Stork* [112], in which enamines of conjugated ketones are reacted with 1,3-dichloro-2-butene (or one of its derivatives) [113–115].

[111] *L. J. Chinn* and *H. L. Dryden*, J. org. Chemistry *26*, 3904 (1961).

[112] *G. Stork, A. Brizzolara, H. Landesmann, J. Szmuszkovicz*, and *R. Terrell*, J. Amer. chem. Soc. *85*, 207 (1963).

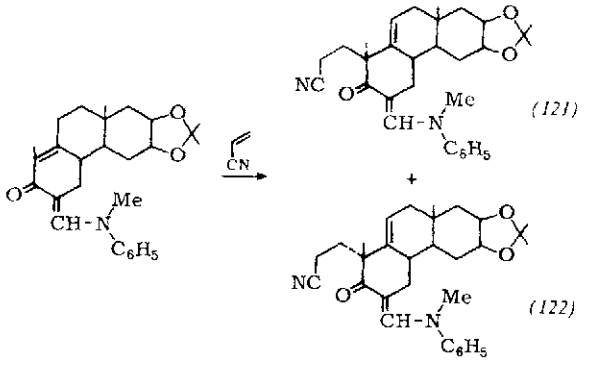
[113] *L. Velluz, G. Nominé, R. Bucourt, A. Pierdet*, and *P. Dufay*, Tetrahedron Letters *1961*, 127.

[114] *L. Velluz, G. Nominé, R. Bucourt, A. Pierdet*, and *J. Tessier*, C. R. hebd. Séances Acad. Sci. *252*, 3903 (1961).

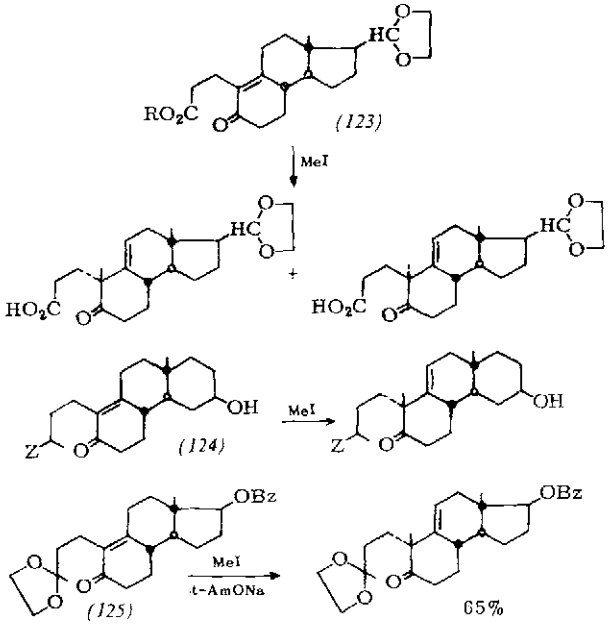
[115] *R. Bucourt, J. Tessier*, and *G. Nominé*, Bull. Soc. Chim. France *1963*, 1923.

The order in which the alkyl groups R and R′ are introduced on C-10 is of some importance to the stereochemistry of this center. If the difference in the accessibility from the α- and from the β-side of the molecule is small, the stereochemistry of the second alkylation at C-10 is governed mainly by the energy of the intermediate state (cf. pp. 185 and 188). Thus the second alkyl residue R′ enters the axial β-position and so directs the first alkyl residue R into the α-position. If access from the β-side is sufficiently hindered, the opposite result is obtained.

The formation of ring A normally fails if ring B already carries the future angular C-19 methyl group, since the chain introduced at C-10 preferentially attacks from the β-side and forces the methyl group into the α-position. This was a weak point in *Woodward*'s total synthesis [116], in which the product contained twice as much 10α-methyl isomer *(121)* as 10β-isomer *(122)*.



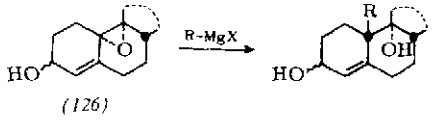
Two solutions have been proposed. One is to use "folded" *cis*-decalin structures, as indicated on p. 190, in which the accessibility of position 10 and the energy of the intermediate state lead to entry of the alkyl group from the α-side. This method has been used by *Banerjee* [66] and *Sarett* [18, 65]. It has the disadvantage, however, that it leads to an 8-iso product, which is frequently difficult to epimerize.



[116] *R. B. Woodward, F. Sondheimer, D. Taub, K. Heusler*, and *W. M. McLamore*, J. Amer. chem. Soc. *74*, 4223 (1952).

The other solution consists in reversal of the alkylation on C-10, *i.e.* in introducing the carbon chain for ring A first, followed by the angular methyl group. The principal product obtained by this method is the 10β-methyl isomer, *e.g.* in the syntheses developed by *Barkley* and *Thompson (123)* [10] and by *Stork (124)* [117]. We have also used this procedure *(125)*.

Finally, the reaction with a 9α,10α-epoxide *(126)* also yields a 10β-alkyl derivative. The alkylating agent attacks from the β-side, and the *trans*-diaxial cleavage of the epoxide ring (cf. p. 188) forces the alkyl group into the 10β-position, while the hydroxyl group appears in the 9α-position. This method has been used for the introduction of an allyl group on C-10 [118].



Tetralin or octalin structures corresponding to rings A and B have also been alkylated on C-10 by the Reimer-Tiemann reaction [119], the vinyl allyl ether rearrangement [120, 121], or by 1,4-addition of cyanide ion [121]. However, these methods have never been used for the introduction of a 10β-alkyl substituent in the total synthesis of steroids.

c) Development of Synthetic Routes

The problems associated with the formation of the asymmetric centers C-13, C-14, and C-10 illustrate the difficulties encountered in the stereospecific total synthesis of steroids. They have influenced the order in which the four rings are built up and restricted the number of useful synthetic routes (despite a large number of theoretically possible combinations). Table 1 shows a few examples illustrating how the synthetic routes used have developed in the course of the last twenty years.

In the first total syntheses, the rings were built up in the sequence A → D, since the object of these syntheses was to prepare steroids containing only a few centers of asymmetry, *i.e.* highly unsaturated structures. The starting materials consisted of an aromatic A or A/B system. Notable examples are the syntheses by *Bachmann* (1939) [122], *Robinson* (1938), *Anner* and *Miescher* (1948) [124], *Johnson* (1945) [93], and *Wilds* (1947).

The order of formation of the rings subsequently changed, but the five-membered ring D still was the last to be formed in all syntheses up till 1958. This was due to the scarcity of methods available at that time for the stereoselective formation of the 13-alkyl-*trans*-hydrindane structure, which made it impractical to start a synthesis with the formation of a C/D-hydrindane system. In order to overcome these difficulties, *Johnson* developed his hydrochrysene synthesis (p. 193) around 1956. This method involved the use of a C/homo-D-decalin system, from which a five-membered ring was produced at the end of the synthesis.

[117] *G. Stork, H. J. E. Loewenthal*, and *P. C. Mukharji*, J. Amer. chem. Soc. *78*, 501 (1956).

[118] *G. Nominé, R. Bucourt*, and *A. Pierdet*, C. R. hebd. Séances Acad. Sci. *254*, 1823 (1962).

[119] *R. B. Woodward*, J. Amer. chem. Soc. *62*, 1208 (1940).

[120] *A. W. Burgstahler* and *I. C. Nordin*, J. Amer. chem. Soc. *83*, 198 (1961).

[121] *M. Torigoe* and *J. Fishman*, Tetrahedron Letters *1963*, 1251.

Table 1. Routes for the total synthesis of steroids.

1. Linear schemes.

Route [a]	Year	Ref.
AB → C → Df	1939	[122]
	1945	[93]
	1961	[123]
A → B → C → Df	1948	[124]
BC → A → Df	1953	[125]
C → Ds → B → A → Df	1952	[116]
C → B → A → Df	1952	[65]
BC → Df → A	1956–60	[61, 66]
	1960	[126–128]
	1961	[111]
AB → Df → C	1961	[129]
CDs → B → A → Df	1956	[89]
	1960	[130]
	1962	[131]
BC → Ds → A	1956	[117]

2. Converging schemes.

Route [a]	Year	Ref.
A, CDs → B → Df	1950–52	[85]
AB, Ds → C → Df	1958	[132]
	1959–62	[83, 19]
A, Df → BC	1960	[106, 133]
AB, Df → C	1961	[135]
	1962	[134]
	1963	[101]
	1963	[103]
	1963	[102]
	1963	[105]
A, CDf → B	1962	[63]
	1963	[135]
BC, Df → C → B → A	1963	[62]

[a] Df and Ds denote five- and six-membered rings D, respectively.

[122] *W. E. Bachmann, W. Cole,* and *A. L. Wilds,* J. Amer. chem. Soc. *61,* 974 (1939).

[123] *W. Nagata, I. Kikkawa,* and *K. Takeda,* Chem. pharm. Bull. Japan *9,* 79 (1961).

[124] *G. Anner* and *K. Miescher,* Helv. chim. Acta *31,* 2173 (1948).

[125] *H. M. E. Cardwell, J. W. Cornforth, S. R. Duff, H. Holtermann,* and *R. Robinson,* J. chem. Soc. (London) *1958,* 361.

[126] *L. Velluz, G. Nominé, J. Mathieu, E. Toromanoff, D. Bertin, J. Tessier,* and *A. Pierdet,* C. R. hebd. Séances Acad. Sci. *250,* 1084 (1960).

[127] *L. Velluz, G. Nominé, J. Mathieu, E. Toromanoff, D. Bertin, R. Bucourt,* and *J. Tessier,* C. R. hebd. Séances Acad. Sci. *250,* 1293 (1960).

[128] *L. Velluz, G. Nominé, J. Mathieu, E. Toromanoff, D. Bertin, M. Vignau,* and *J. Tessier,* C. R. hebd. Séances Acad. Sci. *250,* 1510 (1960).

[129] *D. K. Banerjee, H. N. Khastigir, J. Dutta,* and *E. J. Jacob, W. S. Johnson, C. F. Allen, B. K. Bhattacharya, J. C. Collins, A. L. McCloskey, W. T. Tsatsos, W. A. Vredenburgh,* and *K. L. Williamson,* Tetrahedron Letters *1961,* 76.

[130] *W. Nagata, T. Terasawa, S. Hirai,* and *K. Takeda,* Tetrahedron Letters *1960,* No. 17, p. 27.

[131] *J. A. Marshall* and *W. S. Johnson,* J. Amer. chem. Soc. *84,* 1485 (1962).

[132] *J. E. Cole* and *W. S. Johnson,* Proc. chem. Soc. (London) *1958,* 114.

The most notable syntheses of this time were those by *Johnson* (1956) [89], *Woodward* (1951), *Sarett* (1952) [65], and *Stork* (1956) [117], as well as the aldosterone syntheses by *Wettstein* (1957–58) and *Johnson* (1958) [132], some of which already exhibited a remarkable degree of stereospecificity (over several stages).

The period following 1958 saw the appearance of syntheses which no longer ended with the formation of the five-membered ring D. These were made possible by the increased stereospecificity of the reactions used for the formation of the asymmetric centers C-13 and C-14. Some syntheses even start with a five-membered ring D, so that the sequence of ring formation becomes D → A (*i.e.* the reverse of that used for the earliest total syntheses).

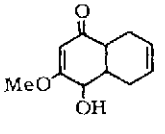
The experimental and theoretical advances, the stereoselectivity of numerous reactions and the choice of synthetic routes became so great in 1959–1960, that it was now possible to attempt a total steroid synthesis which could be used in industry. Until that time, this aim had appeared to be completely Utopian.

There are at least three requirements which must be satisfied by a total synthesis of this type:

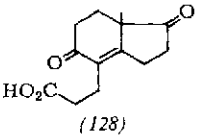
stereoselectivity of each step,
earliest possible resolution of racemates,
convergence of the reaction scheme.

The first of these requirements is obvious, and the problems which it raises have been discussed above, together with the largely satisfactory solutions now available.

The second requirement is related to the cost of production of the optically active end product. Most total syntheses have been carried out with racemates, resolution of the racemic tetracyclic systems being carried out at the end of the synthesis. Resolution at the bicyclic stage offers the advantage of getting early into the active series. The importance of this procedure was recognized in 1954 by the Monsanto group, who tested it with the bicyclic system *(127)*. In 1963, *Velluz, Nominé, Amiard,* et al. made practical use of the resolution of the bicyclic acid *(128)*.



(127)



(128)

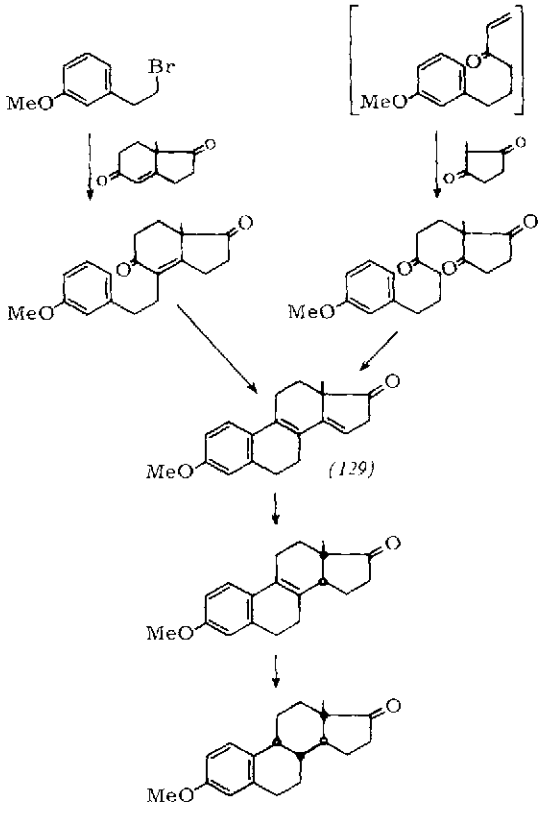
The third requirement which must be satisfied by an industrially applicable total synthesis is convergence of the synthetic scheme. In a multistage synthesis, each stage results in a decrease in the overall yield, and involves the loss of increasingly expensive intermediates. This loss is reduced in a converging synthesis, in which two parts of the future steroid are formed initially, and the combination of these fragments to form expensive intermediates is delayed as long as possible. Most of the syntheses achieved prior to 1961 were linear (cf. Table 1, Part 1). The possibility of using the five-membered ring D or a

[133] *G. A. Hughes* and *H. Smith,* Belgian Pat. 595385 (1961).

[134] *G. Nominé, R. Bucourt, E. Toromanoff,* and *M. Vignau,* unpublished work.

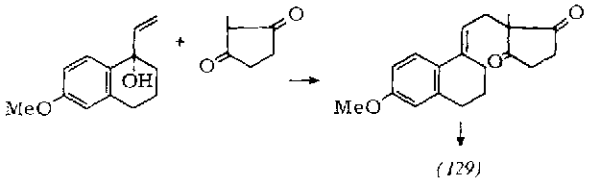
[135] *G. H. Douglas, J. M. H. Graves, D. Hartley, G. A. Hughes, B. J. McLoughlin, J. Siddal,* and *H. Smith,* J. chem. Soc. (London) *1963,* 5072.

hydrindane system as the starting material then permitted the development of converging syntheses (see Table 1, Part 2).



Scheme 3. Total synthesis of steroids according to *Hughes, Smith*, et al. [135, 137].

It finally became possible to achieve the complete synthesis of steroids by a remarkably short route. Scheme 3 shows the result of investigations by *Hughes, Smith*, et al. [135–137] in the racemic series. Another route (also in the racemic series) used by a number of research groups [101–103, 105, 134, 135] is outlined in Scheme 4.

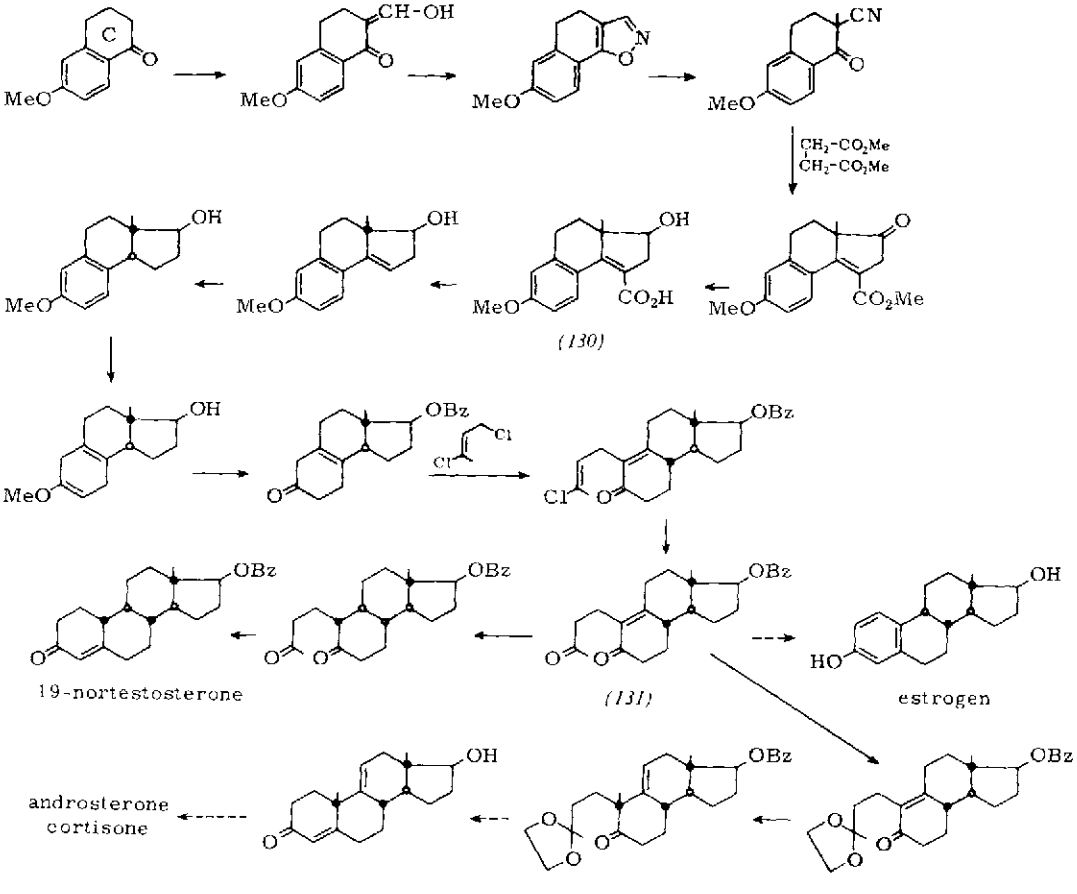


Scheme 4. Another method of synthesizing compound *(129)* of Scheme 3.

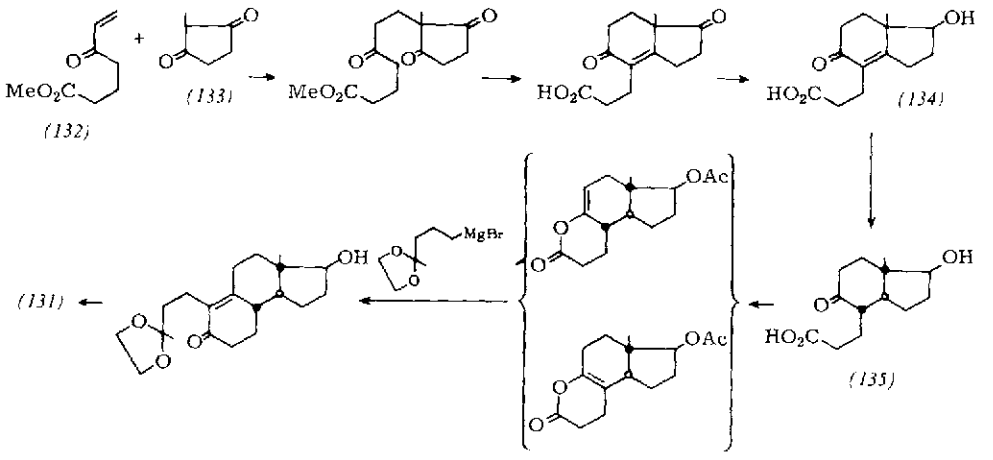
Progress with regard to the stereoselectivity of reactions and the convergence of the synthetic scheme has recently made possible the total synthesis of optically active steroids on the industrial scale. Work carried out in our laboratory initially involved the linear type of synthesis [67, 126–128] (Scheme 5) and corresponded to the sequence BC → Df → A. Resolution of a racemate was achieved at the stage of the tricyclic acid *(130)*, and the synthesis was then completed in the active series.

[136] *H. Smith, G. A. Hughes*, and *B. J. McLoughlin*, Experientia *19*, 177 (1963).

[137] *H. Smith, G. A. Hughes, G. H. Douglas, D. Hartley, B. J. McLoughlin*, and *J. B. Siddall, G. R. Wendt, G. C. Buzby, D. R. Herbst, K. W. Ledig, J. R. McMenamin, T. W. Pattison, J. Suida, J. Tokolics*, and *R. A. Edgren, A. B. A. Jansen, B. Gadsby, D. H. R. Watson*, and *P. C. Phillips*, Experientia *19*, 394 (1963).



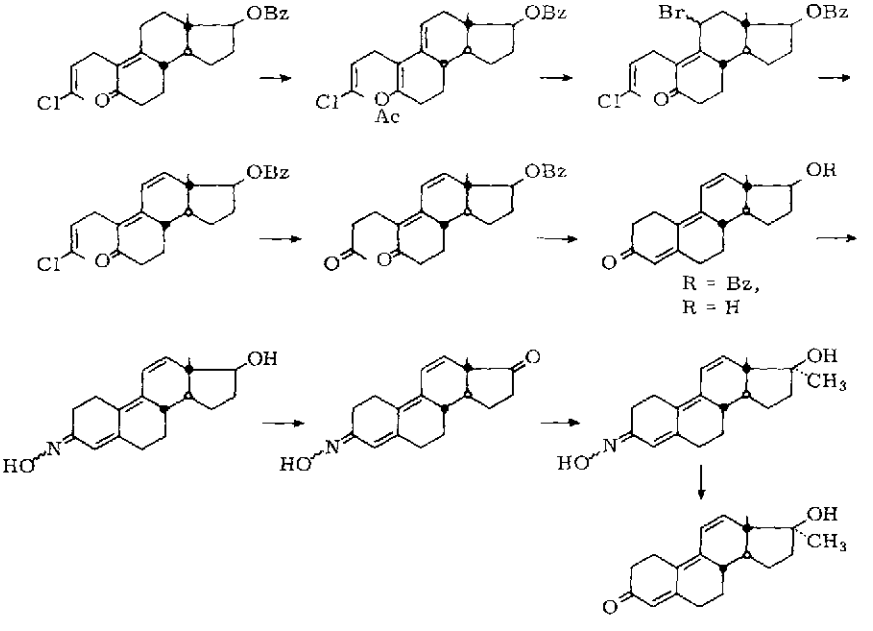
Scheme 5. First total synthesis of optically active steroids on the industrial scale [67, 126–128].



Scheme 6. Converging synthesis of the intermediate *(131)* of Scheme 5.

The principle of the second, converging synthesis [62] is shown in Scheme 6. The two fragments formed initially are the five-membered ring D in the form of a 2-methyl-1,3-cyclopentanedione *(132)* and the elements of the fu-

There is no doubt that the total synthesis of optically active steroids offers the possibility of preparing new therapeutically active structures. However, this aspect is beyond the scope of the present paper. Consequently we shall simply call attention to the recent synthesis



Scheme 7. Total synthesis of a triply unsaturated steroid.

(136)

ture rings C and B as the methyl ester of 5-oxo-6-heptenoic acid *(133)*. Thus the synthesis corresponds to the scheme:

$$\left.\begin{matrix}\text{Df}\\(\text{BC})\end{matrix}\right\}\rightarrow (\text{BC})\text{Df} \rightarrow \text{C} \rightarrow \text{B} \rightarrow \text{A}$$

The racemate is resolved during the conversion of *(134)* to *(135)*.

(Scheme 7) [138] in our laboratory of a triply unsaturated steroid *(136)* which is 50 times more active than methyltestosterone.

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Translated by Express Translation Service, London

[138] *L. Velluz, G. Nominé, R. Bucourt,* and *J. Mathieu,* C. R. hebd. Séances Acad. Sci. *257,* 569 (1963).

Recent Developments in the Chemistry of Heterosiloxanes

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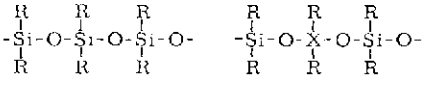
Progress in the chemistry of organoheterosiloxanes is reviewed in the light of the latest preparative and spectroscopic results. Attention is focussed on the heterosiloxane structural unit Si–O–X, the bonding in which – depending on the hetero-atom – differs characteristically from that in the siloxane bridge Si–O–Si.

I. Introduction

Following the great success achieved with silicone-based polymers, attempts were made to satisfy the increasing technological demands on inorganic polymers by synthesizing modified silicones. However, since the search for silicone-like polymers was often unsystematic and lacked firm theoretical foundation, these efforts have frequently met with little success. This is also seen from recent monographs on "Inorganic Polymers" [1,2].

Silicone polymers were modified in two ways. Either the residues R bonded to the siloxane skeleton *(1)* were changed, or hetero-atoms were incorporated into the quasi-silicate siloxane chain. The latter change may involve replacement of oxygen by nitrogen [3] or sulfur, or of silicon by other elements X *(2)*.



(1) *(2)*

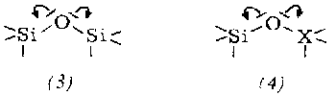
Substances of type *(2)* are termed heterosiloxanes. For many years the main centers of heterosiloxane research have been the schools of *K. A. Andrianov* (Moscow) [4], *D. C. Bradley* (London and Ontario) [1,5], and *M. G. Voronkov* (Leningrad and Riga) [6].

Progress in our understanding of the properties of heterosiloxanes was to be expected only from a better understanding of the bonding. Since investigations of polymers with irregular compositions only rarely yield detailed information, it was necessary to prepare low molecular-weight model substances of definite composition; these should contain all the structural units and building blocks which could be involved in the structures of larger molecules and polymers [7]. The results of work along these lines are reviewed in the present paper.

II. The Siloxane Linkage

Examination of the heterosiloxane linkage, Si–O–X, must be preceded by a discussion of the disiloxane linkage, Si–O–Si.

The unusual thermal and chemical stability of quartz and many silicates led to expect a special type of bonding in the Si–O–Si structural unit; this was later confirmed by the stability of the silicones. Bond energies, force constants, interatomic distances, and valence angles indicate that the Si–O–Si structure *(3)* is a homopolar bond-system with surprisingly little polarization and with unusually high π-bond character [8]. The widely accepted concept of the $d_\pi p_\pi$- or (p → d)π-strengthening of the Si–O σ-skeleton was subjected repeatedly to theoretical calculations and appears to be sufficiently verified [9, 10]. Although this concept may be only one possible interpretation of the experimental findings, it is used in the present paper as a basis for discussion of the bonding in heterosiloxanes.



(3) *(4)*

Replacement of a silicon atom in the Si–O–Si bridge by a hetero-atom, *(3)* → *(4)*, must lead to a fundamental redistribution of the valence electrons; this is determined primarily by the electronegativity and the atomic radius of the atom X, and by the availability of energetically and sterically favorable d-orbitals of X, which, according to molecular-orbital theory, lead to $d_\pi p_\pi$-strengthening of the σ-skeleton by interaction with the p-orbitals of the bridge-oxygen atom. In valence-bond terminology

[1] *F. G. A. Stone* and *W. A. G. Graham*: Inorganic Polymers. Academic Press, New York 1962.

[2] *M. F. Lappert* and *G. J. Leigh*: Development in Inorganic Polymer Chemistry. Elsevier, Amsterdam 1962.

[3] *U. Wannagat* in *H. J. Emeléus* and *A. G. Sharpe*: Advances in Inorganic Chemistry and Radiochemistry. Academic Press, New York, London 1964, Vol. 6, p. 225.

[4] *K. A. Andrianov* et al., Uspekhi Khim. *26*, 895 (1957); *27*, 1257 (1958); J. Polymer Sci. *30*, 513 (1958); Russian Chem. Rev. *5*, 253 (1963), in English).

[5] *D. C. Bradley*: Metalorganic Compounds. Advances in Chemistry Series, Amer. chem. Soc., Washington 1959, Vol. 23.

[6] *M. G. Voronkov*, Habilitation Thesis before the Academy of Sciences of the U.S.S.R., Moscow 1961; Chemistry and the Practical Applications of Organosilicon Compounds. VIth Edition of Conference Reports of the Academy of Sciences of the U.S.S.R., Leningrad 1961.

[7] *H. Schmidbaur*, Habilitation Thesis, Universität Marburg, 1964.

[8] See, for example, *E. A. V. Ebsworth*: Volatile Silicon Compounds. Pergamon Press, Oxford 1963, pp. 124ff. and 156ff.

[9] *D. P. Craig, A. Maccoll, R. S. Nyholm, L. E. Orgel*, and *L. E. Sutton*, J. chem. Soc. (London) *1954*, 332.

[10] *D. P. Craig* and *D. W. Magnusson*, J. chem. Soc. (London) *1956*, 4895.

the ground state of such a heterosiloxane structure would be largely determined by the relative contributions of limiting structures such as *(5a)* and *(5b)*.

$$\geqslant Si\text{-}\overline{O}\text{-}X\leqslant \longleftrightarrow \geqslant Si{=}\overline{O}\text{-}X\leqslant \longleftrightarrow \geqslant Si\text{-}\underline{O}{=}X\leqslant$$

(5) *(5a)* *(5b)*

III. Heterosiloxanes

A. Germanosiloxanes

The most suitable elements for modifying a siloxane skeleton by hetero-atoms are the neighbors of silicon in the periodic system, and in particular its higher homologues; thus, most investigations have so for been concerned with the germano-, stanno-, and plumbo-siloxanes.

1. Preparation

Attempts to prepare germanosiloxane polymers by cohydrolysis of organohalogenosilanes and -germanes met with little success [11]. The first definite germanosiloxanes were obtained by reaction of organosiloxides with organohalogenogermanes [12–14]. Using this method, the parent member *(6)* of the homologous series was prepared in a high yield [Equation (a)].

$$(CH_3)_3SiOLi + ClGe(CH_3)_3 \rightarrow LiCl + \underset{(6)}{(CH_3)_3Si\text{-}O\text{-}Ge(CH_3)_3} \quad (a)$$

More recently, compound *(6)* has also been prepared by the opposite route (h), *i.e.* from lithium trimethylgermoxide and trimethylchlorosilane [15].

$$(CH_3)_3SiCl + LiOGe(CH_3)_3 \rightarrow LiCl + \underset{(6)}{(CH_3)_3Si\text{-}O\text{-}Ge(CH_3)_3} \quad (b)$$

These two synthetic principles also permitted preparation of the higher homologues [13,14,16,17], the most important of which are listed in Table 1. Whereas the germanium atom in *(6)* to *(8)* is only monofunctional (with regard to the siloxane linkage), *(9)* to *(12)* contain di-, tri-, and tetra-functional hetero-atoms, and are thus model substances for linear and branched-chain polygermanosiloxanes.

Table 1. Physical constants of organogermanosiloxanes.

No.	Formula	M.p. [°C]	B.p. [°C/mm Hg]	ν_{as} (Si—O—Ge)	Ref.
(6)	$(CH_3)_3Si\text{-}O\text{-}Ge(CH_3)_3$	−68	117/725	995	[12–15]
(7)	$(C_2H_5)_3Si\text{-}O\text{-}Ge(CH_3)_3$		33/1	995	[14]
(8)	$(CH_3)_3Si\text{-}O\text{-}Ge(C_2H_5)_3$		34/1	995	[14]
(9)	$[(CH_3)_3SiO]_2Ge(CH_3)_2$	−61	165/725	1002/952	[13, 14]
(10)	$[(CH_3)_3SiO]_3GeCH_3$		77/10	1020/948	[14]
(11)	$[(CH_3)_3SiO]_4Ge$	−59	198/725	1020/949	[14, 16]
(12)	$[(C_6H_5)_3SiO]_4Ge$	427	400 (subl.)	—	[17]

2. Properties

Chemical behavior of the simplest germanosiloxanes shows that they are less stable than the analogous siloxanes. For example, the Si–O–Ge bridge is more rapidly hydrolysed, both in acidic and in basic media, to form the parent silanols and germanols. Heterolytic cleavage of the germanosiloxane bridge with aluminum chloride has shown that the Ge–O bond is the reactive center of the Ge–O–Si unit, and gives rise to increased reactivity compared to the Si–O–Si structure [18]: the only products are trimethylchlorogermane and trimethylsiloxyaluminum dichloride *(13a)*; trimethylchlorosilane or trimethylgermoxyaluminum dichloride *(13b)* (which is still unknown) are not formed. This

$$\underset{(6)}{(CH_3)_3Si\text{-}O\text{-}Ge(CH_3)_3} + AlCl_3 \rightarrow \begin{cases} (CH_3)_3SiCl + (CH_3)_3Ge\text{-}O\text{-}AlCl_2 & (13b) \\ (CH_3)_3GeCl + (CH_3)_3Si\text{-}O\text{-}AlCl_2 & (13a) \end{cases}$$

indicates that cleavage occurs at the Ge–O bond only. Likewise, germanosiloxanes are more reactive than siloxanes towards other Lewis acids, such as SO_3, CrO_3, SeO_3, $POCl_3$, and $P_2O_3Cl_4$ [19,20].

Destabilization of the siloxane bridge by introduction of germanium atoms is also reflected in the reduced thermal stability of the germanosiloxanes. Thus compounds *(9)* and *(11)* disproportionate above 200 °C to form siloxanes and germoxanes:

$$x\,(CH_3)_3Si\text{-}O\text{-}Ge(CH_3)_2\text{-}O\text{-}Si(CH_3)_3 \rightarrow x\,(CH_3)_3Si\text{-}O\text{-}Si(CH_3)_3 + [(CH_3)_2GeO]_x \quad (c)$$

The polygermoxanes formed still contain terminal siloxy groups.

3. Spectroscopic Investigations

The proton signal of the trimethylsilyl group in the ^1H-NMR spectrum of germanosiloxane *(6)* is shifted towards higher field-strengths as compared to the signal of hexamethyldisiloxane, indicating greater elec-

[11] *J. K. Stavitskij, S. N. Borisov, V. A. Ponomarenko, N. G. Sviridova,* and *G. Y. Zueva,* Vyssokomolekularnye Ssoedineniya *10*, 1502 (1959).

[12] *H. Schmidbaur* and *M. Schmidt*, J. Amer. chem. Soc. *83*, 2963 (1961).

[13] *H. Schmidbaur* and *M. Schmidt*, Chem. Ber. *94*, 1138 (1961).

[14] *H. Schmidbaur* and *H. Hussek*, J. organomet. Chem. *1*, 235 (1964).

[15] *D. Seyferth* and *D. L. Alleston*, Inorg. Chem. *2*, 418 (1963).

[16] *H. Schmidbaur* and *M. Schmidt*, Angew. Chem. *74*, 589 (1962); Angew. Chem. internat. Edit. *1*, 549 (1962).

[17] *V. Gutmann* and *A. Meller*, Mh. Chem. *91*, 519 (1960).

[18] *H. Schmidbaur* and *M. Schmidt*, Chem. Ber. *94*, 1349 (1961).

[19] *H. Schmidbaur* and *M. Schmidt*, Chem. Ber. *94*, 2137 (1961).

[20] *M. Schmidt, H. Schmidbaur,* and *I. Ruidisch*, Angew. Chem. *73*, 408 (1961).

tron density at the siloxy group of the heterosiloxane [14,21]. This is explained both by the lower electronegativity of germanium as compared to silicon, and by a decrease in the π-bond character of the Ge–O bond as compared to that of the Si–O bond. Both effects tend to strengthen the Si–O bond. Confirmation of this interpretation is provided by comparison with the NMR data for hexamethyldigermoxane. Here, the signal of the trimethylgermyl groups is at a higher field strength than the signal of the trimethylgermyl group in *(6)* (Table 2). The characteristic reduction of the coupling constants $J(^1H-^{13}C)$ and $J(^1H-C-^{29}Si)$ on passing from disiloxane to *(6)* is characteristic of the change in hybridization of the atoms involved [14,21 to

Table 2. ^{1}H-NMR data for some heterosiloxanes and reference substances [*] [14,21,22].

No.	Formula	δSi [cps]	J(HC) [cps]	J(HCSi) [cps]	δX [cps]	J(HC) [cps]	J(HCX) [cps]
	$(CH_3)_3SiOSi(CH_3)_3$	−3.5	118.0	6.85	−3.5	118.0	6.85 [a]
	$(CH_3)_3GeOGe(CH_3)_3$	-	—	—	−18.5	125.5	—
	$(CH_3)_3SnOSn(CH_3)_3$	—	—	—	−14.2	128.8	56.0/53.6 [b]
(6)	$(CH_3)_3SiOGe(CH_3)_3$	0.0	117.0	6.80	−21.0	126.0	—
(14)	$(CH_3)_3SiOSn(CH_3)_3$	+2.5	116.8	6.72	−20.5	128.5	57.4/54.9 [b]
(15)	$(CH_3)_3SiOPb(CH_3)_3$	+3.5	115.5	6.69	−73.0	136.0	69.5 [c]
(16)	$(CH_3)_3SiOSb(CH_3)_4$	+10.0	116.5	6.55	−61.0	131.0	—

[*] Varian A 60, 60 Mc. CCl_4 solutions at 35 °C. Tetramethylsilane as internal standard. Negative δ-values indicate lower field strengths.

[a] X = ^{29}Si. [b] X = ^{119}Sn, ^{117}Sn. [c] X = ^{207}Pb.

23] and again indicates the increased polarity of the Ge–O bond as compared to the Si–O bond. This agrees with the picture derived from the much more complex spectra of higher germanosiloxanes [14].

As expected, the infrared spectra contain a characteristic Si–O–Ge valence vibration; ν_{as}(Si–O–Ge) is displaced towards longer wavelengths compared to ν_{as}(Si–O–Si), and lies midway between ν_{as}(Si–O–Si) and ν_{as}(Si–O–Sn) [12,14]. The changes in the vibration frequencies of the organometallic residues, on the other hand, are much smaller, but again differ from the values for the "pure" siloxanes or germoxanes (Table 1).

B. Stannosiloxanes

1. Preparation

Publications describing the preparation of organostannosiloxanes and the interpretation of their bonding are much more frequent than in the case of germanosiloxanes [1, 2, 17, 24–28]. The parent member of the stannosiloxane series is easily prepared by a method similar to that used for the germanosiloxanes [12, 29]. In general, alkali-metal siloxides react smoothly with organohalogenostannanes to yield the stannosiloxanes (see Table 3 [29]):

$$(CH_3)_3SiONa + ClSn(CH_3)_3 \rightarrow NaCl + (CH_3)_3Si-O-Sn(CH_3)_3 \quad (d)$$

(14)

The preparation from alkali-metal stannoxides and halogenosilanes is also possible, since these stannoxides are now easily available [30].

$$2\,(CH_3)_3SnOLi + (CH_3)_2SiCl_2 \rightarrow 2\,LiCl + [(CH_3)_3SnO]_2Si(CH_3)_2 \quad (e)$$

(17)

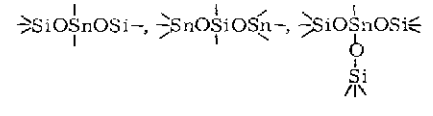
Another method leading quantitatively to stannosiloxanes is the reaction of pseudo-alkali siloxides, such as heptamethylstibiosiloxane with halogenostannanes [31]:

$$(CH_3)_4Sb-O-Si(CH_3)_3 + (CH_3)_3SnCl \rightarrow [(CH_3)_4Sb]Cl + (CH_3)_3Si-O-Sn(CH_3)_3 \quad (f)$$

(14)

Compound *(14)* could not be prepared by cohydrolysis and transesterification [27], but this method can be used to synthesize hexa-alkylstannosiloxanes having longer alkyl residues on the tin atom [27]. Cohydrolysis of trialkylchlorosilanes with dialkyldichlorostannanes also fails to yield simple stannosiloxanes of the type *(19)*, but gives stannoxanes $R_3SiO-[R_2Sn-O-SnR_2O]_n-SiR_3$ containing siloxy end-groups. The structure of these oligomers has been investigated in detail [27, 32].

Numerous phenylstannosiloxanes have recently been prepared, again mostly using the siloxide method [33]. Table 3 covers all types of stannosiloxanes in which the Si-O-Sn unit has been extended to both sides to form straight- or branched-chain polymers [29, 33], *e.g.*



2. Properties

The stannosiloxanes investigated so far are colorless, mostly malodorous, toxic compounds. They are surprisingly volatile and crystallize readily. Molecular-

[21] *H. Schmidbaur*, J. Amer. chem. Soc. *85*, 2336 (1963).

[22] *H. Schmidbaur* and *I. Ruidisch*, Inorg. Chem. *3*, 599 (1964).

[23] *E. A. V. Ebsworth* and *S. G. Frankiss*, J. Amer. chem. Soc. *85*, 3516 (1964).

[24] *S. M. Atlas* and *H. F. Mark*, Angew. Chem. *72*, 249 (1960).

[25] *W. S. Tatlock* and *E. G. Rochow*, J. org. Chemistry *17*, 1555 (1955).

[26] *S. Papetti* and *H. W. Post*, J. org. Chemistry *22*, 526 (1957).

[27] *R. Okawara* et al., J. Amer. chem. Soc. *83*, 1342 (1961); *85*, 4480 (1963); Angew. Chem. *73*, 683 (1961); Proc. chem. Soc. (London) *1961*, 383.

[28] For references to numerous other publications, see [1,2,5,6, 24].

[29] *H. Schmidbaur* and *H. Hussek*, J. organomet. Chem. *1*, 244 (1964).

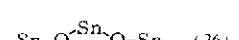
[30] *H. Schmidbaur* and *H. Hussek*, Angew. Chem. *75*, 575 (1963); Angew. Chem. internat. Edit. *2*, 558 (1963).

[31] *H. Schmidbaur* and *M. Schmidt*, Angew. Chem. *73*, 655 (1961).

[32] *D. L. Alleston*, *A. G. Davies*, *M. Hancock*, and *R. F. M. White*, J. chem. Soc. (London) *1963*, 5469.

[33] *C. Thies* and *J. B. Kinsinger*, Inorg. Chem. *3*, 551 (1964).

weight determinations show them to be monomeric. This is in contrast to many distannoxanes which spontaneously oligomerize [27] to form cyclic products (*e.g. (26)*) and indicates a considerable decrease in the donor strength ($d_\pi p_\pi$-bonding) of the stannosiloxane oxygen atoms.



(26)

The thermal stability of alkylstannosiloxanes is generally lower than that of the alkylsiloxanes or alkylstannoxanes. The long-chain compounds *(19)* and *(20)*, in particular, disproportionate above 160 °C to form alkylsiloxanes and alkylstannoxanes:

$$n\ [(CH_3)_3SiO]_2Sn(CH_3)_2 \rightarrow n\ (CH_3)_3Si{-}O{-}Si(CH_3)_3 + [(CH_3)_2SnO]_n \qquad (g)$$

The intermediates in this disproportionation are relatively short stannoxane chains which still contain terminal siloxy groups; the latter can be detected by infrared and NMR spectroscopy.

Stannosiloxanes also differ from siloxanes and stannoxanes in their high reactivity towards nucleophilic and electrophilic reagents. Thus, in contrast to disiloxane (but similar to stannoxane) [34], *(14)* undergoes rapid solvolysis with water, alcohols, amines, mercaptans, *etc.* and is readily cleaved by phenyl-lithium [15], as well as by Lewis acids such as BCl_3, $AlCl_3$, and SO_3 [29,35].

In this respect *(14)* is even more reactive than the germanosiloxane *(6)*. Evidently the chemical behavior of the stannosiloxanes is governed largely by the high reactivity of the Sn-O bond, which undergoes heterolytic cleavage much more readily than the Si-O bond, owing to its higher polarity and lower π-bond character. In agreement with this, an increase in the number of negative substituents on the tin atom has a stabilizing effect on the Sn-O bond, so that compounds of types *(21)* and *(22)* are less sensitive to solvolysis [24–29, 33]. The same effect is achieved for steric reasons by long-chain or branched-chain residues on the tin atom *(17)* [27, 29, 33].

3. Spectroscopic Investigations

The NMR spectra of the stannosiloxanes [21,29] are particularly informative, owing to the presence of the isotopes ^{117}Sn and ^{119}Sn with nuclear spin 1/2; consequently, an interpretation of the spectra after complete assignment of all lines is greatly facilitated [for *(14)*, see Table 2].

The signal of the trimethylsilyl group in *(14)* is shifted towards higher field strenghts than that of hexamethyldisiloxane, and the signal of the trimethylstannyl group towards lower field strengths than that of hexamethyldistannoxane. Similarly, the values of $J(^1H\text{-}C\text{-}^{29}Si)$ and $J(^1H\text{-}C\text{-}^{117,119}Sn)$ are clearly decreased and increased, respectively, compared to those of the siloxanes. A slight effect is even observed for the coupling constant $J(^1H\text{-}^{13}C)$. This indicates an electron distribution in the Si-O-Sn bridge which corresponds to an increased polarity and reduced double-bond character for the Sn-O bond and to a decreased polarity with increased double-bond character of the Si-O bond. For other stannosiloxanes the NMR data indicate a similar situation and a gradation which depends on the number and nature of the alkyl and siloxy groups on the hetero-atom and which corresponds to that observed for germanosiloxanes.

The infrared spectra [25,27,29,33] of stannosiloxanes are characterized by an intense Si–O–Sn valence vibration in the region 950–980 cm^{-1} (Table 3), the position of which depends on the substituents on the silicon and tin atoms. Infrared measurements in the long-wavelength region and Raman measurements remain to be done.

Table 3. Physical constants for organostannosiloxanes

No.	Formula	M.p. [°C]	B.p. [°C/mm Hg]	ν_{as} (Si–O–Sn)	Ref.
(14)	$(CH_3)_3SiOSn(CH_3)_3$	−59	141/720	980	[12, 15, 29]
(17)	$(CH_3)_3SiOSn(C_2H_5)_3$		52/1	980	[27, 29]
(18)	$(C_2H_5)_3SiOSn(CH_3)_3$		49/1	985	[29]
(19)	$[(CH_3)_3SiO]_2Sn(CH_3)_2$	48	75/11	978/952/909	[12, 25, 29]
(20)	$[(CH_3)_3SnO]_2Si(CH_3)_2$		77/1	980/952	[29, 30]
(21)	$[(CH_3)_3SiO]_3Sn(CH_3)$	34	49/1	985/1070	[12, 29]
(22)	$[(CH_3)_3SiO]_4Sn$	64	60/1	938	[12, 25, 29]
(23)	$(C_6H_5)_3SiOSn(C_6H_5)_3$	139–140		966	[26, 33]
(24)	$[(C_6H_5)_3SiO]_2Sn(C_6H_5)_2$	148.5–149.5		962	[33]
(25)	$[(C_6H_5)_3SnO]_2Si(C_6H_5)_2$	94.5–96.5		980	[33]

C. Plumbosiloxanes

Until recently, the literature contained practically no detailed information about organoplumbosiloxanes, despite attempts to prepare modified siloxanes with lead and organolead structural elements [1,2].

1. Preparation [36]

Hexamethylplumbosiloxane *(15)*, the simplest organoheterosiloxane having an Si–O–Pb linkage, is rapidly formed in good yield, even at room temperature, from trimethylbromoplumbane and alkali metal trimethylsiloxides in the molar ratio of 1:1.

$$(CH_3)_3SiONa + BrPb(CH_3)_3 \rightarrow NaBr + (CH_3)_3Si{-}O{-}Pb(CH_3)_3 \qquad (h)$$

(15)

Homologues *(27)* to *(29)* can be readily prepared in a similar manner, if care is taken to avoid hydrolysis and oxidation [36].

It has not yet been possible to prepare higher plumbosiloxanes, *e.g.* with Si-O-Pb-O-Si or Pb-O-Si-O-Pb chains. The low solubility of dialkyl-lead dihalides in organic solvents prevents smooth reaction with siloxides. No alkali metal alkylplumboxides are as yet known.

[34] *H. Kriegsmann, H. Hoffmann,* and *S. Pischtschan*, Z. anorg. allg. Chem. *315*, 283 (1962).

[35] *H. Schmidbaur* and *H. Hussek*, unpublished work.

[36] *H. Schmidbaur* and *H. Hussek*, J. organomet. Chem. *1*, 257 (1964).

2. Properties [36]

The hexa-alkylplumbosiloxanes are all very mobile, colorless liquids with an unbearable odor, and presumably very poisonous. Their high volatility and unlimited miscibility with organic solvents is unusual for organolead compounds, such as halides, oxides, sulfides, alkoxides *etc.*, and may be useful for the synthesis of other organolead derivatives. The physical constants of the compounds are shown in Table 4.

It can be seen that *(15)* can be distilled even at normal pressure without decomposition, if the operation is carried out in an atmosphere of a dry inert gas. In the presence of oxygen, explosion occurs at about 140 °C, with evolution of black clouds of lead.

All plumbosiloxanes are highly reactive and very sensitive to heterolytic attack. The Pb–O–Si bridges are hydrolysed even by traces of moisture. Cleavage with Lewis acids (BCl_3, $AlCl_3$, $SOCl_2$) and Lewis bases (CH_3OH, CH_3Li, CH_3SH) shows that the reactive center is the Pb–O bond. The plumbosiloxanes are the most reactive heterosiloxanes of the Group IV elements (*i.e.* the Pb–O bond is the most reactive X–O bond). In addition, the Pb–C bonds are less stable than the analogous C–C–, Si–C, Ge–C, and Sn–C bonds, not only to heterolytic cleavage, but also to oxidation and heat.

3. Spectroscopic Investigations

Hexa-alkylplumbosiloxanes are excellent subjects for NMR spectroscopy [36]. The presence in sufficiently high concentrations of the isotopes ^{207}Pb, ^{29}Si and ^{13}C with nuclear spins leads to NMR spectra which are relatively complex but can be readily interpreted. Table 1 shows the NMR data for compound *(15)*, and Figure 1 shows the experimental (A) and the calculated (B) spectra of *(27)*.

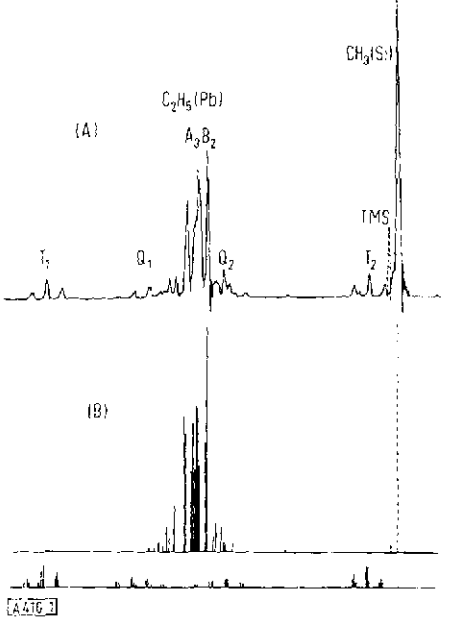


Fig. 1. Experimental (A) and calculated (B) NMR spectra of *Pb*-triethyl-*Si*-trimethylplumbosiloxane *(27)*.

T_1 and T_2 = Triplets from $^1H-C-C^{207}Pb/^1H-C-C-^1H$
Q_1 and Q_2 = Quartets from $^1H-C^{207}Pb/^1H-C-C-^1H$

The plumbosiloxanes occupy an extreme position in the series of heterosiloxanes of the Group IV elements, as regards polarity of the X–O bond and strengthening of the Si–O bond by π-bond character. This was to be expected from the classical electronegativity series C > Si ≈ Ge > Sn > Pb [37]. It is impossible to interpret the experimental findings by other assumptions [38, 39].

Table 4. Physical constants for organoplumbosiloxanes.

No.	Formula	M.p. [°C]	B.p. [°C/mm Hg]	ν_{as} (Si–O–Pb)	Ref.
(15)	$(CH_3)_3SiOPb(CH_3)_3$	−1	172/720	960	[12, 36]
(27)	$(CH_3)_3SiOPb(C_2H_5)_3$		111.5/10	961	[36]
(28)	$(C_2H_5)_3SiOPb(CH_3)_3$		65/1	957	[36]
(29)	$(C_2H_5)_3SiOPb(C_2H_5)_3$		100/1	957	[36]

The infrared bands of the plumbosiloxanes also show, to a first approximation, the gradations expected from the masses and force constants when compared with the infrared bands of analogous heterosiloxanes [12, 36].

D. Alumino- and Gallo-siloxanes

The alumino- and gallo-siloxanes are among the most interesting compounds encountered in heterosiloxane chemistry. Owing to the electron deficiency on the hetero-atom, the structural principles are entirely different, with the result that these compounds contrast significantly with the other types of heterosiloxanes. Moreover, the alumino- and gallo-siloxanes merit attention, since they are related to the purely inorganic aluminosilicates as the siloxanes are to quartz and the silicates. Table 5 lists a number of compounds of this group together with their physical constants.

Table 5. Physical constants of organo-alumino- and -gallo-siloxanes.

No.	Formula	M.p. [°C]	B.p. [°C/mm Hg] [a]	Ref.
(32a)	$[(CH_3)_3SiOAlCl_2]_2$	88–89	102/4	[41, 42, 45]
(32b)	$[(CH_3)_3SiOAlBr_2]_2$	113–114.5	127–128/4.5	[41, 42, 45]
(32c)	$[(CH_3)_3SiOAlI_2]_2$	100 (decomp.)	—	[45]
(33a)	$[(CH_3)_3SiOAlClH]_2$	20.5	63–65/1	[51]
(33b)	$[(CH_3)_3SiOAlBrH]_2$	7–8	54–57/1	[52]
(33c)	$[(CH_3)_3SiOAlIH]_2$	0–2	69–75/1 (decomp.)	[52]
(34a)	$[(CH_3)_3SiOAlH_2]_2$	80–82	40/1 (subl.)	[52]
(35)	$[H_3SiOAl(CH_3)_2]_2$	41–42	109–112 (extr.)	[53]
(36a)	$[(CH_3)_3SiOAl(CH_3)_2]_2$	45.5	81.5/11	[44, 54]
(36b)	$[(CH_3)_3SiOAl(C_2H_5)_2]_2$	105–113	115/1	[54]
(36c)	$[(C_2H_5)_3SiOAl(CH_3)_2]_2$	14–16	110–114/1	[52]
(38a)	$\{[(CH_3)_3SiO]_3Al\}_2$	238	155/1 (subl.)	[60, 61]
(38b)	$\{[(CH_3)_3SiO]_3Ga\}_2$	208	135/1 (subl.)	[60, 61]

[a] subl. = sublimes; extr. = extrapolated.

[37] *L. Pauling*: The Nature of the Chemical Bond. 3rd Edit., Cornell University Press, Ithaca, N.Y., 1960.

[38] *A. L. Allred* and *E. G. Rochow*, J. inorg. nuclear Chem. *5*, 269 (1958).

[39] Analogous investigations on related heterosilazanes have meanwhile lead to similar results: [21], *O. J. Scherer and M. Schmidt*, J. organomet. Chem. *2*, 490 (1964).

[40] *M. G. Voronkov*, *B. N. Dolgov*, and *A. N. Dmitrieva*, Dokl. Akad. Nauk U.S.S.R. *84*, 959 (1952); Chem. Abstr. *47*, 3228 (1953).

[41] *N. F. Orlov*, Dokl. Akad. Nauk U.S.S.R. *114*, 1033 (1957); Chem. Abstr. *52*, 2742 (1958).

[42] *A. H. Cowley*, *F. S. Fairbrother*, and *N. Scott*, J. chem. Soc. (London) *1959*, 717.

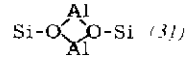
1. Organosiloxyaluminum Halides

Low molecular-weight compounds having Si–O–Al bridges are most readily prepared by cleavage of siloxanes with aluminum halides. In this way, hexaorganodisiloxanes yield triorganosiloxyaluminum halides *(30)* in addition to triorganohalogenosilanes [40–42]:

$$R_3Si{-}O{-}SiR_3 + AlX_3 \rightarrow R_3SiX + R_3Si{-}O{-}AlX_2 \quad (i)$$

X = Halogen *(30)*

Reactions of this type have been known for more than ten years, and their mechanism has recently attracted much interest [43]. For a long time, however, the structures of the products remained unknown. Recent experiments [44,45] have shown that compounds of the type $R_3Si{-}O{-}AlX_2$ always occur as coordination dimers (Figure 2) which are characterized by a planar (or almost planar) structure *(31)*. The planar arrangement of the ligands at the triply coordinated oxygen



(31)

atoms in the four-membered ring appears to be of similar significance as that of the silyl groups on the nitrogen atom in planar trisilylamine [46,47].

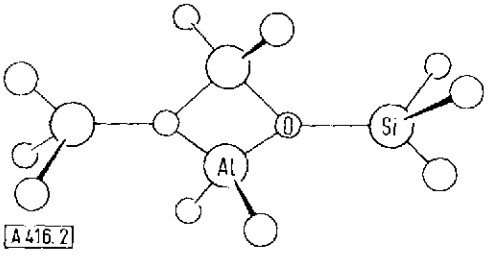


Fig. 2. Structure of the dimeric organosiloxyaluminum halides.

In the light of these results, the course of the cleavage of linear and cyclic diorganopolysiloxanes $(R_2SiO)_n$, n = 3, 4, ∞, with AlX_3 was a surprise: In agreement with Russian authors [48], we have found [49] that the reaction yields $[(CH_3)_2Si]_4Al_3Cl_5O_6$ (m.p. 152–154 °C), which can be crystallized and sublimed, the structure of which, however, is still unknown. Corresponding reactions with $AlBr_3$ and AlI_3 give products of similar composition: $[(CH_3)_2Si]_4Al_3(Y)_5O_6$ [m.p. 159 °C with Y = Br; decomposition point 160 °C with Y = I] [49]. The same heterosiloxanes can be prepared in high yields from octamethyltrisiloxane (trimethylchlorosilane occurs as a by-product; α,ω-dichlorodimethylsiloxanes are also formed in the case of cyclo- and poly-siloxanes [48, 49]). Investigations of these substances are still incomplete [*].

As mentioned above, trialkylsiloxyaluminum dihalides are also formed in the cleavage of heterosiloxanes of germanium, tin, and lead with aluminum halides [18,45], but not from carbosiloxanes [45]. The Si–O–C bridge is always broken at the Si–O bond and never at the C–O bond, so that the products are halogenosilanes and alkoxyaluminum dihalides, as shown in Equation (k).

$$R_3Si{-}O{-}CR_3 + AlX_3 \rightarrow R_3SiX + R_3C{-}O{-}AlX_2 \quad (k)$$

X = Halogen

2. The Reaction of Gallium Halides with Siloxanes [50]

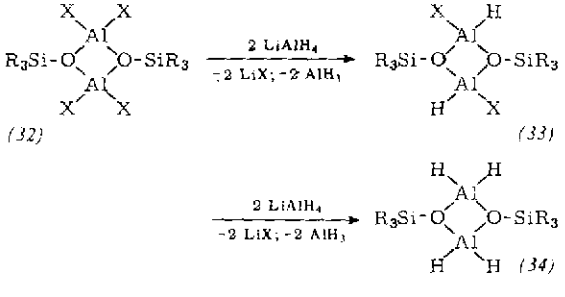
Contrary to expectations, the reaction of gallium halides with organosiloxanes does not yield the desired siloxygallium dihalides. Even under mild conditions, the gallium is always alkylated:

$$(CH_3)_3Si{-}O{-}Si(CH_3)_3 + GaCl_3 \rightarrow CH_3GaCl_2 + (CH_3)_3SiCl + [(CH_3)_2SiO]_n \quad (l)$$

Octamethylcyclotetrasiloxane and $GaCl_3$ give, in addition to CH_3GaCl_2, only a non-volatile methylsiloxane polymer containing halogen. Owing to the favorable reaction conditions, the ease of isolation, and the good yields, this is the best method of preparing methylgallium dihalides [50].

3. Organosiloxyaluminum Halide Hydrides [51]

The halogen atoms on the four-membered aluminosiloxane ring *(32)* can be replaced without opening the ring. Hydrogenation with lithium aluminum hydride leads, *via* a complex aluminum hydride, to trialkylsiloxyaluminum halide hydrides *(33)*, and ultimately to the dihydrides *(34)*.



These aluminum hydrides, which can be readily crystallized and distilled, decompose, at elevated temperatures, with elimination of triorganosilanes:

$$(R_3Si{-}O{-}AlXH)_2 \rightarrow 2\ R_3SiH + 2/n(AlXO)_n \quad (m)$$

Compound *(34)* tends to polymerize and is stable only for a short time as the dimer [52].

[43] For references, see [6] and [45].

[44] *H. Schmidbaur* and *M. Schmidt*, J. Amer. chem. Soc. *84*, 1069 (1962).

[45] *H. Schmidbaur, H. Hussek*, and *F. Schindler*, Chem. Ber. *97*, 255 (1964).

[46] *K. Hedberg*, J. Amer. chem. Soc. *77*, 6491 (1955). See also [8].

[47] *J. Goubeau* and *J. Jimenez-Barbera*, Z. anorg. allg. Chem. *303*, 217 (1960).

[48] *K. A. Andrianov*, Russian Chem. Rev. *5*, 253 (1963), in English.

[49] *H. Schmidbaur* and *W. Findeiss*, unpublished work.

[*] Note added in proof: Meanwhile other authors have reached the same conclusions. However, they too were unable to solve the structural problem (*C. Ercolani* and *G. Sartori*, Rome, personal communication). Infrared and NMR-spectroscopic investigations [49] as well as an X-ray structural analysis are in progress (*P. Corradini*, Naples).

[50] *H. Schmidbaur* and *W. Findeiss*, Angew. Chem. *76*, 752, 753 (1964); Angew. Chem. internat. Edit. *3*, 696, 697 (1964).

[51] *H. Schmidbaur* and *F. Schindler*, Chem. Ber. *97*, 952 (1964).

[52] *H. Schmidbaur* and *F. Schindler*, unpublished work; *F. Schindler*, Ph. D. Thesis, Universität Marburg, 1964; Angew. Chem. *75*, 1115 (1963); Angew. Chem. internat. Edit. *3*, 151 (1964).

Compound *(35)* has the "reverse" configuration, *i.e.* hydrogen on the silicon atom and methyl groups on the aluminum atom; this compound is formed by cleavage of disiloxane with dimethylaluminum bromide:

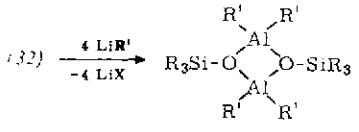
$$2\ H_3Si{-}O{-}SiH_3 + [(CH_3)_2AlBr]_2 \rightarrow [H_3Si{-}O{-}Al(CH_3)_2]_2 + 2\ H_3SiBr \quad (n)$$

(35)

It is very unstable and decomposes spontaneously with the elimination of monosilane [53].

4. Pentaorganoaluminosiloxanes [54]

The parent members of the aluminosiloxanes carrying only organic substituents, $R_3Si{-}O{-}AlR_2$, can be obtained in high yields and in a very pure form by two versatile methods. Substitution of the halogen atoms of the organosiloxyaluminum halides *(32)* with organolithium compounds leads to aluminosiloxanes *(36)* without ring cleavage.



(36)

Another method of preparation is the reaction of diorganohalogenoalanes with alkali metal triorganosiloxides:

$$2\ R'_2AlX + 2\ MOSiR_3 \rightarrow 2\ MX + [R_3Si{-}O{-}AlR'_2]_2 \quad (o)$$

M = Alkali metal *(36)*

In some cases cleavage of siloxanes with trialkylaluminum is successful [55]:

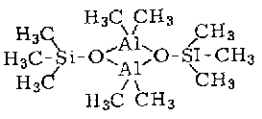
$$2\ (C_2H_5)_3Al + 2\ (CH_3)_3Si{-}O{-}Si(CH_3)_3 \rightarrow 2\ C_2H_4 + 2\ (CH_3)_3SiH + [(CH_3)_2Si{-}O{-}Al(C_2H_5)_2]_2 \quad (p)$$

(36b)

All aluminosiloxanes obtained by these methods are dimeric. Spectroscopic investigations [54] and X-ray structural analyses [56] show that these molecules, like the isosteric silazane *(37)* [57,58], have a planar skeleton. The correspondence of the physical data of *(36a)* and *(37)* is amazing and reflects the largely analogous nature of the bonds [54], in particular the planar arrangement of the ligands on the oxygen and nitrogen atoms. This is confirmed by ^{1}H-NMR spectroscopy [44,54].

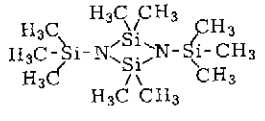
Interestingly enough, the corresponding dialkyl-t-butoxyaluminum compounds are also dimeric and have similar structures although they do not contain silicon. However, the planarity of these ring systems has not yet been checked, and an irregular geometry may be found in these cases [59].

The pentaorganoaluminosiloxanes are thermally relatively stable. They decompose above about 180 °C with the elimination of tetraorganosilanes. The Al–C bonds render these compounds very reactive and make them sensitive to oxidation and hydrolysis. Compared to other alkylaluminum compounds, however, they are relatively inert.



(36a)

m. p. 45.5 °C
b. p. 85 °C/15 mm
monoclinic ($P2_1/n$): $\beta = 104°49'$
$a = 7.00$, $b = 13.22$
$c = 11.02$ Å
$d_4^{25} = 0.997$



(37)

m. p. 38.5 °C
b. p. 85 °C/7 mm
monoclinic ($P2_1/n$): $\beta = 104°23'$
$a = 6.75$, $b = 13.18$
$c = 11.22$ Å
$d_4^{25} = 0.984$

5. Tris(triorganosiloxy)-aluminum and -gallium Compounds [60,61]

Complete substitution of the halogen atoms of the aluminum and gallium trihalides by reaction with alkali metal siloxides leads to another class of alumino- and gallo-siloxanes *(38)* in which only siloxy groups are bonded to the metal atoms.

$$2\ MCl_3 + 6\ NaOSi(CH_3)_3 \rightarrow \{[(CH_3)_3SiO]_3M\}_2 + 6\ NaCl$$

M = Al, Ga *(38)*

Compounds of type *(32)* also react with siloxides to form tris(triorganosiloxy)aluminum compounds *(38a)*.

$$(32) + 4\ MOSi(CH_3)_3 \rightarrow 4\ MX + \{[(CH_3)_3SiO]_3Al\}_2$$

(38a)

In some cases silanols react with metallic aluminum to form aluminosiloxanes of type *(38a)*, with liberation of hydrogen [62,63].

Tris(triorganosiloxy)-aluminum and -gallium compounds have a strong tendency to form coordination dimers [60,61,64]. Physico-chemical investigations indicate a structure *(39)* in which the metals carry both bridging and terminal siloxy residues. This is indicated by the two ^{1}H-NMR signals present in both cases. As expected, the bridge-siloxy signals are more strongly shifted towards lower field strengths; this is characteristic of a decreased (p → d)π-stabilization of the Si–O–Al bridges. Similarly, infrared investigations [64] show the presence of two types of siloxy groups. Here, too, the analogous t-butoxyaluminum compounds have similar structures [65].

[53] *W. A. Kriner, A. G. MacDiarmid,* and *E. Ch. Evers,* J. Amer. chem. Soc. *80,* 1546 (1958).

[54] *H. Schmidbaur,* J. organomet. Chem. *1,* 28 (1963).

[55] *H. Jenkner,* Z. Naturforsch. *14b,* 133 (1959).

[56] *P. J. Wheatley,* J. chem. Soc. (London) *1963,* 2562.

[57] *W. Fink,* Helv. chim. Acta *45,* 1081 (1962).

[58] *P. J. Wheatley,* J. chem. Soc. (London) *1962,* 1721.

[59] *E. G. Hoffmann* and *W. Tarnau,* Angew. Chem. *73,* 578 (1961).

[60] *H. Schmidbaur* and *M. Schmidt,* Angew. Chem. *74,* 328 (1962); Angew. Chem. internat. Edit. *1,* 328 (1962).

[61] *H. Schmidbaur,* Chem. Ber. *96,* 2692 (1963).

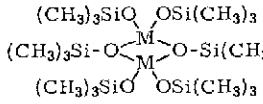
[62] *K. A. Andrianov* et al., Izv. Akad. Nauk U.S.S.R., Otdel. khim. Nauk *1956,* 74; *1959,* 466; Chem. Abstr. *53,* 17561 (1959).

[63] *K. A. Andrianov, A. A. Zhdanov, N. A. Kurashevo,* and *V. G. Dulova,* Dokl. Akad. Nauk U.S.S.R. *112,* 1050 (1957).

[64] *D. G. Barraclough, D. C. Bradley, J. Lewis,* and *J. M. Thomas,* J. chem. Soc. (London) *1961,* 2601.

[65] *V. J. Shiner, D. Whittaker,* and *V. P. Fernandez,* J. Amer. chem. Soc. *85,* 2318 (1963).

The compounds *(38)* are relatively stable. They dismutate above 280 °C to form siloxanes and alumina. There is reason to believe that the dimers disappear only above 200 °C, and that it is the monomer which then decomposes. As water-repelling compounds they are fairly insensitive towards hydrolysis. In the presence of organic solvents (alcohol, acetone), however, solvolysis proceeds rapidly even at room temperature.



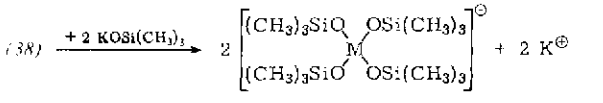
(38)

M = Al, Ga

6. Anionic Alumino- and Gallo-siloxanes [16, 66–69]

The tendency of the oxygen atoms in siloxane and heterosiloxane bridges to form stabilizing (p → d)π-bonds greatly restricts the donor strength of these atoms. Siloxanes and heterosiloxanes therefore are extremely weak Lewis bases. In agreement with this, the four-membered ring systems of type *(38)*, in which the high acceptor strength of the aluminum atoms forces the bridge-oxygen atoms to assume a donor function, are coordinately unsaturated. The tendency of the bridge-oxygen atoms to revert to the two-coordinated state and to form energetically more favorable (p → d)π-systems facilitates the addition of many nucleophilic reagents, and in particular permits the preparation of novel anionic heterosiloxanes.

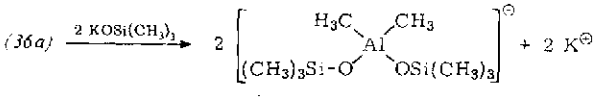
Compounds of type *(38)* react readily and completely with alkali metal siloxides, even at room temperature, to form alkali metal tetrakis(trimethylsilyl)-aluminates and -gallanates *(39)*.



(39)

M = Al, Ga

Similarly, pentamethylaluminosiloxane *(36a)* adds on alkali metal siloxides to form the new alkali metal octamethyldisiloxyalanates *(40)*.



(40)

The anions *(39)* and *(40)* can be regarded as structural units of the purely inorganic aluminosilicates and felspars which have been "monomerized" by organic substituents. (We have also prepared analogous heterosiloxanes of trivalent iron, which have a similar structure [70, 71]).

[66] *H. Schmidbaur*, Chem. Ber. *97*, 459 (1964).

[67] *H. Schmidbaur*, Angew. Chem. *75*, 137 (1963); Angew. Chem. internat. Edit. *2*, 94 (1963).

[68] *H. Schmidbaur*, Chem. Ber. *97*, 842 (1964).

[69] *H. Schmidbaur*, Angew. Chem. *75*, 683 (1963).

[70] *H. Schmidbaur* and *M. Schmidt*, J. Amer. chem. Soc. *84*, 3600 (1962).

[71] *H. Schmidbaur*, Chem. Ber. *97*, 836 (1964).

Substitution of the pseudo-alkali siloxide heptamethylstibiosiloxane *(16)* for the alkali metal siloxides in the reactions leading to *(39)* and *(40)* gives crystallizable products $[(CH_3)_4Sb]^{\oplus}[M(OSi(CH_3)_3)_4]^{\ominus}$ with M = Al, Ga, Fe [68] which are isomorphously orthorhombic (Table 6). According to X-ray analysis, the heterosiliconate anions have the C_{2v}-symmetry shown in Figure 3. The bond lengths and angles [72] as well as the infrared and NMR spectra [68] confirm the assumed stabilization by π-bonding of the Si–O–Al bridges, which thus correspond to those of the aluminosilicates.

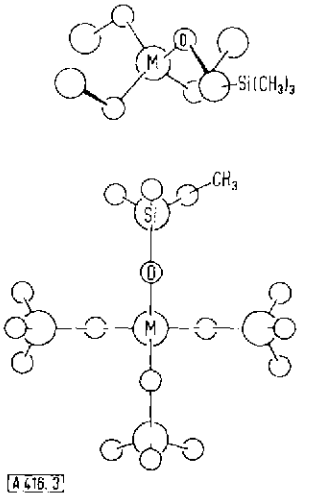


Fig. 3. Structure of the heterosiliconate anions $\{M[OSi(CH_3)_3]_4\}^{\ominus}$

In accordance with this, the compounds have a high thermal stability and decompose only above 250–300 °C. However, their chemical stability is relatively low and is greatly surpassed by that of the corresponding siloxanes and silicates. This is again attributable to the ease of cleavage of the metal-oxygen bonds. Degradations of inorganic silicates, in which Si-O-Si skeletons were "picked out" by simultaneous "saturation" of the functional groups formed with trimethylsilanol, have recently shown [73] that the reactive center in the silicates is again the bond between the hetero-atom and oxygen, and not the Si-O bond.

Heterosiloxanes of thallium have not yet been described. Attempts to cleave siloxanes with $InCl_3$ were unsuccessful [74]; the reaction of $InCl_3$ with alkali metal siloxides led to non-uniform products [74, 74a].

[72] *P. J. Wheatley*, J. chem. Soc. (London) *1963*, 3200.

[73] *Ch. W. Lentz*, Inorg. Chem. *3*, 574 (1964).

[74] *H. Schmidbaur*, *J. A. Perez-Garcia*, and *W. Findeiss*, unpublished work; see also [50].

[74a] Note added in proof: Meanwhile pentamethylgallosiloxane *(36c)* (m.p. 16.5 °C; b.p. 34.5 °C/3 mm) and pentamethylindosiloxane *(36d)* (m.p. 16.5 °C; b.p. 57 °C/3 mm) have been synthesized from trimethylsilanol and trimethylgallium etherate or trimethylindium etherate, respectively:

$$2\ (CH_3)_3M{\cdot}O(C_2H_5)_2 + 2\ HOSi(CH_3)_3 \xrightarrow{-2\,(C_2H_5)_2O} 2\ CH_4 + [(CH_3)_3SiOM(CH_3)_2]_2$$

(36c), M = Ga
(36d), M = In
(36e), M = Tl

Compound *(36d)* is the first indium-containing heterosiloxane that has been prepared. Analyses and molecular-weight determinations as well as infrared and NMR data are consistent with structures analogous to *(36a)*. – Recently pentamethylthallosiloxane *(36e)*, m.p. 98°C, subl. 90°C/1mm, has been prepared from dimethylthallium chloride and sodium trimethylsiloxide.

Table 6. Physical and X-ray data of tetramethylstibonium tetrakis(trimethylsilyl)metallates [67,68].

No.	Formula	M.p. [°C]	Subl. temp. [°C/mm Hg]	d_{exp}	d_{calc}	U[Å]
(41a)	$[(CH_3)_4Sb]\{Al[OSi(CH_3)_3]_4\}$	180.5	180/1	1.17	1.191	1577.8
(41b)	$[(CH_3)_4Sb]\{Ga[OSi(CH_3)_3]_4\}$	190.5	190/1	1.26	1.275	1584.4
(41c)	$[(CH_3)_4Sb]\{Fe[OSi(CH_3)_3]_4\}$	193.0	190/1	1.25	1.246	1584.9

d_{exp} = Density [g/cm³] determined by flotation.
d_{calc} = Density [g/cm³] calculated from crystallographic data.
U = Size of the unit cell.

E. Arsinosiloxanes

Of the heterosiloxanes containing elements of Group V, those with nitrogen and phosphorus have been deliberately omitted from this paper, since, according to their properties, they should be regarded rather as silyl esters of the oxyacids of these elements than as heterosiloxanes. For the same reason the boron derivatives are omitted from the heterosiloxanes of Group III elements [75].

Arsenic and antimony form a series of heterosiloxane monomers and polymers, in which these elements exhibit various valence states (see Table 7) [1,2,31,76–82].

Table 7. Physical constants of arsino- and stibio-siloxanes.

No.	Formula	M.p. [°C]	B.p. [°C/mm Hg]	Ref.
(42)	$(CH_3)_3SiOAs(CH_3)_2$	−70	116/725	[31,76]
(43)	$[(CH_3)_3SiO]_2As(C_6H_5)$	119–120		[79]
(45)	$(CH_3)_3SiOSb(CH_3)_2$		144/720	[31,76]
(46)	$(CH_3)_3SiOSb(C_6H_5)_2$	59		[76]
(47)	$(CH_3)_3SiOSb(CH_3)_4$	−32	164–165/725	[31,76]
(48)	$[(CH_3)_3SiO]_2Sb(CH_3)_3$	21	210/725	[31,76]
(49)	$(CH_3)_3SiOSb(C_6H_5)_4$	76–78		[76]
(50)	$[(CH_3)_3SiO]_2Sb(C_6H_5)_3$	89	161/1	[76]

1. Preparation

The parent member *(42)* of the arsinosiloxanes with trivalent arsenic is formed in high yield from dimethylchloroarsine and sodium trimethylsiloxide [31,76]:

$$(CH_3)_2AsCl + (CH_3)_3SiONa \rightarrow NaCl + (CH_3)_3Si{-}O{-}As(CH_3)_2 \quad (q)$$
(42)

Phenyl compounds such as *(43)* are also readily obtainable by this method.

Heterosiloxanes with pentavalent arsenic (which, however, has a coordination number of only 4) can be synthesized by oxidation of arsinosiloxanes such as *(42)*, and also from halogenosilanes and metal salts of the corresponding organoarsonic acids [79].

All attempts to prepare arsinosiloxanes with 5-coordinated arsenic have so far failed [76]. The reactions of organoarsenic halides of the types R_4AsX, R_3AsX_2, and R_2AsX_3 with siloxides did not yield the desired products. In the case of the tetra-alkylarsonium halides the reason probably is the insolubility of these (purely ionic [83]) salts in organic solvents. Although the trialkylarsenic dihalides did react owing to more favorable solubilities and structures, the products were trialkylarsenic oxides and siloxanes:

$$(CH_3)_3AsCl_2 + 2\ NaOSi(CH_3)_3 \rightarrow 2\ NaCl + (CH_3)_3AsO + (CH_3)_3Si{-}O{-}Si(CH_3)_3 \quad (r)$$

It may be assumed that *(44)* is formed as an intermediate and decomposes even under mild conditions to give the above products. Thus the coordination number 5 on the arsenic

$$(CH_3)_3SiO\overset{\curvearrowright}{O}{-}As(CH_3)_3{-}\overset{\curvearrowright}{O}Si(CH_3)_3 \quad (44)$$

atoms is avoided by formation of a semipolar double bond to the oxygen atom.

2. Properties

Arsinosiloxanes with trivalent arsenic are stable, colorless, malodorous compounds, and, like the germanosiloxanes, are sensitive to solvolysis. A pronounced sensitivity to oxidation is also noticeable, particularly in the case of the aliphatic derivatives. Thus *(42)* can be distilled in a dry inert-gas atmosphere at 116 °C without decomposition, but is immediately oxidized and hydrolysed in contact with air, ultimately yielding trimethylsilanol and dimethylarsonic acid [76].

Like almost all other heterosiloxanes, the arsinosiloxanes are degraded by thionyl chloride [31,76]; this demonstrates the ease of heterolytic cleavage and can serve as proof of constitution:

$$(CH_3)_3Si{-}O{-}As(CH_3)_2 + SOCl_2 \rightarrow (CH_3)_3SiCl + SO_2 + (CH_3)_2AsCl \quad (s)$$

By contrast, the Si–O–Si bridge in siloxanes does not give this reaction under comparable conditions.

[75] These compounds will form the subject of a review article to be published later.

[76] *H. Schmidbaur, H. S. Arnold,* and *E. Beinhofer,* Chem. Ber. *97,* 449 (1964).

[77] *M. Schmidt* and *H. Schmidbaur,* Angew. Chem. *71,* 553 (1959).

[78] *M. Schmidt, I. Ruidisch,* and *H. Schmidbaur,* Chem. Ber. *94,* 2451 (1961).

[79] *B. L. Chamberland* and *A. G. MacDiarmid,* J. Amer. chem. Soc. *82,* 4542 (1960); *83,* 549 (1961).

[80] *M. G. Voronkov* and *N. F. Orlov,* Izv. Akad. Nauk U.S.S.R., Otdel. khim. Nauk *1959,* 1506; Chem. Zbl. *1961,* 7155.

[81] *K. A. Andrianov, A. A. Zhdanov,* and *F. A. Kashutina,* Dokl. Akad. Nauk U.S.S.R. *126,* 1261 (1959); Chem. Abstr. *53,* 21624 (1959).

[82] *R. M. Kary* and *K. C. Frisch,* J. Amer. chem. Soc. *79,* 2140 (1957).

[83] *E. Collins, D. J. Sutor,* and *F. G. Mann,* J. chem. Soc. (London) *1963,* 4051.

3. Spectroscopic Investigations

Arsinosiloxanes have so far been investigated by infrared spectroscopy [76, 79] only to establish the characteristic frequencies. The valence vibration ν_{as} (Si-O-As) for derivatives with aliphatic substituents is at 934 cm^{-1}, and that for derivatives with aromatic substituents at 877 cm^{-1} [79]. NMR data are not yet available.

F. Stibiosiloxanes

Our investigations on the heterosiloxanes of antimony were more successful than those on arsinosiloxanes, since many derivatives of the pentavalent element could be obtained easily in this case [76].

1. Preparation

Reaction of dimethylbromostibine with alkali metal trimethylsiloxides leads directly to high yields of the simplest organostibiosiloxane compound *(45)* with trivalent antimony:

$$(CH_3)_2SbBr + (CH_3)_3SiONa \rightarrow NaBr + \underset{(45)}{(CH_3)_3Si{-}O{-}Sb(CH_3)_2} \quad (t)$$

The alkylhalogenostibines $(CH_3)_4SbCl$ and $(CH_3)_3SbCl_2$ also react smoothly with alkali metal siloxides to yield the stibiosiloxanes *(47)* and *(48)* with 5-coordinated antimony:

$$(CH_3)_4SbCl + LiOSi(CH_3)_3 \rightarrow LiCl + \underset{(47)}{(CH_3)_3Si{-}O{-}Sb(CH_3)_4}$$

$$(CH_3)_3SbCl_2 + 2\ LiOSi(CH_3)_3 \rightarrow 2\ LiCl + \underset{(48)}{(CH_3)_3Si{-}O{-}Sb(CH_3)_3{-}O{-}Si(CH_3)_3}$$

Aryl-substituted stibiosiloxanes of both tri- and pentavalent antimony (Table 7) can be synthesized in the same way.

2. Properties

The stibiosiloxane *(45)* is much more sensitive to hydrolysis and oxidation than the arsinosiloxane *(42)*; it explodes in the presence of oxygen at about 40 °C. However, this instability is much less pronounced in the case of the aryl derivative *(46)*. On the other hand, the stibiosiloxanes having pentavalent antimony are stable in the presence of oxygen even at high temperatures, but are all sensitive to hydrolysis.

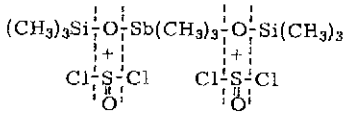
Stibio(V)-siloxanes such as *(47)* are unique pseudo-alkali siloxides. Their pronounced tendency, on heterolytic cleavage to split off the sp^3d-hybridized 5-coordinated antimony atom in tetra-alkylstibonium cations with an sp^3-hybridized antimony atom makes these compounds suitable for many applications [14, 67, 68]. Hydrolysis of *(47)* yields strongly alkaline solutions of tetramethylstibonium hydroxide:

$$(CH_3)_3Si{-}O{-}Sb(CH_3)_4 + H_2O \rightarrow [(CH_3)_4Sb]^{\oplus}OH^{\ominus} + (CH_3)_3SiOH \quad (u)$$

Acid anhydrides convert *(47)* into the stibonium salts. Disiloxanes are formed as by-products:

$$2\,(CH_3)_3Si{-}O{-}Sb(CH_3)_4 + SO_2 \rightarrow [(CH_3)_4Sb]_2^{\oplus}SO_3^{2\ominus} + (CH_3)_3Si{-}O{-}Si(CH_3)_3 \quad (v)$$

Compound *(48)* is one of the thermally and chemically most stable heterosiloxanes. It is solvolysed only slowly by water and alcohols. Degradation with thionyl chloride yields trimethylchlorosilane, trimethyldichlorostibine, and sulfur dioxide:

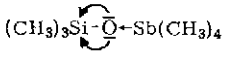


$$\rightarrow 2\ (CH_3)_3SiCl + (CH_3)_3SbCl_2 + 2\ SO_2 \quad (w)$$

Bis(trimethylsiloxy)triphenylstibine *(50)* is stable up to about 280 °C.

3. Spectroscopic Investigations

The abnormal behavior of *(47)* as a "stibonium siloxide" causes a particularly large chemical shift of the ^{1}H-NMR signal of the trimethylsiloxy group and a distinct reduction of the coupling constants $J(^1H{-}C{-}^{29}Si)$ and $J(^1H{-}^{13}C)$. An electron distribution in the heterosiloxane bridge as shown in *(47a)* evidently facilitates



(47a)

formation of the stibonium cation and rehybridization of the antimony atom. As expected, compound *(48)* does not show these strong shifts (cf. Table 2) [76].

Stibiosiloxanes can be recognized in the infrared spectra by characteristic Si–O–Sb valence vibrations in the region of 940–980 cm^{-1}.

Heterosiloxanes of bismuth are unknown, and, to our knowledge, have not been investigated. Heterosiloxanes containing elements of Groups VI and VII of the periodic table must be classified almost exclusively as silyl esters of the inorganic acids, according to their properties.

These silyl esters, the numerous siloxy derivatives of the transition elements, and the metal siloxides will form the subject of a review article to be published later.

IV. Conclusion

Numerous attempts have been made to prepare from heterosiloxanes new inorganic polymers, which are superior to the silicones in chemical stability. The results, however, have been relatively poor. This seems

understandable in the light of recent investigations. Nevertheless, the incorporation of hetero-atoms may be of advantage in preparing siloxanes for special applications. The properties of the heterosiloxanes synthesized so far clearly show the wide range of possibilities.

The author's own investigations reported in this article were made possible only by the dedicated cooperation of Dr. H. S. Arnold, Dipl.-Chem. W. Findeiss, Dr. H. Hussek, Dr. J. A. Perez-Garcia, and Dr. F. Schindler. We would like to thank Prof. Max Schmidt for his constant and generous support.

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Light-Induced Formation of Acids from Cyclic Ketones

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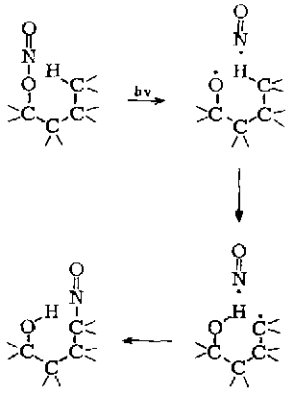
Ultraviolet irradiation of aqueous solutions of cyclic ketones having a tetrahedral carbon atom in at least one of the two positions adjacent to the light-absorbing carbonyl group results in ring opening accompanied by the formation of a carboxylic acid. Cyclohexadienones which are blocked in the ortho-position are converted to hexadienoc acids. Cycloalkanones give saturated carboxylic acids and, in the presence of oxygen, also some unsaturated ones. The scope of the reactions is illustrated, and favorable conditions are described. The structure of the products and the route by which they are presumably formed are discussed.

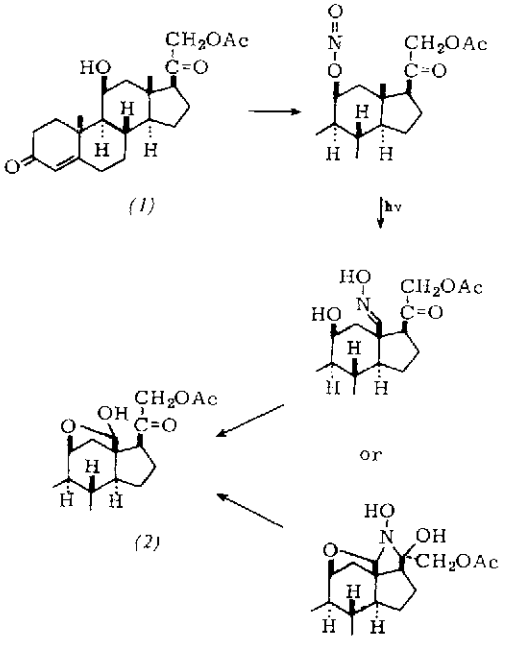
I. Introduction

Much work has recently been carried out in the field of organic photochemistry, since both efficient chromatographic methods capable of separating complex mixtures of products, and serviceable light sources [*] are now available.

Photochemical reactions are no longer curiosities, even in the syntheses of natural products. A few examples may serve to illustrate this:



Scheme 1. Principle of the Barton reaction [1].



(1)

(2)

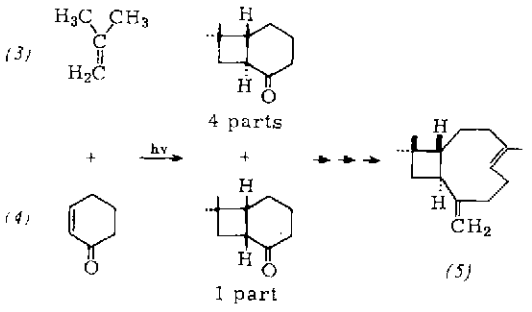
or

[*] The development of organic photochemistry has been reviewed by *A. Schönberg*: Präparative Organische Photochemie. Springer, Berlin 1958; *P. de Mayo* in: Advances in Organic Chemistry. Interscience, New York 1960, Vol. II, p. 367; *P. de Mayo* and *S. T. Reid*, Quart. Reviews *15*, 393 (1960); and by various authors in Advances in Photochemistry. Interscience, New York 1963, Vol. I. (The last-named book could not be considered for the purpose of this manuscript).

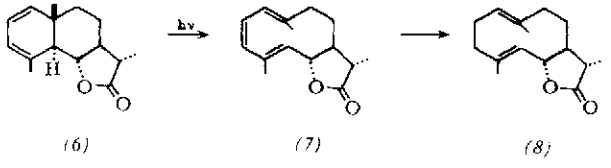
[1] *D. H. R. Barton, J. M. Beaton, L. E. Geller*, and *M. M. Pechet*, J. Amer. chem. Soc. *82*, 2640 (1960); *83*, 4076 (1961); *A. L. Nussbaum, F. E. Carlon, E. P. Oliveto, E. R. Townley, P. Kabasakalian*, and *D. H. R. Barton*, ibid. *82*, 2973 (1960); *D. H. R. Barton* and *J. M. Beaton*, ibid. *83*, 750 (1961); *84*, 199 (1962); *C. H. Robinson, O. Gnoj, A. Mitchel, R. Wayne, E. R. Townley, P. Kabasakalian, E. P. Oliveto*, and *D. H. R. Barton*, ibid. *83*, 1772 (1961); *A. L. Nussbaum, C. H. Robinson, E. P. Oliveto*, and *D. H. R. Barton*, ibid. *83*, 2400 (1961); *H. Reimann, A. S. Copomaggi, T. Strauss, E. P. Oliveto*, and *D. H. R. Barton*, ibid. *83*, 4481 (1961); *M. Akhtar* and *D. H. R. Barton*, ibid. *84*, 1496 (1962); *M. Akhtar, M. Akhtar, D. H. R. Barton, J. M. Beaton*, and *A. G. Hortmann*, ibid. *85*, 1512 (1963); *P. Kabasakalian* and *E. R. Townley*, ibid. *84*, 2711, 2723, 2724 (1962); *P. Kabasakalian, E. R. Townley*, and *M. D. Yudis*, ibid. *84*, 2716, 2718 (1962); *M. Akhtar* and *M. M. Pechet*, ibid. *86*, 265 (1964); Review: *A. L. Nussbaum* and *C. H. Robinson*, Tetrahedron *17*, 35 (1962).

The reaction discovered by *Barton* [1] (Scheme 1) provides a remarkably simple partial synthesis of aldosterone *(2)* from corticosterone acetate *(1)* [2].

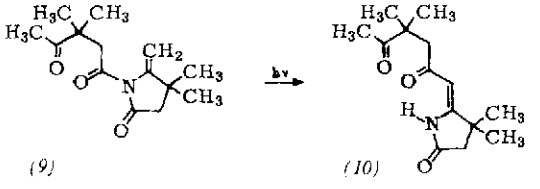
Corey has developed two elegant total syntheses of sesquiterpenes. The synthesis of DL-caryophyllene *(5)* begins with the photochemical addition of isobutylene *(3)* to cyclohexen-2-one *(4)* [3].



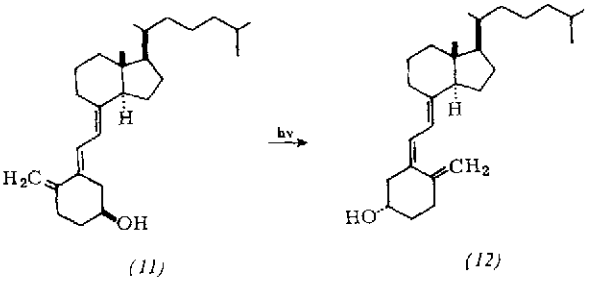
The synthesis of dihydrocostunolide *(8)* involves a light-induced rearrangement of the conjugated cyclohexadiene *(6)* to its valence isomer, the conjugated triene *(7)* [4].



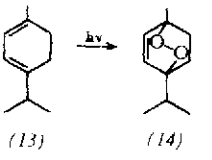
Eschenmoser used a photochemical acyl rearrangement *(9)* → *(10)* in his studies on the synthesis of highly substituted corrin derivatives [5].



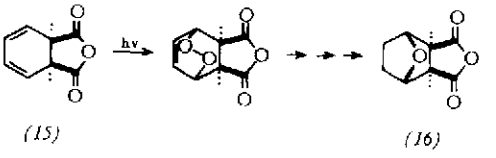
The last step in *Inhoffen*'s total synthesis of vitamin D_3 is the photochemical *trans-cis* isomerization of 5,6-*trans*-vitamin D_3 *(11)* to give the 5,6-*cis*-vitamin D_3 *(12)* [6].



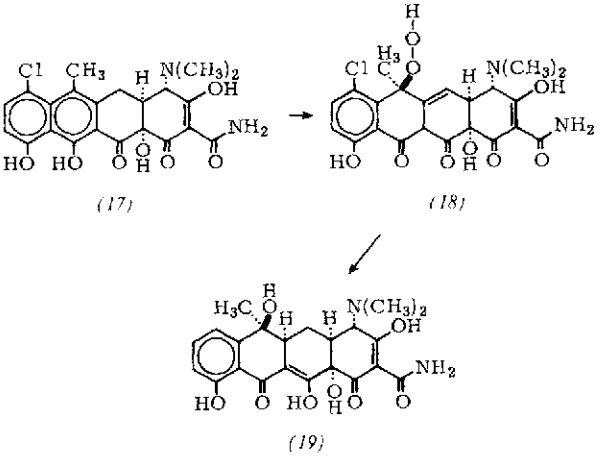
Schenck and *Ziegler* used the photosensitized autoxidation of α-terpinene *(13)* for the partial synthesis of ascaridol *(14)* [7],



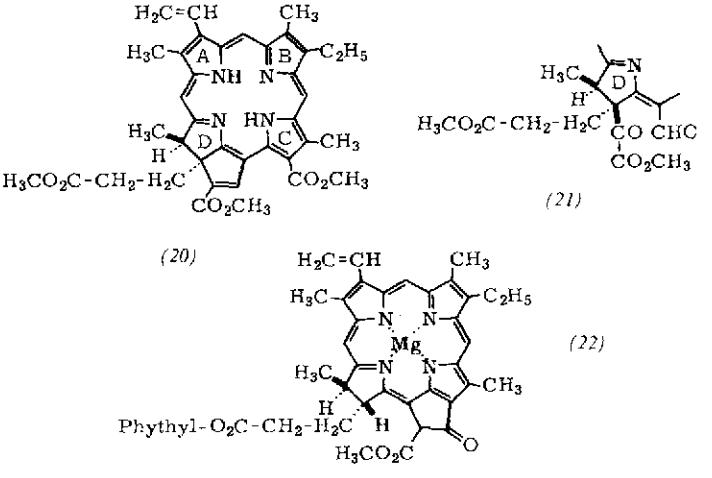
and were able to synthesize cantharidin *(16)* from dehydrocantharidin *(15)* using the same reaction [8].



According to *Scott* [9], the unsensitized photo-oxidation of 7-chlorоanhydrotetracycline *(17)* leads to formation of the 6-hydroperoxy compound *(18)* which can be catalytically hydrogenated to tetracycline *(19)*; this reaction sequence provides a partial synthesis of tetracycline.



Finally, the light-induced selective autoxidation of purpurin *(20)* to the ketoaldehyde *(21)* plays an important part in *Woodward*'s synthesis of chlorophyll a *(22)* [10].



[2] *D. H. R. Barton* and *J. M. Beaton*, J. Amer. chem. Soc. *82*, 2641 (1960); *83*, 4083 (1961).

[3] *E. J. Corey*, *R. B. Mitrau*, and *H. Uda*, J. Amer. chem. Soc. *85*, 362 (1963).

[4] *E. J. Corey* and *A. G. Hortmann*, J. Amer. chem. Soc. *85*, 4033 (1963).

[5] *A. Eschenmoser*, Pure appl. Chem. *7*, 297 (1963).

[6] *H. H. Inhoffen*, *G. Quinkert*, *H.-J. Hess*, and *H. Hirschfeld*, Chem. Ber. *90*, 2544 (1957); Review: *H. H. Inhoffen* and *K. Irmscher*, Fortschr. Chem. org. Naturstoffe *17*, 70 (1959); *K. Irmscher* in *H. Lettré*, *H. H. Inhoffen*, and *R. Tschesche*: Über Sterine, Gallensäuren und verwandte Naturstoffe. 2nd Edit., Thieme, Stuttgart 1959, Vol. II.

[7] *G. O. Schenck* and *K. Ziegler*, Naturwissenschaften *32*, 157 (1944); Review: *G. O. Schenck*, Angew. Chem. *64*, 12 (1952).

[8] *K. Ziegler*, *G. O. Schenck*, *E. W. Krockow*, *A. Siebert*, *A. Wenz*, and *H. Weber*, Liebigs Ann. Chem. *551*, 1 (1942); *G. O. Schenck* and *R. Wirtz*, Naturwissenschaften *40*, 581 (1953); Review: *G. O. Schenck* and *K. Ziegler* in: Festschrift A. Stoll. Birkhäuser, Basel 1957, p. 620.

[9] *A. I. Scott* and *C. T. Bedford*, J. Amer. chem. Soc. *84*, 2271 (1962).

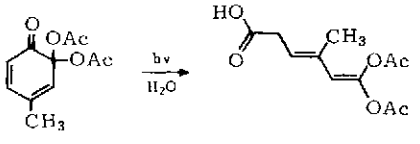
[10] *R. B. Woodward* et al., J. Amer. chem. Soc. *82*, 3800 (1960); Review: *R. B. Woodward*, Angew. Chem. *72*, 651 (1960); Pure appl. Chem. *2*, 383 (1961).

The following review deals with three photochemical reactions which lead to similar results: cyclic ketones are converted to open-chain carboxylic acids by the action of ultraviolet light. Although the mechanisms of the three reactions are not yet fully known, they certainly differ from one another in detail. Nevertheless, a review ought to be useful even at this stage. The following discussion will be deductive, *i. e.* for the sake of clarity the general principle will be explained first and after a provisional interpretation has been given, the experimental facts will be described.

II. Photochemical Formation of Substituted Hexadienoic Acids or Their Derivatives from ortho-Blocked Cyclohexadienones

1. General

If, for example, a solution of *(23)* in ether saturated with water is irradiated with the unfiltered light from a high-pressure mercury lamp, the unsaturated carboxylic acid *(24)* can be isolated after a short reaction-time.



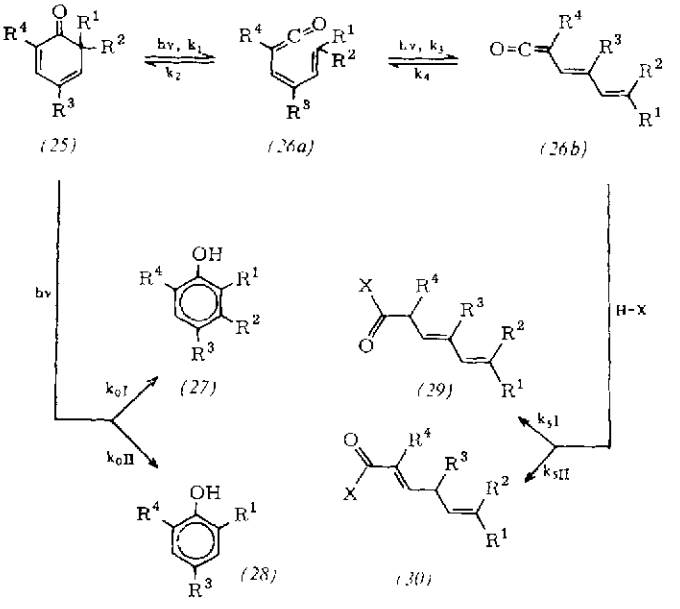
(23) *(24)*

This example is typical of the recently discovered photochemical ring-opening in cyclohexadienones having blocked *ortho*-positions [11], which has already proved to be widely useful (see Table 1). The yield of about 50 % [11a] is certainly not the best possible, since the ketene diacetate grouping in *(24)* is very unstable.

The ease with which the reaction proceeds depends on the number and positions of the substituents in the cyclohexadienone molecule, and on the nucleophilic character of the protonic compound H–X which must be added to the solution.

2. Reaction Mechanism

After the ketone molecule *(25)* [11b] is excited by the absorption of light, it is stabilized by cleavage of the bond between the carbonyl group and the adjacent tetrahedral carbon atom. This results in the formation of a conjugated diene-ketene which can occur in two geometrically isomeric configurations *(26a)* and *(26b)*. In the photostationary state the isomers *(25)*, *(26a)*, and *(26b)* are present together. Their ratio depends on the rate constants k_1, k_2, k_3, and k_4, *i. e.* on the wavelength of the incident light [11c], as well as on the difference between the free energies of *(25)* and *(26a)* on the one hand, and of *(26a)* and *(26b)* on the other. Disturbance of the system leading to a permanent chemical change, can occur either by reaction of the unsaturated ketenes with a nucleophile H–X containing a proton to give the acids or their derivatives, or by irreversible removal of the substituent R^2 from *(25)*. In the latter case, phenols are formed, either by a dienone/phenol photo-rearrangement to *(27)*, or by homolytic photo-dissociation followed by abstraction of hydrogen, *e.g.* from the solvent, to give *(28)*.



(25) *(26a)* *(26b)* *(27)* *(28)* *(29)* *(30)*

Scheme 2. Possible courses for the photochemical reaction of cyclohexadienones having blocked *ortho*-positions.

Assuming that the values of k_1, k_2, and k_4 are relatively large, the extent to which the competing reactions take place is determined by k_{0I} and k_{0II}, and by the sums $(k_3 + k_{5I})$ and $(k_3 + k_{5II})$. Provided that the substituents in *(26b)* do not cause mutual steric hindrance, k_3 is so large that a weakly nucleophilic reactant H–X is sufficient to make the rates of the reactions *via (26b)* considerably greater than the rate of phenol formation. If, on the other hand, mutual repulsion occurs between R^1 or R^2 and R^3, and between R^3 and R^4 in *(26b)*, k_3 decreases and the formation of the acid derivatives *(29)* and *(30)* predominates over the formation of phenols only if a strong nucleophile H–X (*e.g.* a primary amine) is used. With weaker nucleophiles H–X (*e.g.* H_2O), $(k_3 + k_{5I})$ and $(k_3 + k_{5II})$ are comparable to k_{0I} and k_{0II}, and in the extreme case only phenols are formed. This situation always exists when a solution of *(25)* is irradiated with ultraviolet light in the absence of protonic nucleophiles.

[11] *D. H. R. Barton* and *G. Quinkert*, Proc. chem. Soc. (London) *1958*, 197; J. chem. Soc. (London) *1960*, 1.

[11a] The yield determined by ultraviolet spectroscopy of the irradiation product is 86 %.

[11b] The structure of the excited ketones and the mechanism of their physical and chemical stabilization are not considered in this paper.

[11c] The photochemical investigations described here were usually carried out with the unfiltered light from a high-pressure mercury lamp. In glass vessels the reactions are qualitatively the same, though somewhat slower, as those in quartz vessels.

However, in the reactions leading to phenol formation the substituent R^2, which is to be eliminated, must have certain characteristics. The dienone/phenol photorearrangement *(25)* → *(27)* requires R^2 to be a nucleophilic group. The term "dienone/phenol photorearrangement" refers only to the overall reaction; the assumption that polar species are involved in the primary photochemical step [11–13] remains to be proved.

3. Scope of the Reaction

Table 1 contains a list of *ortho*-blocked cyclohexadienones, the photochemical behavior of which corresponds to Scheme 2. Apart from *(41)* (which will be discussed in greater detail below), all *ortho*-blocked cyclohexadienones investigated yield acid derivatives of type *(29)* or *(30)* in the presence of a suitable

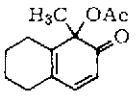
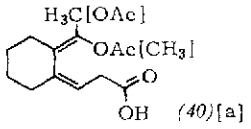
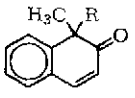
Table 1. Photochemical reactions of *ortho*-blocked cyclohexadienones according to Scheme 2.

Cyclohexadienone [type *(25)*]	Irradiation product [type *(29)* or *(30)*] in the presence of	
	water	cyclohexylamine
(31) $R^1 = CH_3$, $R^2 = OAc$, $R^3 = R^4 = H$ [11]	type *(29)* $R^1 = CH_3$, $R^2 = OAc$, $R^3 = R^4 = H$, $X = OH$ or $R^1 = OAc$, $R^2 = CH_3$, $R^3 = R^4 = H$, $X = OH$ [a, b]	type *(29)* $R^1 = CH_3$, $R^2 = OAc$, $R^3 = R^4 = H$, $X = NH{-}C_6H_{11}$ or $R^1 = OAc$, $R^2 = CH_3$, $R^3 = R^4 = H$, $X = NH{-}C_6H_{11}$ [c, d]
(32) $R^1 = R^2 = CH_3$ $R^3 = R^4 = H$ [11]	type *(29)* $R^1 = R^2 = CH_3$, $R^3 = R^4 = H$, $X = OH$ [d]	
(33) $R^1 = R^2 = OAc$ $R^3 = R^4 = H$ [14]	type *(29)* $R^1 = R^2 = OAc$, $R^3 = R^4 = H$, $X = OH$ [e]	
(23) [11]	type *(29)* $R^1 = R^2 = OAc$, $R^3 = CH_3$, $R^4 = H$, $X = OH$ [= *(24)*]	
(34) $R^1 = R^3 = CH_3$ $R^2 = OAc$, $R^4 = H$ [11]	oily mixture consisting mainly of type *(30)* $R^1 = R^3 = CH_3$, $R^2 = OAc$, $R^4 = H$, $X = OH$ or $R^1 = OAc$, $R^2 = R^3 = CH_3$, $R_4 = H$, $X = OH$ [c] and up to 10 % of a phenol [f]	type *(30)* $R^1 = R^3 = CH_3$, $R^2 = OAc$, $R^4 = H$, $X = NH{-}C_6H_{11}$ or $R^1 = OAc$, $R^2 = R^3 = CH_3$, $R^4 = H$, $X = NH{-}C_6H_{11}$ [d]
(35) $R^1 = R^4 = CH_3$, $R^2 = OAc$, $R^3 = H$ [11]	oily mixture of roughly equal parts of *(29)* and *(30)* type *(29)* $R^1 = R^4 = CH_3$, $R^2 = OAc$, $R^3 = H$, $X = OH$ or $R^1 = OAc$, $R^2 = R^4 = CH_3$, $R^3 = H$, $X = OH$ type *(30)* $R^1 = R^4 = CH_3$, $R^2 = OAc$, $R^3 = H$, $X = OH$ or $R^1 = OAc$, $R^2 = R^4 = CH_3$, $R^3 = H$, $X = OH$	type *(29)* $R^1 = R^4 = CH_3$, $R^2 = OAc$, $R^3 = H$, $X = NH{-}C_6H_{11}$ or $R^1 = OAc$, $R^2 = R^4 = CH_3$, $R^3 = H$, $X = NH{-}C_6H_{11}$ [d]
(36) $R^1 = R^4 = CH_3$, $R^2 = CH_2{-}CH{=}CH_2$, $R^3 = H$ [11]		type *(29)* $R^1 = C_2H_5$, $R^2 = R^4 = CH_3$, $R^3 = H$, $X = NH{-}C_6H_{11}$ or $R^1 = R^4 = CH_3$, $R^2 = C_2H_5$, $R^3 = H$, $X = NH{-}C_6H_{11}$ [d]
(37) $R^1 = R^3 = R^4 = CH_3$, $R^2 = CH_2{-}CH{=}CH_2$ [11]		type *(30)* $R^1 = C_2H_5$, $R^2 = R^3 = R^4 = CH_3$, $X = NH{-}C_6H_{11}$ or $R^1 = R^3 = R^4 = CH_3$, $R^2 = C_2H_5$ $X = NH{-}C_6H_{11}$ [d]
(38) $R^1 = R^3 = R^4 = CH_3$, $R^2 = OAc$ [11]	also in the absence of a nucleophile mixture of various phenols, including *(27)* with $R^1 = R^3 = R^4 = CH_3$, $R^2 = OAc$ [a] and *(28)* with $R^1 = R^3 = R^4 = CH_3$ [f]	type *(30)* $R^1 = OAc$, $R^2 = R^3 = R^4 = CH_3$, $X = NH{-}C_6H_{11}$ or $R^1 = R^3 = R^4 = CH_3$, $R^2 = OAc$, $X = NH{-}C_6H_{11}$ [c]

[12] *H. E. Zimmermann* and *D. I. Schuster*, J. Amer. chem. Soc. *84*, 4527 (1962); *H. E. Zimmermann*, Tetrahedron *1963*, 393.

[13] *W. G. Dauben, K. Koch, O. L. Chapman*, and *S. L. Smith*, J. Amer. chem. Soc. *83*, 1768 (1961); *O. L. Chapman* and *S. L. Smith*, J. org. Chemistry *27*, 2291 (1962).

Table I. (Continued)

 *(39)* [15]	 *(40)*[a] together with a mixture of phenols, including 1-methyl-5,6,7,8-tetrahydro-2-naphthol [g]	
 [15] *(41a)*, R = OAc *(41b)*, R = CH_3	mixture of dimers from *(41a)*	*(41b)* may yield <5% of amide

[a] Chemically proved.

[b] On irradiation in the absence of a nucleophile, *(28)* with $R^1 = CH_3$, $R^3 = R^4 = H$ is formed together with other phenols.

[c] Irradiation of *(31)* in the presence of aniline yields the crystalline anilide of type *(28)*, with $R^1 = CH_3$, $R^2 = OAc$, $R^3 = R^4 = H$, $X = NH{-}C_6H_5$ or $R^1 = OAc$, $R^2 = CH_3$, $R^3 = R^4 = H$, $X = NH{-}C_6H_5$.

[d] Verified by ultraviolet spectroscopy.

[e] Deduced by analogy.

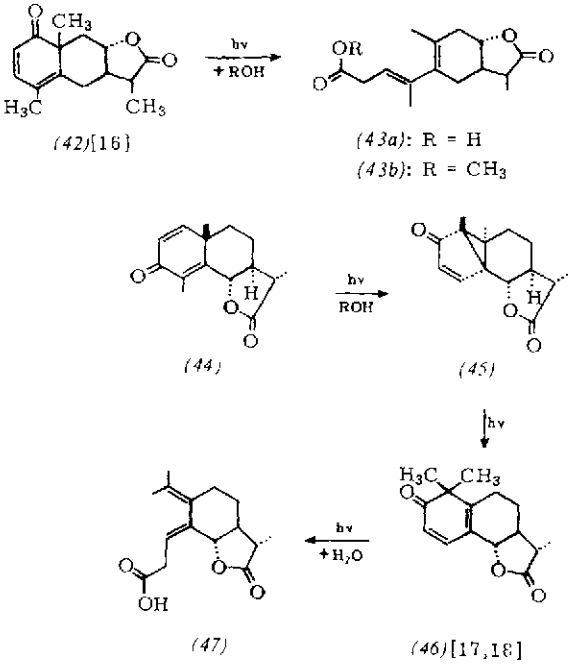
[f] Determined by paper chromatography.

[g] Mixture of phenols on irradiation in the absence of nucleophiles.

protonic nucleophile. The strongly nucleophilic cyclohexylamine gives the highest yields, and – with the exception of *(41)* – always leads to the product formed by ring cleavage. Water, being a weaker nucleophile (small values of k_{5I} and k_{5II}), does not form carboxylic acids if there are two 1,3-interactions [cf. *(26b)*] between substituents R^1 (or R^2) and R^3 and between R^3 and R^4. This is the case with, for example, *(37)* and *(38)*. In contrast to *(37)*, compound *(38)* can be converted to phenols. The formation of a phenol in competition with the formation of acid derivatives is noticeable even if only substituents R^1 (or R^2) and R^3 are present, as in *(34)*; up to 10% of phenol are formed in this case [13a]. A number of cyclohexadienones having an acetoxy group on the tetrahedral ring-carbon atom were irradiated in the absence of protonic compounds; they all reacted to form phenols [see *(31)*, *(38)*, *(39)*].

The peculiar behavior of *(41)* can be explained by the fact that one of the two C=C bonds of the cyclohexadienone system belongs to a fused aromatic ring. Consequently, *(41a)* preferentially undergoes dimerization in the presence of water, like an α,β-unsaturated ketone. Even in the presence of cyclohexylamine, no amide could be isolated from *(41b)* [15]; if any was formed, the yield must have been less than 5%. That the fused ring must be aromatic in order to produce the behavior of *(41)* is shown by the irradiation of *(39)*: in aqueous ether, the main product is *(40)*; this is accompanied by a mixture of phenols, in which 1-methyl-5,6,7,8-tetrahydro-2-naphthol has been identified. As expected, therefore, *(39)* behaves like *(34)* [15].

The light-induced conversion of *ortho*-blocked cyclohexadienones to dienecarboxylic acids has also been used in natural-product chemistry. Thus *(43a)* has been obtained from *(42)* which was derived from Ψ-santonin [16], and photosantoninic acid *(47)* has been produced from the recently discovered cyclohexadienone *(46a)* [17, 18], which is itself formed from santonin *(44)*, *via* lumisantonin *(45)*, by the action of light [19].



(42)[16] *(43a)*: R = H *(43b)*: R = CH_3 *(44)* *(45)* *(47)* *(46)*[17,18]

The racemization of optically active usnic acid [*(48a)* or *(48b)*] is interpreted [20] as involving the ketene *(49)*, which is formed by ring opening, as an intermediate. In keeping with this

[13a] The mother liquor was not investigated in the case of *(23)*.

[14] *G. Billek*, *J. Swoboda*, and *F. Wessely*, Tetrahedron *1962*, 909.

[15] *G. Quinkert*, *G. Buhr*, and *A. Strijewski*, unpublished work.

[16] *W. G. Dauben*, *D. A. Lightner*, and *W. K. Hayes*, J. org. Chemistry *27*, 1897 (1962).

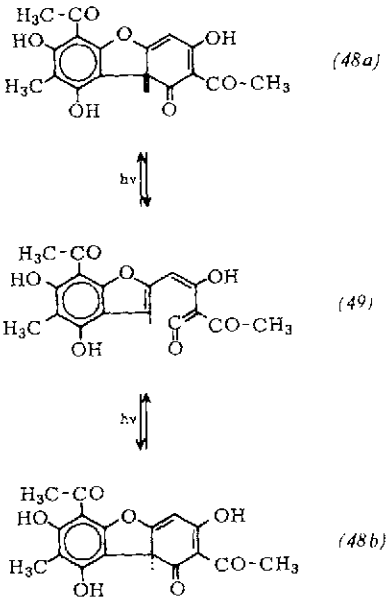
[17] *O. L. Chapman* and *L. F. Englert*, J. Amer. chem. Soc. *85*, 3028 (1963).

[18] *M. H. Fisch* and *J. H. Richards*, J. Amer. chem. Soc. *85*, 3029 (1963).

[19] *D. H. R. Barton*, *P. de Mayo*, and *M. Shafiq*, J. chem. Soc. (London) *1958*, 3314; *D. Arigoni*, *H. Bosshard*, *H. Bruderer*, *G. Büchi*, *O. Jeger*, and *L. J. Krebaum*, Helv. chim. Acta *40*, 1732 (1957); *E. E. van Tamelen*, *S. H. Levin*, *G. Brenner*, *J. Wolinsky*, and *P. Aldrich*, J. Amer. chem. Soc. *81*, 1666 (1959).

[20] *G. Stork*, Chem. and Ind. *1955*, 915.

interpretation, optically active usnic acid looses its optical activity [21] and is converted into the racemate [11] when irradiated with ultraviolet light.



(48a) *(49)* *(48b)*

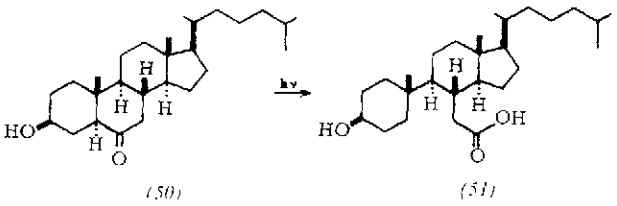
4. Structure of the Reaction Products

A priori it is difficult to predict which of the two diene-carboxylic acids in Scheme 2 [*(29)* and/or *(30)* or their derivatives] will be formed. It is conceivable that the primary product is not the most stable one and undergoes partial or complete isomerization [11], especially in the presence of an amine; however, it is more likely that competing 1,2- and 1,4-additions onto *(26b)* or even onto *(26a)* occur [21a]. The constitution of *(29)* and the configuration of the internal double bond of the conjugated diene portion follow from the characteristic ultraviolet absorption [11].

III. Photochemical Conversion of Cycloalkanones to Open-Chain Saturated Carboxylic Acid Derivatives

1. General

If a solution of 5α-cholestan-3β-ol-6-one *(50)* in acetic acid is irradiated in a quartz vessel under nitrogen with the unfiltered light of a high-pressure mercury-lamp, 5,6-seco-cholestan-3β-ol-6-carboxylic acid *(51)* can be isolated in 54 % yield. This is a typical example [22] of the "photochemical hydrolysis" of unconjugated [22a] open-chain or cyclic ketones, discovered shortly after the turn of the century by *Ciamician* and *Silber* [23–27].



(50) *(51)*

For a long time these reactions have attracted little attention and have only recently found application in the assignment of constitution in terpene chemistry [28,29]. Their mechanism has recently been largely elucidated [30–33]. Investigation of the light-induced formation of carboxylic acids (and their derivatives) from cyclic unconjugated ketones of different ring sizes and different degrees of substitution in the presence of a protonic nucleophile has led to the interpretation shown in Scheme 3.

2. Reaction Mechanism

The ketone molecule *(52)* is excited by the absorption of light and is stabilized by homolytic cleavage of the bond between the carbonyl group and the C-atom which most favors fission owing to the nature and the number of its substituents. The alkyl-acyl diradical *(53)*, which is the primary product of the photochemical reaction [33a], then preferentially undergoes reactions in which both radicals disappear simultaneously.

Recombination leading to the reformation of *(52)* is reflected in the quantum yield. If coupling of the un-

[21] *S. Mackenzie*, J. Amer. chem. Soc. *77*, 2214 (1955).

[21a] In the ultraviolet irradiation of verbenone [*J. J. Hurst* and *G. H. Whitham*, J. chem. Soc. (London) *1960*, 2864] in the presence of protonic nucleophiles, base-catalysed isomerization of the primary product to that isolated was found to be unlikely.

[22] *G. Quinkert, B. Wegemund, F. Homburg*, and *G. Cimbollek*, Chem. Ber. *97*, 958 (1964).

[22a] The term "unconjugated ketones" includes saturated ketones, as well as unsaturated ketones in which the unsaturated function is not conjugated with the carbonyl group.

[23] *G. Ciamician* and *P. Silber*, Ber. dtsch. chem. Ges. *36*, 1582 (1903).

[24] *G. Ciamician* and *P. Silber*, Ber. dtsch. chem. Ges. *40*, 2415 (1907).

[25] *G. Ciamician* and *P. Silber*, Ber. dtsch. chem. Ges. *41*, 1071 (1908).

[26] *G. Ciamician* and *P. Silber*, Ber. dtsch. chem. Ges. *41*, 1928 (1908).

[27] *G. Ciamician* and *P. Silber*, Ber. dtsch. chem. Ges. *43*, 1340 (1910).

[28] *D. Arigoni, D. H. R. Barton, R. Bernasconi, C. Djerassi, J. S. Mills*, and *R. E. Wolff*, Proc. chem. Soc. (London) *1959*, 306; J. chem. Soc. (London) *1960*, 1900.

[29] *J. Krepinsky, M. Romanik, V. Herout*, and *F. Sorm*, Tetrahedron Letters *1960*, No. 7, 9; *1962*, No. 5, 169; *H. Hikino, Y. Hikino, Y. Takeshita, K. Meguro*, and *T. Takemoto*, Chem. pharmac. Bull. (Tokyo) *11*, 1207 (1963).

[30] *G. Quinkert, B. Wegemund*, and *E. Blanke*, Tetrahedron Letters *1962*, No. 6, 22.

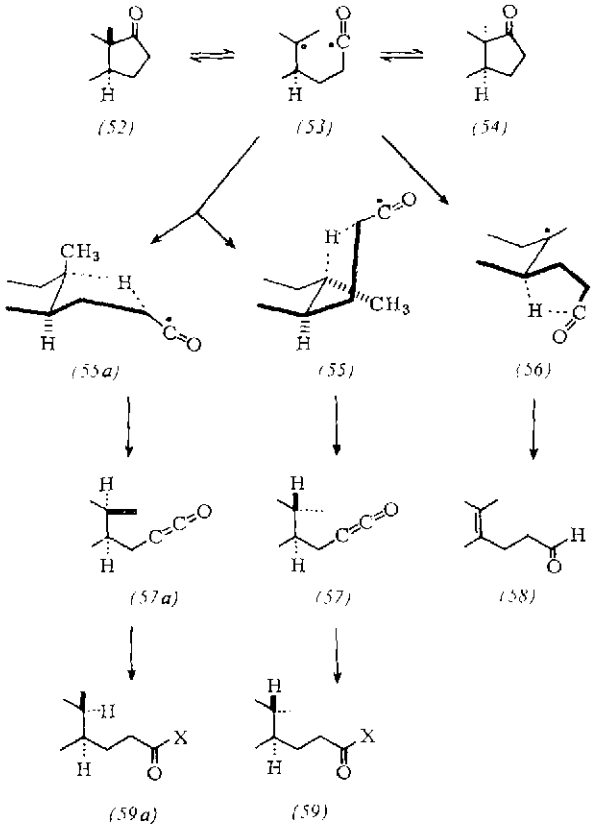
[31] *G. Quinkert, B. Wegemund, F. Homburg*, and *G. Cimbollek*, Chem. Ber. *97*, 958 (1964).

[32] *G. Quinkert, E. Blanke*, and *F. Homburg*, Chem. Ber. *97*, 1799 (1954).

[33] *G. Quinkert, G. Buhr*, and *A. Moschel*, Chem. Ber., in the press.

[33a] In contrast to the alkyl-acyl radical pairs formed in gas-phase photolysis of open-chain ketones below 100 °C [40], occurrence of the alkyl-acyl diradical of cyclic ketones has not been experimentally proved. Nevertheless, the light-induced formation of carboxylic acid derivatives from cyclic ketones *via* the alkyl-acyl diradical is discussed here; until formation of this diradical will be experimentally confirmed or refuted, this is justified by analogy with open-chain ketones. Regarding the problem of intermediate diradicals, see [41].

paired electrons leads to the formation of an unsymmetrically substituted center, the epimeric configurations *(54)* and *(52)* may arise. Since both ketones absorb in approximately the same spectral region, the system reaches a photostationary state *via* the diradical. The position of this state depends on the wavelength of the incident light and on the difference between the rates of the competing recyclization reactions.



Scheme 3. Photochemical formation of carboxylic acid derivatives from unconjugated ketones.

In the case of 17-ketosteroids, this photo-epimerization was first observed by *Butenandt* [34]. It was used preparatively in this field [35–38] and was later recognized to be reversible [39]. The photochemical pseudo-equilibrium between *(52)* and *(54)* lies far on the side of *(54)*.

Intramolecular disproportionations of *(53)* (by migration of a hydrogen atom from the position adjacent to the acyl radical to the alkyl radical-site) can lead to the formation of the isomeric ketenes *(57)* or *(57a)*, or to a mixture of both. These react with water to give the carboxylic acids *(59)*, X = OH, and *(59a)*, X = OH; reaction with cyclohexylamine yields the amides *(59)*, X = NH–C_6H_{11}, and *(59a)*, X = NH–C_6H_{11}. When the ketone *(52)* is irradiated in the absence of protonic nucleophiles, the intermediate formation of ketenes can be detected by infrared spectroscopy [32].

A reaction which competes with the formation of ketenes is the formation of the unsaturated aldehyde *(58)*, also by intramolecular disproportionation; in this case, a hydrogen atom migrates from the position adjacent to the alkyl radical to the acyl radical-site. Such ring cleavages of unconjugated cyclic ketones leading to unsaturated aldehydes have been known since the time of *Ciamician* and *Silber* [24–27,42,43]; other examples were described recently [31,44–49].

That the H-migrations leading to the formation of *(57)*, *(57a)*, and *(58)* from *(53)* are intramolecular has been shown with the aid of deuterated ketones, both in the formation of ketenes [31] and of aldehydes [45]. Owing to the competition between both photo-isomerizations of the epimers *(52)* and *(54)*, the yields of *(57)*, *(57a)*, and *(58)* are mutually interdependent. The cyclic transition states of the competing processes can be represented by formulae *(55)*, *(55a)*, and *(56)*. All other factors being equal, the extent to which each disproportionation occurs will be determined by the differences in ring strain [33].

Intramolecular hydrogen shifts are important in the chemistry of free radicals. They may remain unnoticed, or cause branching in a growing polymer chain [50]. A six-membered cyclic transition state seems to be most favorable [51]. This is so in the Hofmann-Löffler-Freytag reaction [52] as well as in the photo-isomerizations described here and in the case of the Barton reaction [1,52a]. In contrast to the formation of the aldehyde *(58)*, there is no uncertainty regarding the source of the migrating H-atom in the formation of the ketenes *(57)* and *(57a)*. If the terminus of the hydrogen shift becomes an unsymmetrical center [as in the case of *(57)* and *(57a)*], its configuration generally cannot be predicted. If the homolytic transfer of the H-atom in *(53)* leads *via* *(55)* and *(55a)* to different reaction products

[34] *A. Butenandt* and *A. Wolff*, Ber. dtsch. chem. Ges. *72*, 1121 (1939); *A. Butenandt* and *L. Poschmann*, ibid. *73*, 893 (1940); *A. Butenandt, A. Wolff*, and *P. Karlsen*, ibid. *74*, 1308 (1941); *A. Butenandt, W. Friedrich*, and *L. Poschmonn*, ibid. *75*, 1931 (1942); *A. Butenandt* and *L. Poschmann*, ibid. *77*, 392, 394 (1944).

[35] *J. R. Billeter* and *K. Miescher*, Helv. chim. Acta *34*, 2053 (1951).

[36] *D. H. R. Barton, A. da Campos-Neves*, and *A. I. Scott*, J. chem. Soc. (London) *1957*, 2698.

[37] *J. P. L. Bots*, Recueil Trav. chim. Pays-Bas *77*, 1010 (1958).

[38] *H. Zeugner*, Ph. D. Thesis, Technische Hochschule Braunschweig, 1963.

[39] *H. Wehrli* and *K. Schaffner*, Helv. chim. Acta *45*, 385 (1962).

[40] *E. W. R. Steacie*: Atomic and Free Radical Reactions. 2nd Edit., Reinhold, New York 1954, Vol. I.

[41] *G. Quinkert*, Pure appl. Chem., in the press.

[42] *G. Ciamician* and *P. Silber*, Ber. dtsch. chem. Ges. *42*, 1510 (1909).

[43] *G. Ciamician* and *P. Silber*, Ber. dtsch. chem. Ges. *46*, 3077 (1913).

[44] *M. S. Kharasch, J. Kuderna*, and *W. Nudenberg*, J. org. Chemistry *18*, 1225 (1953).

[45] *R. Srinivasan*, J. Amer. chem. Soc. *81*, 1546 (1959).

[46] *R. Srinivasan*, J. Amer. chem. Soc. *81*, 2601 (1959).

[47] *R. Srinivasan*, J. Amer. chem. Soc. *81*, 2604 (1959).

[48] *R. Srinivasan*, J. Amer. chem. Soc. *81*, 5541 (1959).

[49] *P. Bladon, W. McMeekin*, and *I. A. Williams*, J. chem. Soc. (London) *1963*, 5727.

[50] *C. Walling*: Free Radicals in Solution. Wiley, New York 1957, p. 195.

[51] *C. A. Grob* and *H. Kammüller*, Helv. chim. Acta *40*, 2139 (1957).

[52] *E. J. Corey* and *W. R. Hertler*, J. Amer. chem. Soc. *82*, 1657 (1960).

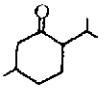
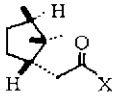
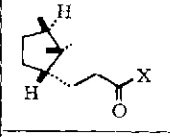
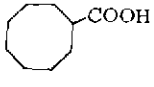
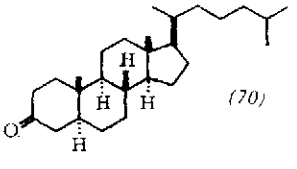
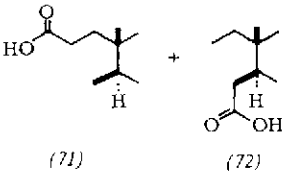
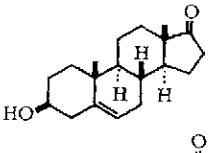
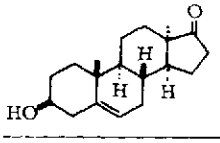
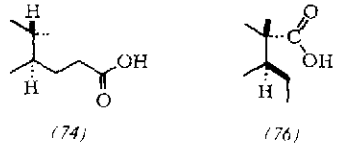
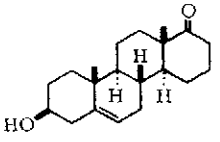
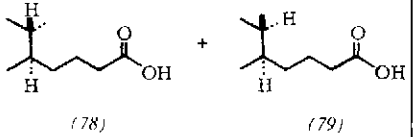
[52a] Note added in proof: see also *K. Heusler* and *J. Kalvoda*, Angew. Chem. *76*, 518 (1964); Angew. Chem. internat. Edit. *3*, 525 (1964).

(57) and *(57a)*, the difference in the ring strains of *(55)* and *(55a)* influences the stereoselectivity of this reaction (see below and especially [33]).

3. Scope of the Reaction

Apart from acetone and methyl ethyl ketone (which give acetic acid together with methane or ethane on irradiation in aqueous solution [23,24]), only cyclic ketones were studied. Table 2 shows a number of examples which illustrate the scope of the reaction and the relationship between the structures of the cycloalkanones irradiated and the resulting carboxylic acids.

Table 2. Photochemical conversion of cycloalkanones to saturated carboxylic acids and their derivatives according to Scheme 3.

Cyclanone	Irradiation product	Ref.
(60)	$HOOC-(CH_2)_5-CH_3$ *(61)*	[25]
 *(62)*	$HOOC-CH_2-\underset{\displaystyle CH_3}{\underset{\vert}{CH}}-(CH_2)_3-\underset{\displaystyle CH_3}{\underset{\vert}{CH}}-CH_3$ *(63)*	[24]
(64)	 *(65)*	[27, 30, 33]
(66)	 *(67)*	[30, 33]
(68)	 *(69)*	[53]
 *(70)*	 *(71)* *(72)*	[31]
 *(73)*  *(75)*	 *(74)* *(76)*	[30–32]
 *(77)*	 *(78)* *(79)*	[33]

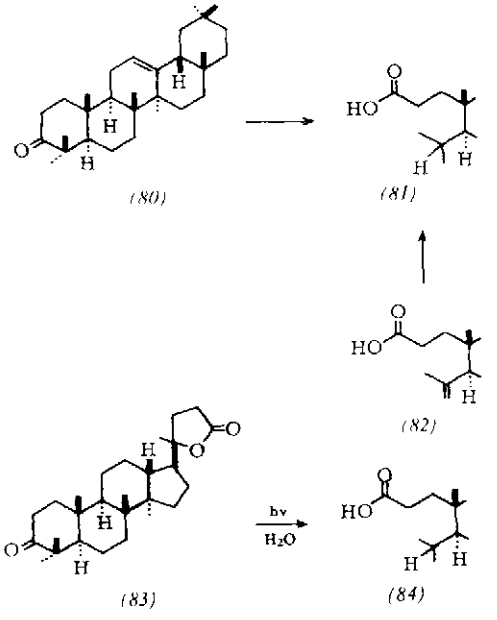
The yields of the acidic products or their derivatives are generally between 30 and 70 %.

In the case of the ketones *(68)* and *(70)* no preferred direction for the α-cleavage is to be expected. While *(69)* gives no nidication of the site of the ring cleavage, the 3-ketosteriod *(70)* yields two carboxylic acids *(71)* and *(72)* by approximately equal cleavage of ring A between C-3 and C-2 and between C-3 and C-4. The other ketones listed in Table 2 are substituted with alkyl groups to varying degrees at the positions adjacent to the carbonyl group. In each case, only the product corresponding to ring cleavage on the side of the more highly substituted α-C-atom was described. The 17-ketosteroids *(73)* and *(75)* have been particularly closley studied with respect to the specificity of the ketene formation [33]: in the presence of water, both *(73)* and

[53] *F. Homburg*, Ph. D. Thesis, Technische Hochschule Braunschweig, 1964.

(75) yield only the primary carboxylic acid *(74)*; the tertiary acid *(76)* is not formed [53a].

The photochemical conversion of unconjugated cycloalkanones into the carboxylic acids by addition of one mole of H_2O has also been used in natural-product chemistry [28]. The ultraviolet irradiation of β-amyrone *(80)* yields the dihydro derivative *(81)* of nyctanthic acid *(82)*. The structure of *(82)* was deduced from this reaction [54]. Likewise, the γ-lactone *(83)* obtained from hydroxydammarenol-II can be converted to *(84)* which was correlated to a reaction product of dammarenolic acid.

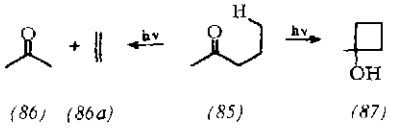


(80) *(81)* *(82)* *(83)* *(84)*

Only very small quantities of an acid derivative are obtained on irradiation of solutions of camphor *(64)* containing a protonic nucleophile. Comparison with homocamphor *(66)* shows that ketene formation increases with the transition from the cyclopentanone ring to the higher homologue. The same is true for the homologues *(73)* and *(77)*. The compound with the cyclopentanone ring *(73)* gives a 28% yield of the carboxylic acid *(74)*, while *(77)* is converted into the corresponding carboxylic acids in a yield of almost 50% [33].

Besides the formation of unsaturated aldehydes, which is related to the formation of ketenes, there are other competing reactions which limit the synthetic usefulness of this method of preparing acids or their derivatives. Such reactions may be due to the structure of the ketone to be irradiated: α,α'-phenyl- [55, 56] or vinyl-substituted [57] ketones undergo rapid light-induced decarbonylation which prevails over the formation of acids (or their derivatives).

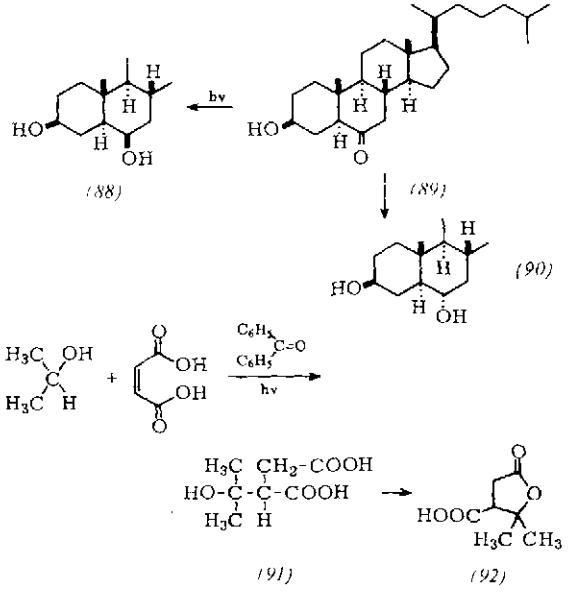
The formation of acids (or their derivatives) can also decrease as a result of photoreduction. If a hydrogen atom occupies a favorable position with respect to the photochemically excited keto group, as in *(85)*, then a photofragmentation [*e.g.* to yield *(86)* and *(86a)*] or a photocyclization [59], *e.g.* leading to *(87)*, may take place. These reactions are initiated by an intramolecular hydrogen shift. Of course, the entire process may occur in a single step [59a].



(86) *(86a)* *(85)* *(87)*

Scheme 4. Photofragmentation and photocyclization of ketones.

If the structural requirements for intramolecular hydrogen transfer to the oxygen atom of the photochemically excited keto group (Scheme 4) are not satisfied, other reactants (particularly the solvent) may assume the role of H-donors. Depending on the nature of the ketone and the coreactant, the products may be alcohols [*e.g.* *(88)* and *(90)* from *(89)*] [31] or alcoholic condensation products [*e.g.* in the addition of isopropanol to maleic acid, photosensitized by benzophenone, to form *(91)* which reacts further to yield *(92)*] [63, 64].



(88) *(89)* *(90)* *(91)* *(92)*

[53a] The absence of *(76)* is consistent with the ketene formation by homolytic hydrogen abstraction from the position adjacent to the acyl radical, since α-cleavage of *(73)* and *(75)* between C-16 and C-17 yields an alkyl-acyl diradical with no hydrogen in the position adjacent to the acyl radical.

[54] *G. H. Whitham*, J. chem. Soc. (London) *1960*, 2016.

[55] *G. Quinkert, K. Opitz, W. W. Wiersdorff*, and *J. Weinlich*, Tetrahedron Letters *1963*, 1863.

[56] *K. Mislow* and *A. J. Gordon*, J. Amer. chem. Soc. *85*, 3521 (1963).

[57] *O. L. Chapman, D. J. Pasto, G. W. Borden*, and *A. A. Griswold*, J. Amer. chem. Soc. *84*, 1220 (1962); *G. O. Schenck* and *R. Steinmetz*, Chem. Ber. *96*, 520 (1963); *D. L. Schuster, M. Axelrod*, and *J. Auerbach*, Tetrahedron Letters *1963*, 1911.

[58] *R. G. Norrish* and *M. E. S. Appleyard*, J. chem. Soc. (London) *1934*, 874; *W. Davis jr.* u. *W. A. Noyes jr.*, J. Amer. chem. Soc. *69*, 2153 (1947); *J. N. Pitts jr.*, J. chem. Educat. *34*, 112 (1957); *R. Srinivasan*, J. Amer. chem. Soc. *81*, 5061 (1959).

[59] *N. C. Yang* and *D. H. Yang*, J. Amer. chem. Soc. *80*, 2913 (1958).

[59a] In particular, see the photofragmentations and photocyclizations carried out with steroid ketones in the laboratories of *O. Jeger* and *N. C. Yang* [60–62].

[60] *J. M. Erikson* and *D. L. Forbess* in: Steroid Reactions. Holden-Day, San Francisco 1963, p. 327.

[61] *N. C. Yang, A. Morduchowitz*, and *D. H. Yang*, J. Amer. chem. Soc. *85*, 1017 (1963).

[62] *I. Orban, K. Schaffner*, and *O. Jeger*, J. Amer. chem. Soc. *85*, 3033 (1963); *K. Schaffner, D. Arigoni*, and *O. Jeger*, Experientia *16*, 169 (1960).

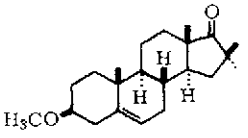
[63] *G. Ciamician* and *P. Silber*, Ber. dtsch. chem. Ges. *44*, 1280 (1911); *G. O. Schenck*, Angew. Chem. *69*, 579 (1957); *A. Schönberg*: Präparative Organische Photochemie. Springer, Berlin 1958, p. 109; *P. de Mayo* in: Advances in Organic Chemistry. Interscience, New York 1960, Vol. II, p. 372; *W. G. Moore, G. S. Hammond*, and *R. P. Foss*, J. Amer. chem. Soc. *83*, 2789 (1961); *G. S. Hammond, W. P. Baker*, and *W. M. Moore*, J. Amer. chem. Soc. *83*, 2795 (1961).

[64] *G. O. Schenck, G. Koltzenburg*, and *H. Grossmann*, Angew. Chem. *69*, 177 (1957).

The solvent should have the lowest possible tendency to donate hydrogen atoms to free radicals. This condition is best satisfied by water and benzene; however, these can scarcely be considered as solvents for the formation of carboxylic acids, since ketones usually are not sufficiently soluble in water, and the water required for the reaction is not sufficiently soluble in benzene. Acetonitrile, glacial acetic acid, and alcohols (particularly tertiary alcohols) have been used, whereas aliphatic or cycloaliphatic ethers strongly favor the intermolecular photoreduction.

Finally, a group of unconjugated ketones should be mentioned, from which the light-induced formation of acids or their derivatives is impossible. In fenchone *(93)* and 16,16-dimethyl-3β-methoxy-Δ^5-androsten-17-one *(94)*, neither C-atom adjacent to the light-absorbing carbonyl group carries a hydrogen atom; consequently, these compounds cannot undergo intramolecular hydrogen shift to form a ketene. On irradiation in the presence of water, *(93)* and *(94)* do not yield the carboxylic acids which would arise by incorporation of the elements of water [32,65].

(93)



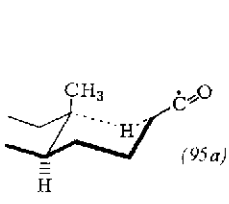
(94)

4. Structure of the Reaction Products

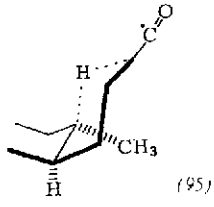
The structure of the carboxylic acids and their derivatives which result from the photochemical reaction of a cycloalkanone [*e.g. (52)*] is determined by constitution-specific cleavage of the ketone ring to yield the most stable diradical [*e.g. (53)*], and consequently depends on the nature of the substituents in the α- and α'-positions. The rule that light-induced cleavage of cyclic ketones takes place on the side of the more highly alkyl-substituted carbon atom was stated by *Ciamician* and *Silber* [24,25,42] and has subsequently been used repeatedly as a guide (*e.g.* [28]) [65a].

Unsaturated substituents, the *p*-orbitals of which overlap with the *p*-orbital of the alkyl radical, favor homolysis and help to determine the site of ring cleavage.

The configuration of the carboxylic acid (or derivative) formed cannot be predicted when a center of asymmetry is involved in the light-induced ring cleavage, as in the case of *(73)* and *(77)*. Comparison of the products obtained in these cases [*(74)* from *(73)*, and *(78)* + *(79)* from *(77)*] shows that the stereoselectivity [67a] decreases as the size of the cycloalkanone ring increases. This can be plausibly explained by assuming that a six-membered ketone gives less ring strain in the cyclic transition state for the formation of ketenes than a five-membered ketone [higher yield of acid from *(77)*



(95a)



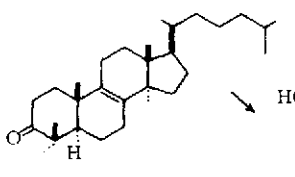
(95)

than from *(73)*], and that the difference between the ring strains of the transition states *(95)* and *(95a)*, which are configurational isomers, is less than in the case of *(55)* and *(55a)*.

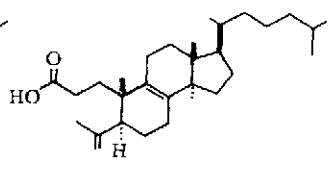
IV. Photochemical Conversion of Cycloalkanones to Open-Chain, Unconjugated, Unsaturated Carboxylic Acids

1. General

If a solution of Δ^8-lanosten-3-one *(96)* and cyclohexylamine in benzene [68a] is irradiated with the unfiltered light of a high-pressure mercury lamp, while oxygen is continuously passed through the solution, a 20 % yield of 3,4-seco-$\Delta^{4(23),8}$-lanostadien-3-oic acid *(97)* can be isolated after 24 hours.



(96)



(97)

This is a typical example of the recently discovered autoxidative ring cleavage of cyclic unconjugated ketones to unsaturated carboxylic acids containing one

[65] *B. Wegemund*, Diploma Thesis, Technische Hochschule Braunschweig, 1960.

[65a] The constitution-specific α-cleavage is not self-evident, since this reaction starts with a photochemically excited molecule. In the gas-phase photolysis, *e.g.* of methyl ethyl ketone, α-cleavage occurs in both possible directions [66]. It seems likely that two different excited species are responsible for the formation of the different reaction products. If the photolysis is carried out in the gas phase at low pressure, the electronically excited molecule reacts from the vibrational state reached in the excitation. In solution, deactivation by a chemical reaction is preceded by thermodynamic equilibration of the vibrational energy with the surroundings; this is shown in the gas-phase photolysis of methyl ethyl ketone by the decrease in specificity of the α-cleavage with decreasing wavelength of the incident light [66]. Apart from the chemical reaction, fluorescent emission also yields information as to the nature of the excited species. Whereas the absorption spectrum of a substance in solution normally shows that the electronically excited molecule is also vibrationally excited, the fluorescent emission spectrum of the same compound in solution shows that the emitting molecule is already in the vibrational ground state [67].

[66] See [40], p. 358.

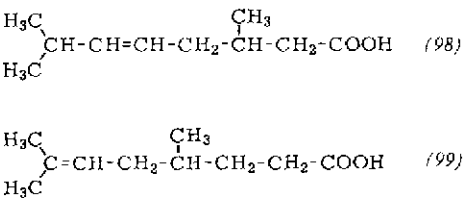
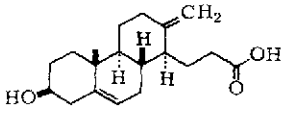
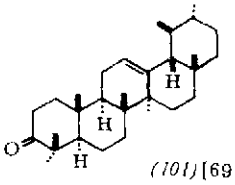
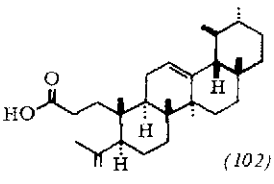
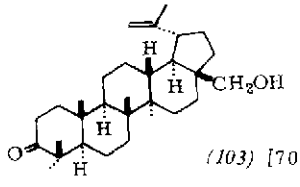
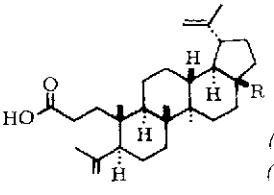
[67] *T. Förster*: Fluoreszenz Organischer Verbindungen. Vandenhoeck und Rupprecht, Göttingen 1951, p. 133; *A. Ehrenberg* and *H. Theorell* in *M. Florkin*: Comprehensive Biochemistry. Elsevier, Amsterdam 1962, Vol. 3, p. 170.

[67a] The terms "constitution-specific" and "stereoselective" imply a connection between the constitution of the starting material and that of the product, but none between their configurations. Thus, the formation of the carboxylic acid *(74)* with a 13α–CH_3 group from both *(73)* and *(75)* is constitution-specific and stereoselective; see [33,68].

[68] *H. E. Zimmerman, L. Singer*, and *B. S. Thyagarajan*, J. Amer. chem. Soc. *81*, 108 (1959).

[68a] Cyclohexylamine is added to convert the ketenes, which are also formed in the presence of oxygen (see Section III), to cyclohexylamides. This facilitates isolation of the acids formed by autoxidation.

Table 3. Photochemical conversion of cyclic ketones to unsaturated carboxylic acids according to Scheme 5.

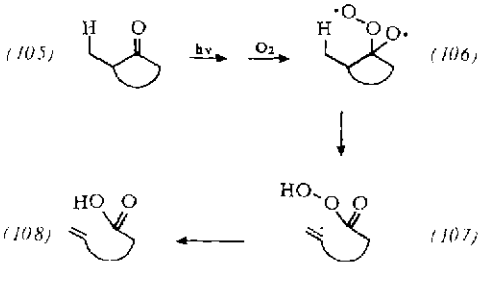
Cyclanone	Acidic photo-oxidation product
(62) [71]	 *(98)* *(99)*
(73) and *(75)* [69,70]	 *(100)*
(80) [69,70]	*(82)*
 *(101)* [69,70]	 *(102)*
 *(103)* [70]	 *(104a)*: R = CH_2OH *(104b)*: R = CH_3

oxygen atom more than the original ketone [69,70]. This reaction has been used in partial syntheses, especially of the 3-ketotriterpenes (see Table 3).

2. Reaction Mechanism

The products assumed or shown to be formed when unconjugated cyclic ketones are irradiated with ultraviolet light in the absence of oxygen (see Section III) are not precursors of the unsaturated carboxylic acids which are formed in the presence of oxygen. The hypothetical diradical, *e.g. (53)*, which has been assigned a key position as the product of the primary photochemical process is also a possible reaction partner for the molecular oxygen. However, such a reaction is ruled out by the structure of the acidic photo-oxidation products [69,70] and by experiments aimed at testing the unknown reactivity of diradicals towards O_2 [72]. For structural reasons, the ketene photoisomer of *(52)*, *e.g. (57)*, cannot be an intermediate of the photo-oxidation, and the other disproportionation product *(58)* of the alkyl-acyl diradical *(53)* can also be ruled out [69,70].

As a working hypothesis it is assumed that the cyclic ketone *(105)* in the photoactivated state reacts with the oxygen molecule [70a]. The postulated hydroxy-hydroperoxy diradical *(106)* undergoes intramolecular rearrangement to yield the unsaturated peroxyacid *(107)* which then forms a carboxylic acid *(108)* in the usual manner (see Scheme 5).



Scheme 5. Photo-oxidation of cyclic ketones to unsaturated carboxylic acids.

Reaction of the photo-oxidation product *(106)* is initiated by an intramolecular hydrogen-shift [cf. the light-induced conversion of *(85)* to *(86)* and *(86a)*]; of course, this reaction may also proceed in a single step. A six-membered cyclic transition state is required for both processes. Thus the cyclic ketone must have at least one H-atom in the β-position with respect to the carbonyl group; furthermore, the orientation of this H-

[69] *G. Quinkert* and *H.-G. Heine*, Tetrahedron Letters *1963*, 1659.

[70] *H.-G. Heine*, Ph. D. Thesis, Technische Hochschule Braunschweig, 1964.

[70a] Photo-oxidations which proceed in the absence of sensitizers, and which do not involve the reaction of radicals formed by photodissociation with O_2, have so far received little attention [see *R. M. Hochstrasser* and *G. B. Porter*, Quart. Reviews *14*, 146 (1960)].

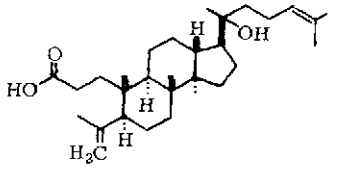
[71] *G. Quinkert* and *H. Oehlschläger*, unpublished work.

[72] *H. H. Rieckert*, Diploma Thesis, Technische Hochschule Braunschweig, 1963.

atom must be such that the centers H-C(β)-C(α)-C–O–O in the hydroxy-hydroperoxy diradical can assume a cyclic arrangement.

3. Scope of the Reaction

Table 3 shows a number of cases studied so far, in which a cyclic ketone is converted to an unsaturated carboxylic acid containing an additional oxygen atom. With the exception of *(62)*, all the ketones contain a CH_3-substituent α to the carbonyl group. In these examples the new C=C double bond, which is formed together with the carboxyl group, is always terminal.



(109)

Consequently, this new photo-oxidation can be used as a step in the partial synthesis of 3,4-seco-triterpene-carboxylic acids with a $\Delta^{4(23)}$-double bond from 3-keto-triterpenes [*e.g. (96)* → *(97)*].

Unsaturated carboxylic acids of this type have very recently been found in nature: dammarenolic acid *(109)* [28], nyctanthic acid *(82)* [28,54], roburic acid *(102)* [73], and canaric acid *(104b)* [74].

Compounds *(102)* and *(82)* have been obtained in 20 % yield by irradiation of α-amyrone *(101)* and β-amyrone *(80)* in the presence of oxygen [69]. Similarly, betulone *(103)* gave the doubly unsaturated hydroxycarboxylic acid *(104a)* [70] which presumably occurs in nature, too.

I obtained my first impressions of photochemistry from the instructive "studies in the vitamin D series" carried out together with Prof. H. H. Inhoffen. I then had the good fortune to witness the development of the study of "photochemical transformations" under Prof. D. H. R. Barton, and subsequently embarked on the investigation of "light-induced reactions" together with capable young colleagues who find a challenge in unsolved problems and who are mentioned by name in the list of references. To all with whom I could work together I am sincerely grateful.

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[73] *L. Mangoni* and *M. Belardini*, Tetrahedron Letters *1963*, 921.
[74] *R. M. Carman* and *D. E. Cowley*, Tetrahedron Letters *1964*, 627.

Fused Salts and Their Use as Reaction Media [*]

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Apart from being of interest for physicochemical investigations, ionic liquids are a very important supplement to the non-aqueous and water-like solvents. The present discussion of the physical properties and current ideas on the structure of fused salts is followed by a report on the solubilities of gases, salts and metals. Our knowledge of fused salt baths and their use in electrochemical and electrometallurgical processes has recently been considerably expanded. Special attention is drawn to chemical reactions in fused electrolytes. Fused salts can also act as catalysts, so that they may often be advantageous reaction media for synthesis, if not the only media which can be used.

I. Introduction

Most operations in modern preparative chemistry are carried out either in or with the participation of a liquid phase, in which the mobility of the molecules is similar to that in the vapor phase, but where the density of matter is almost the same as that of a solid. However, reactions are not confined to aqueous systems and to solutions in organic solvents, which could also be regarded as "molecular melts". Very profitable use is made, both in the laboratory [1] and in industry, of reaction media which range from condensed gases to melts of predominantly covalent metal halides, and which are characterized by a slight self-dissociation, similar to that of water. Surprisingly, however, we rarely find papers describing the preparative use of ionic liquids as solvents, although the physicochemical properties of these liquids suggest that they should also be useful in fields other than electrochemistry.

Fused electrolytes are generally completely dissociated into ions, and are excellent solvents for salts, metals, and

[*] Extended version of lectures delivered to the International Congress for Pure and Applied Chemistry, London, July 15th, 1963, and in Bonn (Germany) on January 14th, 1964.

[1] *G. Jander, H. Spandau*, and *C. C. Addison*: Chemie in nichtwäßrigen Lösungsmitteln. Vieweg, Braunschweig 1963.

gases. They are steadily gaining in technological importance, owing to their high thermal stability, low vapor pressure, good electrical conductivity, low viscosity, extremely wide useful temperature range, and the very high temperatures which can be reached. It is not surprising, therefore, that electrochemical [2–7] and physicochemical investigations [8] have recently been intensified with a view to the possibility of general industrial applications of fused salts, particularly in nuclear technology [9]. Growing interest is directed towards new electrometallurgical processes, and to the development of fuel elements with a low internal resistance, or of the "molten salt reactor". However, as can be seen from the increasing number of publications from 1900 to 1960 [10], special attention has been devoted to the structural characteristics of molten salts in the hope of gaining an insight into this extreme form of the liquid state. This as well as the electrochemical and chemical reactions which can be carried out using fused salts as solvents form the subject of the present paper.

II. Physical Properties and Structures of Fused Salts

Silicates, borates, and phosphates [11–13] are omitted from the discussion of molten electrolytes because of the different physical and structural properties of these compounds, which result mainly from the polymeric anion structure. Owing to their high viscosities, the molecules of these compounds are not sufficiently mobile to crystallize on cooling; consequently, they normally solidify in a vitreous state in which the disorder equilibrium of the melt is largely retained. Similarly, fused halides with predominantly covalent bonding (*e.g.* halides of aluminum, arsenic, antimony, and mercury), are discussed only when used in combination with other salts.

Salts which are highly ionic in the crystalline state are expected to dissociate almost completely into ions or groups of ions when fused. Anions and cations cannot be randomly distributed in the melt; instead, each ion is surrounded by a certain number of oppositely charged ions as a result of Coulomb interactions. We thus have a quasi-lattice structure [14], in which random distribution is possible only within the anionic or cationic partial lattice and within the immediate vicinity of a single ion [15, 16]. Although melts have no long-range order such as is present in crystals, the kinetic properties of fused salts can be better discussed in the light of the theory of defects in solids than by comparison with solutions of strong electrolytes.

The validity of this picture of ionic liquids as highly disordered crystals is confirmed by the radial distribution function of the ions in the melt, which can be derived from X-ray or neutron diffraction measurements. The result was surprising. It was found that the degree of order in a melt, at least slightly above the melting point, is similar to that in the solid and does not correspond to the disorder of the gaseous state, as had formerly been assumed. Furthermore, the most probable distance between an ion in the first coordination sphere and a given central ion is up to 9% less than in the crystal lattice (cf. Table 1). This high degree of order is also indicated

Table 1. Coordination numbers (CN) and cation-anion distances in solid and fused alkali metal halides.

Salt	Crystal		Melt at m.p.		Decrease of distance on melting [%]
	CN	Distance [Å]	Mean CN	Distance [Å]	
LiCl	6	2.66	3.7	2.46	7.1
LiBr	6	2.85	5.2	2.68	6.0
LiI	6	3.12	5.6	2.85	8.6
NaI	6	3.35	4.0	3.15	6.0
KCl	6	3.26	3.6	3.10	4.9
CsCl	6	3.57	4.6	3.53	1.0
CsBr	6′	3.72	4.6	3.55	4.4
CsI	6′	3.94	4.5	3.85	2.3

by the fact that the entropy of fusion is only about one quarter of the entropy of vaporization. This agrees with the assumption that at the onset of crystallization extensive preorientation occurs at the melt/crystal interface with the formation of "islands" which are already subject to a certain "ordering" opposing the thermal motion. Crystal growth from the melt can therefore be regarded as a special case of crystalline transitions [17].

Whereas the presence of ordered regions in fused salts slightly above the melting point needs further study, a distinct after-melting effect has been detected by differential thermal analysis, *i.e.* up to 14% of the enthalpy of fusion is absorbed only after completion of the melting process proper [18]. The size distribution of the submicroscopic ordered regions is a function of temperature [19]. On the other hand, the assumption of a quasi-crystalline structure has been refuted in the case of molten metals. The short-range ordering is regarded as a surface effect [20], and the atom distribution in the melt cannot be interpreted in terms of a distorted crystal lattice [21].

[2] *R. Lorenz*: Die Elektrolyse geschmolzener Salze. Halle 1905.

[3] *R. Lorenz* and *F. Kaufler*: Handbuch der angewandten physikalischen Chemie. Leipzig 1909, Vol. 11, p. 1.

[4] *P. Drossbach*: Elektrochemie geschmolzener Salze. Springer, Berlin 1938.

[5] *P. Drossbach*: Grundriß der allgemeinen technischen Elektrochemie. Springer, Berlin 1952.

[6] *H. Bloom* and *J. O'M. Bockris*: Modern Aspects of Electrochemistry. Butterworths Scientific Publications No. 2, London 1959.

[7] *Ju. K. Delimarskii* and *B. F. Markov*, Electrochemistry of Fused Salts. Sigma Press, Washington 1961.

[8] Landolt-Börnstein: Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik. Vol. II, Part 3, Schmelzgleichgewichte. Springer, Berlin-Göttingen-Heidelberg 1956.

[9] *H. U. Woelk*, Chem.-Ing.-Techn. *32*, 765 (1960).

[10] *G. J. Janz*: Bibliography on Molten Salts. Rensselaer Polytechnic Institute, Troy, N.Y. 1961.

[11] *I. E. Campbell*: High Temperature Technology. Wiley, New York 1956.

[12] *J. D. Mackenzie*, Chem. Reviews *56*, 455 (1956).

[13] *G. W. Morey*: The Properties of Glass. American Chemical Society Monograph No. 124, 2nd Edit., Reinhold Publishing Corporation, New York 1954.

[14] *M. Temkin*, Acta physicochim. U.S.S.R. *20*, 411 (1945).

[15] *F. H. Stillinger*, *J. G. Kirkwood*, and *P. J. Wojtowicz*, J. chem. Physics *32*, 1837 (1960).

[16] See, however, *L. Winkler*, Ph. D. Thesis, Universität Bonn, 1961.

[17] *H. Peibst*, Z. physik. Chem. *216*, 304 (1961).

[18] *B. Pedel*, Naturwissenschaften *49*, 463 (1962); Z. Metallkunde *54*, 206 (1963).

[19] *H. Cordes*, Lecture on the Structure of Molten Metals, Braunschweig (Germany), July 19th, 1961.

[20] *W. K. Prochorenko* and *I. S. Fischer*, Zh. fiz. Khim. *33*, 1852 (1959).

[21] *S. Steeb*, Z. Metallkunde *52*, 422 (1961).

At the same time, however, increases of up to 25% in the molar volume have been reported on fusion of salts [22–24] which have a high coordination number in the crystal lattice. This increase in volume can be only partly explained by a structural change in the first coordination spheres [24, 25]. Consequently, the structure of a molten salt must contain a large proportion of empty volumes, on the nature of which there are two different views (see Figures 1a–1c).

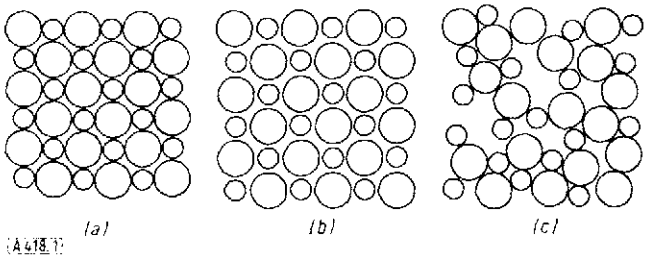


Fig. 1. (a) NaCl crystal; (b) cell model of an NaCl melt; (c) hole model of an NaCl melt.

In the so-called cell model (Fig. 1b) [26], each ion is regarded as an independent linear oscillator vibrating in a three-dimensional cell, the boundaries of which are given by the neighboring ions. The empty volume is thus distributed as free volume between the ions. According to this view the mean coordination number in the melt should correspond to that in the crystal, and the mean interionic distance should increase in parallel with the volume change which occurs on fusion and which should amount to only 6 or 7%; furthermore, electrolytic transport should be due almost exclusively to the smaller cations, which is not confirmed by experiment [27].

The experimental facts rather support the hole model (Fig. 1c) [28–30], according to which the free volume again increases on fusion. However, it has been calculated from the compressibility of molten salts [31] that only about 2% of the total increase in volume can be ascribed to the formation of free volume by an increased amplitude of the vibrations of the ions about their migrating normal positions. The remaining 10 to 20% is attributed to anionic and cationic holes.

This hypothesis is confirmed by the fact that the mean coordination number in fused salts is always appreciably smaller than the maximum value expected from the ratio of the ionic radii (cf. Table 1) [32]. Because of electrical neutrality, however, it is difficult to imagine that, in a quasi-lattice structure, there will always be only one hole with the dimensions of an anion or a cation in one sixth to one fifth of all "lattice sites". Instead, some of the positive holes seem to be discharged by a free electron [33], and almost half of the empty volume appears to consist of neutral cation-anion double holes [34, 35]. This is confirmed by cryometric investigations in fused salts [36]. Since ideal solutions are formed even when salts containing ions of very different sizes are mixed, it can be concluded that holes or gaps are present in the quasi-crystalline lattice.

In a kinetic consideration, it must naturally be assumed that the holes are randomly distributed, not only spatially, but also with respect to their size and shape. Consequently, the term "soft volume" has been coined [37] to avoid references either to a cell or to holes. From the high empty-volume concentration, it is concluded that the forces acting on some of the ions in the melt are no longer symmetrically distributed, so that the formation of ion pairs or molecules is favored. In fact, it is possible to set up a general equation of state for fused electrolytes, one term of which describes the complete formation of molecules (as on vaporization) and the other the ideal solid, and which agrees with the experimental results (*e.g.* the unexpectedly large increase in volume on fusion of ionic crystals) if the individual terms are combined in a certain ratio [38]. However, no conclusion can be drawn from this with regard to the fusion process itself [37].

Provided that a simultaneous structural transition can be ruled out, the sudden large increase in the molar volume on fusion can be explained by the fact that below the melting point the thermal disorder equilibrium reaches an excessively low value as a result of the strong lattice forces and the correspondingly high disorder energy. It is only when the kinetic energy of an individual structural unit has become so large that it can break away completely from the lattice, that the energy required for the formation of a hole decreases spontaneously, and a new thermodynamic disorder equilibrium is set up, with the absorption of a certain quantity of energy (heat of fusion).

Melts of salts with polyvalent cations have not been studied so thoroughly, since here a large number of structural units can be imagined which determine the physicochemical properties of the melt. It is not yet known with certainty to what extent alkaline earth halides, for example, are dissociated, and what complex units they form.

Molten halides of the transition elements form structures such that the melts cannot be described as purely ionic liquids. Whereas beryllium fluoride forms polymeric chains [39], fused zinc chloride may be regarded as consisting of two-dimensionally cross-linked layers [40, 41]. As in the case of the halides of Group III and IV elements (which form water-like molecular melts) these structures dissolve to form complexes only on addition of alkali metal halides. This process corresponds to solvation in other solvents.

Alkali metal salts with anions which are not spherically symmetrical also exhibit irregular properties: groups of associated ions are observed in fused nitrates and nitrites

[22] *H. Schinke* and *F. Sauerwald*, Z. anorg. allg. Chem. *287*, 313 (1956).

[23] *H. Schinke* and *F. Sauerwald*, Z. anorg. allg. Chem. *304*, 25 (1960).

[24] *J. W. Johnson*, *P. A. Agron*, and *M. A. Bredig*, J. Amer. chem. Soc. *77*, 2734 (1955).

[25] *J. O'M. Bockris*, *A. Pilla*, and *J. L. Barton*, J. physic. Chem. *64*, 507 (1960).

[26] *J. E. Lennard-Jones* and *A. F. Devonshire*, Proc. Roy. Soc. (London) A *163*, 53 (1937); A *165*, 1 (1938); A *169*, 317, 464 (1939). See also *J. M. H. Levelt* and *R. P. Hurst*, J. chem. Physics *32*, 96 (1960).

[27] *A. Z. Borucka*, *J. O'M. Bockris*, and *J. A. Kitchener*, Proc. Roy. Soc. (London) *241*, 554 (1957).

[28] *J. Frenkel*, Acta physicochim. *3*, 633, 913 (1935).

[29] *W. Altar*, J. chem. Physics *5*, 577 (1937).

[30] *R. Fürth*, Proc. Cambridge philos. Soc. *37*, 352 (1941).

[31] *J. O'M. Bockris* and *N. E. Richards*, Proc. Roy. Soc. (London) *241*, 44 (1957).

[32] *H. A. Levy*, *P. A. Agron*, *M. A. Bredig*, and *M. D. Danford*, Ann. New York Acad. Sci. *79*, 762 (1960).

[33] *M. Abraham* and *J. Brenet*, C. R. hebd. Séances Acad. Sci. *251*, 2921 (1960).

[34] *F. Seitz*, Rev. mod. Physics *18*, 384 (1946).

[35] *G. J. Dines*, J. chem. Physics *16*, 620 (1948).

[36] *Y. Doucet*, J. Chim. physique Physico-Chim. biol. *56*, 578 (1959).

[37] The author is very grateful to Prof. *H. Eyring* for detailed discussions.

[38] *T. R. Thompson*, *H. Eyring*, and *T. Ree*, Proc. nat. Acad. Sci. U.S.A. *46*, 333 (1960).

[39] *J. D. Mackenzie*, J. chem. Physics *32*, 1150 (1960).

[40] *W. Bues*, Z. anorg. allg. Chem. *279*, 104 (1955).

[41] *J. D. Mackenzie* and *W. K. Murphy*, J. chem. Physics *33*, 366 (1960).

[42] and the changes in volume are not so pronounced as with the halides, which indicates that the difference between the disorder energies in the crystal and in the melt is less than for alkali metal halides. With fused salt systems containing complexes [23,43], the degree of disorder typical of the liquid state is reached at a lower temperature than with the pure components. Moreover, sudden changes in volume at the melting point are no longer observed. In the case of the thiocyanates, the crystal lattice is so extensively deformed that a pronounced "premelting" occurs [44].

Thermal and electrical transport in melts can hardly be explained unless the presence of holes which can change places with the ions is accepted. Although the transport number, diffusion, and viscosity at a given temperature depend on the size, polarizability, and electrical charge of the ion, they are particularly dependent on the hole concentration; this also explains the high electrical conductivity of fused salts [45]. The objection was made [46] that the electrical conductivity actually decreases when the defect concentration is increased, as in the crystal, by the addition of divalent cations, so that holes seem not to contribute towards transport processes. However, this ignores the fact that larger groups of ions, or even compounds are formed in the melt, which leads to an appreciable decrease in the electrical conductivity [*].

III. Solubility in Fused Salts

A. Gases

Gases often react rapidly and quantitatively in fused salts, although the solubility *e.g.* of inert gases is very low.

While the solubility of helium in fluoride melts between 600 and 800 °C is 10×10^{-8} to 20×10^{-8} mole/cm³ that of xenon is only 0.1×10^{-8} to 2×10^{-8} mole/cm³, *i.e.* the solubility decreases with increasing atomic weight [48–50]. It increases with rising temperature and pressure. The solubility of xenon in a sodium nitrate/potassium nitrate melt between 260 and 450 °C is 8×10^{-8} to 10^{-7} mole/cm³ [51] [**].

The assumptions that the quantity of gas dissolved corresponds to the free volume [53] and that the enthalpy of solution is related to the energy required for the formation of holes were confirmed in the case of molten fluorides [49].

However, if ion-dipole interactions or compound formation takes place between the melt and the gas, the solubility of the gas increases appreciably. This is shown by the strong green coloration occurring near the anode during the electrolysis of fused halides [43]. The solubility of chlorine in alkali metal chlorides was found to be of the order of 10^{-6} mole/cm³, while the solubilities of bromine and iodine in the corresponding alkali metal halides are about ten times greater [54]. The chlorine is probably present as the Cl_3^- ion. It may be assumed that species similar to the chloroiodates are formed on dissolution of iodine in alkali metal chlorides; in any case, iodine has been detected in the valence states of −1, 0, and +1 [55]. Compound formation on dissolution of hydrogen fluoride in NaF/ZrF_4 is well known; as the sodium fluoride concentration increases, the solubility rises from 10^{-5} to 10^{-4} mole/cm³ [56].

B. Salts

Whereas many data are available on the solubility of salts in the melts of other salts [8], information on the solubilities of oxides is less abundant, although these data are important in connection with the corrosion of oxidic container materials. The solubility of magnesium oxide in binary and ternary systems of the alkali metal and alkaline earth halides is less than 0.05% by weight at 800 °C [57] (0.07% in $CaCl_2$ at 1000 °C [58]), while that of Fe_2O_3 in potassium fluoride at 1100 °C is 24% by weight [59]. An important point in electrometallurgical processes is the solubility of titanium, zirconium, and hafnium oxides in alkali metal fluorides [60], which is about 0.1% by weight. Qualitative investigations on the solubilities of oxides in a LiCl/KCl melt at 500 °C have led to a series in which almost all the important oxides are classified according to solubility [61].

A similar classification has been carried out for the sulfides [62]: the highest solubilities are shown by the alkali metal and alkaline earth sulfides, while the sulfides of most of the sub-group elements are insoluble in melts of this type. More detailed experiments were carried out to find the solubility of zinc sulfide; zinc chloride and the eutectics of zinc chloride with sodium chloride and with potassium chloride are particularly good solvents (solubility 0.3 to 0.5 mole/kg of melt at 700 °C) [63]. Almost

[42] *W. J. Davis, S. E. Rogers,* and *A. R. Ubbelohde,* Proc. Roy. Soc. (London) A *220,* 14 (1953).

[43] *W. Sundermeyer,* unpublished work.

[44] *E. Rhodes,* Pure appl. Chem. *2,* 257 (1961).

[45] *F. R. Duke* and *G. Victor,* J. Amer. chem. Soc. *83,* 3337 (1961).

[46] *R. W. Laity,* J. chem. Educat. *39,* 67 (1962).

[*] The reader is referred to excellent reviews of structural investigations on fused electrolytes by electrochemical [7,47], thermochemical, optical, and other methods [47].

[47] *G. Watelle-Marion,* J. Chim. physique *56,* 302 (1959).

[48] *W. R. Grimes, N. V. Smith,* and *G. M. Watson,* J. physic. Chem. *62,* 862 (1958).

[49] *M. Blander, W. R. Grimes, N. V. Smith,* and *G. M. Watson,* J. physic. Chem. *63,* 1164 (1959).

[50] *G. M. Watson, R. B. Evans, W. R. Grimes,* and *N. V. Smith,* J. chem. Engng. Data *7,* 285 (1962).

[51] *P. I. Protsenko* and *A. G. Bergman,* Zh. obshch. Khim. *20,* 1365 (1950).

[**] A comparison of the solubility of helium in fused lithium silicate, *e.g.* at 1400 °C, with that in ionic melts [52] should be regarded with caution, since the polymeric anion structure gives rise to cavities which have nothing in common with the empty volume of ionic melts.

[52] *H. Scholze* and *H. O. Mulfinger,* Angew. Chem. *74,* 75 (1962); Angew. Chem. internat. Edit. *1,* 52 (1962). Owing to the highly covalent character of the bonds in the silicate skeleton, many silicates contain empty spaces (in the crystallographic sense) even in the solid state, in which smaller ions such as Li^+ and Be^{2+}, as well as He and H_2, can be embedded. It is therefore obvious that the solvent capacity for helium must decrease on addition of lithium oxide. This also applies to silicate melts.

[53] *H. U. Woelk,* Nukleonik *2,* 278 (1960).

[54] *H. v. Wartenberg,* Z. Elektrochem. angew. physik. Chem. *32,* 330 (1926).

[55] *M. Leroy,* Bull. Soc. chim. France *1962,* 968.

[56] *J. H. Shaffer, W. R. Grimes,* and *G. M. Watson,* J. physic. Chem. *63,* 1999 (1959).

[57] *R. L. Martin* and *J. B. West,* J. inorg. nucl. Chem. *24,* 105 (1962).

[58] *W. Fischer,* Angew. Chem. *75,* 173 (1963); Angew. Chem. internat. Edit. *2,* 162 (1963).

[59] *R. Scholder* and *M. Mansmann,* Z. anorg. allg. Chem. *321,* 255 (1963).

[60] *Y. K. Delimarskii,* Ukr. khim. Zh. *28,* 565 (1962).

[61] *Guy Delarue,* J. electroanalyt. Chem. *1,* 285 (1960).

[62] *Guy Delarue,* Bull. Soc. chim. France *1960,* 906.

[63] *G. Gashurov* and *A. K. Levine,* J. chem. Engng. Data *5,* 517 (1960).

the same solubility was found for calcium sulfide in lithium chloride [64].

Nitrides are insoluble in all common solvents, but dissolve in fused salts, particularly those of lithium. The solubility of calcium nitride is 0.07 mole/mole of LiCl at 650 °C, and that of lithium nitride is 0.15 mole/mole of LiCl. The solubility decreases on addition of potassium chloride [64]. The same is true of carbides, for which lithium halides have the best solvent properties of all the alkali metal halides. The other alkali metal halides react to a slight extent with formation of the alkali metal [65]. Whereas 20% by weight of lithium carbide or 17% of calcium carbide are soluble in lithium chloride at 820 °C, only 5.7% of calcium carbide can be dissolved in calcium chloride [65, 66].

It is generally known that the hydrides of the alkali and alkaline earth metals are soluble in fused salts and (as is also assumed for the oxides, sulfides, nitrides, and carbides) are dissociated into ions [67]. Nevertheless, hardly any quantitative data are available.

For lithium hydride in a LiCl/KCl melt at 400 °C a solubility of only 1–2 by weight was reported [68], while an eutectic was found for the system LiH/LiCl at 486 °C and a lithium hydride concentration of about 37 mole-% [65]. Sodium and calcium hydrides are also sufficiently soluble in alkali metal halides and hydroxides to take part in chemical reactions [43] (*e.g.* the solubility of sodium hydride in sodium hydroxide at 375 °C is 20% by weight).

C. Metals

The metal/fused salt systems are particularly interesting, not only because of their preparative applications, but also in view of their structural characteristics, which have not yet been fully elucidated. While metals are mostly insoluble in solid salts, an appreciable solubility is observed in the melts of their halides (cf. Table 2). Above

Table 2. Solubility (S) of metals in fused salts.

Metal	Melt	Temp. [°C]	S [mole-%]
Na	NaCl	895	4.3
K	KCl	770	16
Mg	$MgCl_2$	800	1.1
Ca	$CaCl_2$	1000	16
Sr	$SrCl_2$	1000	24.6
Ba	$BaCl_2$	1000	30
La	$LaCl_3$	826	9
Ce	$CeCl_3$	800	33
Pr	$PrCl_3$	659	18.5
Nd	$NdCl_3$	841	30.5
Cd	$CdCl_2$	650	16
Hg	$HgCl_2$	350	50
Bi	$BiCl_3$	320	45

a characteristic temperature, the metal and the melt are completely miscible and form a homogeneous liquid. Below this temperature progressive separation into two phases occurs.

The alkali metal systems have been investigated in detail: with a given anion, the miscibility appears to be the better, the larger the cation [69–71]. The alkaline earth metals are also readily soluble or even completely miscible with their halides, depending on the temperature [72–74]; for example, this makes the isolation of barium by melt electrolysis extremely difficult. The electrical conductivity of such systems is considerably greater, even at low metal concentrations, than that of the pure fused salts [75]. This suggests that the dissolved metal contributes an electronic conductivity component to the ionic conductivity already present. In particular the solubilities of rare earth metals in their halides promise a deeper insight into the structural relationships in metal/fused salt systems.

The discovery of very small metal droplets in rapidly cooled metal/melt systems led to the assumption that these systems were colloidal solutions referred to as "pyrosols" [76]. This is contradicted, however, by the depression of the melting point at low concentrations of the metal. More likely, at least in the case of the more electropositive elements, is a combination of the lattice of the salt with a hypothetical lattice of the metal, consisting of cations and F centers [77], *i.e.* the metal dissolves in the ionic form; the cation belongs to the quasi-lattice structure of the melt and the electron – although localized – can no longer be assigned to any one definite cation. This view is supported by the particularly high solubilities of metals in melts of their own salts. As the concentration of the metal increases, a quasi-periodic arrangement of the F centers seems to be formed, which ultimately leads to overlapping of the valence electron levels and hence to electronic conduction similar to that in the metal. The conductivity in the system LaI_3/La is even higher than that of the metal; formation of the "diiodide" is therefore proposed, in which the metal is present in the oxidized form [78]:

$$La + 2\ La^{3+}(I^-)_3 \rightarrow 3\ La^{3+}(I^-)_2e^- \quad (1)$$

Whereas the solubility of lanthanum [79] and cerium [80] in melts of their chlorides is normal, and the conductivity of the system $Ce/CeCl_3$ [81,82] also indicates the presence of relatively mobile electrons, a continuous transition from electronic to purely electrolytic conduction and to stable

[64] *M. Fild*, Diploma Thesis, Universität Göttingen, 1964.

[65] *W. A. Barber* and *C. L. Sloan*, J. physic. Chem. *65*, 2026 (1961).

[66] *W. A. Barber* and *C. L. Sloan*, U.S.-Pat. 3031413 (April 24th, 1962).

[67] *D. T. Hurd*: Chemistry of the Hydrides. Wiley, New York 1952, p. 31.

[68] *L. M. Litz* (Parma, Ohio) personal communication.

[69] *M. A. Bredig, J. W. Johnson*, and *W. T. Smith*, J. Amer. chem. Soc. *77*, 307, 1454 (1955).

[70] *J. W. Johnson* and *M. A. Bredig*, J. physic. Chem. *62*, 604 (1958).

[71] *M. A. Bredig* and *J. W. Johnson*, J. physic. Chem. *64*, 64, 1899 (1960).

[72] *D. Cubicciotti* and *C. D. Thurmond*, J. Amer. chem. Soc. *71*, 2149 (1949).

[73] *H. Schäfer* and *A. Niklas*, Angew. Chem. *64*, 610 (1952).

[74] *D. T. Peterson* and *J. A. Hinkebein*, J. physic. Chem. *63*, 1360 (1959).

[75] *H. R. Bronstein* and *M. A. Bredig*, J. Amer. chem. Soc. *80*, 2077 (1958).

[76] *R. Lorenz* and *W. Eitel*: Pyrosole. Akademie Verlag, Leipzig 1926. See, however, *W. Eitel* and *B. Lange*, *Z.* anorg. allg. Chem. *171*, 168 (1928).

[77] *K. S. Pitzer*, J. Amer. chem. Soc. *84*, 2025 (1962).

[78] *J. D. Corbett, L. F. Druding, W. J. Burkhard*, and *C. B. Lindahl*, Discuss. Faraday Soc. *32*, 79 (1961).

[79] *F. J. Kenesha* and *D. Cubicciotti*, J. chem. Engng. Data *6*, 507 (1961).

[80] *G. W. Mellors* and *S. Senderoff*, J. physic. Chem. *63*, 1110 (1959).

[81] *G. W. Mellors* and *S. Senderoff*, J. physic. Chem. *64*, 294 (1960).

[82] *H. R. Bronstein, A. S. Dworkin*, and *M. A. Bredig*, J. physic. Chem. *64*, 1344 (1960); *66*, 44 (1962).

compounds in lower oxidation states can be observed for the lighter rare earth metals. In the case of neodymium, for example, the following equation can be written [83]:

$$Nd + 2\ Nd^{3+}(I^-)_3 \rightarrow 3\ Nd^{2+}(I^-)_2 \quad (2)$$

Praseodymium occupies an intermediate position [84]. The greater the tendency to accommodate one or more valence electrons in the shell of the cation and not in zones of energy states of the whole system, the more probable is the formation of a "sub-compound". The anions are of decisive importance in this connection, since these must be compatible with the high concentration of F centers. There appears to be a relation between the reducing power (the "aggressiveness") of the dissolved metal and the "mobility" of its electrons. The more firmly the electrons are bound, the lower will be the reducing power of the system, since the electrons are used for the formation of compounds in low oxidation states.

Subhalides, which have also been discussed in the case of the alkali and alkaline earth metals (*e.g.* CaCl or Na_2Cl) [75], are clearly evident from the phase diagrams of $HgCl_2$/Hg [85], $CdCl_2$/Cd [86], and $BiCl_3$/Bi [87]. These systems exhibit no electronic conduction, and the specific conductivity decreases on addition of the metal. Mercury dissolves in molten mercury(II) chloride to form $Hg^{2+}(e^-)_2\ Hg^{2+}$. Similar species, presumably trimeric and tetrameric Bi_3^{3+} and Bi_4^{4+}, are formed by bismuth in bismuth trichloride.

Investigations on quenched melts can only rarely yield informations about the conditions in the liquid phase [88]. In the case of cadmium, it was assumed that the metal forms solvated complexes such as $Cd{\cdot}nCdCl_2$ with adjacent cadmium chloride molecules [89]; however, it is impossible to differentiate between these complexes and subhalides. Since the solutions are diamagnetic, the existence of Cd^+ ions (or CdCl) can be ruled out [90]. More recent investigations have shown that dimers such as Cd_2^{2+} are also present in the system $Cd/CdCl_2$. By the use of suitable anions, it was possible to stabilize the cadmium(I) oxidation state, and to isolate $Cd_2(AlCl_4)_2$ as a stable compound [91].

The solubilities of metals in their salts are in some cases greatly reduced by the addition of salts of other metals. This is of advantage in the technical use of molten salts as extractants and in the electrolytic production of metals. Table 3 shows the effects of monovalent, divalent, and trivalent foreign cations on the solubility of bismuth [92] and cadmium [93]. The decrease in the solubility of the metal is inversely proportional to the ratio of the number of anions to the number of cations of the foreign salt and directly proportional to the electropositive

Table 3. The decrease in the solubilities of bismuth and cadmium in melts of their salts, on addition of foreign ions.

Melt	Bi Solubility [mole-%]	Melt	Cd Solubility [mole-%]
$BiCl_3$	45	$CdCl_2$	15
$BiCl_3{\cdot}NaCl$	10	$CdCl_2{\cdot}KCl$	1
$BiCl_3{\cdot}CaCl_2$	30	$CdCl_2{\cdot}CaCl_2$	4
$BiCl_3{\cdot}CuCl$	33	$CdCl_2{\cdot}CeCl_3$	10
$BiCl_3{\cdot}ZnCl_2$	34	$CdCl_2{\cdot}ZnCl_2$	6
		$CdCl_2{\cdot}MgCl_2$	10
		$CdCl_2{\cdot}MnCl_2$	12

character of the foreign cation. It is assumed that the energy levels of the quasi-lattice of the melt are raised by the foreign cation, so that the metal to be dissolved can no longer give up its valence electrons so easily to the energy bands of the whole system, *i.e.* i.s solubility is reduced [93].

IV. Electrochemical Preparation of Compounds [*]

For a long time electrochemistry in fused salts referred exclusively to the electrometallurgical production of the elements. Although development in this field is by no means complete (cf. for example, the electrolytic production of titanium and other metals, *e.g.* niobium, tantalum, uranium, thorium, zirconium, beryllium, and boron, which are used in the construction of reactors and rockets) we shall be more concerned in the present paper with the preparation of compounds by the reaction of electrolytic products (for example with the electrode material).

The cathodic formation of calcium carbide in fused salts is achieved by the reaction of calcium with a porous carbon electrode or by electrolysis of dissolved calcium carbonate as a source of carbon [94]. Sodium carbide can be prepared in a similar manner at 450 to 800 °C in the presence of active charcoal [95]:

$$2\ NaCl + 2\ C \rightarrow Na_2C_2 + Cl_2 \quad (3)$$

The carbides dissolve readily in fused salts [65] and can react further in these media (cf. Section V).

Fluorocarbons, in particular CF_4, C_2F_6, and small quantities of higher homologues [96], can be prepared on an industrial scale by electrolysis of oxide-free mixtures of alkali metal fluorides, alkaline earth fluorides, or aluminum fluoride at about 600 to 1000 °C, using an anode consisting of fine carbon particles bonded with pitch. The proportion of hexafluoroethane in the product can be increased to 70% if the current density at the anode is not too high and the electrolysis is carried out at 750 to 850 °C [97]; at about 1200 °C only tetrafluoromethane

[83] *L. F. Druding* and *J. D. Corbett*, J. Amer. chem. Soc. *83*, 2462 (1961).

[84] *L. F. Druding*, *J. D. Corbett*, and *B. N. Ramsey*, Inorg. Chem. *2*, 869 (1963).

[85] *S. J. Yosim* and *S. W. Mayer*, J. physic. Chem. *64*, 909 (1960).

[86] *L. E. Topol* and *A. L. Landis*, U.S. Atomic Energy Comm. NAA-SR 5310 (1960); J. Amer. chem. Soc. *82*, 6291 (1960).

[87] *S. J. Yosim*, *A. J. Darnell*, *W. G. Gehman*, and *S. W. Mayer*, J. physic. Chem. *63*, 230 (1959).

[88] *A. Hershaft* and *J. D. Corbett*, Inorg. Chem. *2*, 979 (1963); see also [7], p. 224.

[89] *E. Heymann*, Austral. chem. Inst. J. Proc. *4*, 38 (1937).

[90] *J. Farquharson* and *E. Heymann*, Trans. Faraday Soc. *31*, 1004 (1935).

[91] *J. D. Corbett*, *W. J. Burkhard*, and *L. F. Druding*, J. Amer. chem. Soc. *83*, 76 (1961).

[92] *G. Cleary* and *D. Cubicciotti*, J. Amer. chem. Soc. *74*, 557 (1952).

[93] *D. Cubicciotti*, J. Amer. chem. Soc. *74*, 1198 (1952).

[*] The electrolysis of metals in a melt and the use of fused salts in physical operations, *e.g.* as heating baths, for recrystallization, as cooling agents or cores in nuclear reactors [9], in electroplating, and as lubricants will be reviewed elsewhere.

[94] *J. M. Finn*, *L. M. Litz*, and *M. N. Plooster*, U.S.-Pat. 2952591 (Sept. 13th, 1960).

[95] *H.T. Reid*, U.S.-Pat. 3066083 (Nov. 27th, 1962).

[96] *F. Olstowski* and *J. J. Newport*, U.S.-Pat. 3033767 (May 8th, 1962).

[97] *W. R. Wolfe jr.*, Brit. Pat. 863602 (March 22nd, 1961).

is formed [98]. Chlorofluorocarbons or bromofluorocarbons are obtained if chlorides or bromides are added to the melt [99], or if the anode is flushed with chlorine or bromine during electrolysis [100]. The reaction is very unspecific, however, and leads to a large number of perhalogenofluorocarbons. Partially fluorinated products are obtained, on the other hand, if hydrocarbons (acetylene) or halogenocarbons [101], possibly mixed with an inert gas, are blown through the porous anode. Alkali metals simultaneously separate out at solid cathodes (Ni). When lead, tin, aluminum, or calcium are used as liquid cathodes, the corresponding alloys with the alkali or alkaline earth metals are formed in yields of up to 96%, calculated on the cathode current [102].

If alkali metal pseudo-halides, in particular cyanides or thiocyanates, are added to the molten fluorides, nitriles of fluorocarbons, *e.g.* CF_3CN, are obtained together with perfluorocarbons [103]. Similar products are formed if gaseous cyano compounds, *e.g.* cyanogen, cyanogen chloride, hydrogen cyanide, *etc.*, are passed into molten fluorides with simultaneous electrolysis [104]. This process may be referred to as high-temperature electrofluorination.

When inert electrodes are used, the electrolytic products can be reacted with substances which are introduced into the melt. For example, when sodium is deposited electrolytically from a sodium hydroxide/potassium hydroxide melt, and the cathode is simultaneously flushed with ammonia, sodamide forms instantaneously at the cathode. The NH_2^- ions migrate to the anode, where they are probably discharged to form hydrazine, which immediately decomposes into ammonia and nitrogen. No hydrogen can be detected [43]. Traces of hydrazine were detected and the decomposition reaction was confirmed by electrolysis experiments using high-purity graphite electrodes and high-purity alkali metal amides [105]. Elements which form nitrides can react at a cathode flushed with nitrogen. Lithium nitride thus formed during the electrolysis of a mixture of lithium chloride and potassium chloride goes into solution (cf. Section III) and leaves the surface of the lithium free to react further. In general, reactions in fused salts proceed more rapidly and more completely than the reactions of the elements alone.

The importance of a clean metal surface becomes clear in the formation of hydrides from alkali metals and hydrogen. The reaction proceeds to completion only in the presence of a fused salt as the solvent, *e.g.* in the electrolysis of NaOH/KOH using an iron cathode flushed with hydrogen [43]. Instead of the usual graphite or metal anodes, liquid sodium amalgam anodes can also be used as a source of the sodium [106]. Solutions of alkali metal or alkaline earth hydrides in fused salts can be used for hydrogenations (cf. Section V), and it was by electrolysis of these systems and of pure fused lithium hydride, that the complete dissociation of the salt-like hydrides and the anodic liberation of hydrogen in quantitative current yield was proved [107]. Here a liquid aluminum cathode was used to intercept the lithium, after earlier attempts had failed owing to the high solubility of lithium in lithium hydride and owing to the recombination of the metal with the hydrogen.

An example of an electrochemical process in which the product separates at the anode is the electrolysis of alkali metal borohydrides, in particular $NaBH_4$, in fused salts. The alkali metal is removed as an amalgam, and diborane is obtained in good yield, together with a little pentaborane, at the inert anode [108].

Electrochemical reactions can also be used as stages in continuous or discontinuous cyclic preparative processes, generally to regenerate the initial state.

V. Chemical Reactions in Fused Salts

Chemical reactions in fused salts can be divided into three types:

1. Reactions involving participation of the melt and consumption of one or more of its components, with no simple means of regenerating the latter.

2. Reactions in which the melt simply acts as a solvent for the reactants, or in which the components of the melt are formed as by-products, or in which the by-products can be chemically or electrochemically reconverted into the starting compounds.

3. Reactions in which the melt acts as a catalyst (cf. Section VI).

In all these reactions it is naturally desirable to remove the products from the melt by evaporation, to decant them in the liquid form from two-phase systems, or to deposit them electrochemically. Products which remain suspended in the melt can if necessary be isolated with the aid of a high-temperature centrifuge [109], otherwise they can only be isolated by extraction from the cooled melt.

A. Digestion

Reactions in fused salts are familiar even to the chemistry student. Thus basic oxides such as Fe_2O_3, Al_2O_3, TiO_2, and $FeO{\cdot}Cr_2O_3$ are digested with acidic melts such as pyrosulfates or borates. Similarly, acidic oxides, such as SiO_2, and silicates dissolve readily in strongly basic melts such as sodium and potassium carbonates, sodium hydroxide or oxide, and mixtures of these. Samples containing elements which can form thio-salts can be digested with sodium polysulfide, which is also formed in

[98] *L. G. Blosser*, U.S.-Pat. 2990347 (June 27th, 1961).

[99] *F. Olstowski* and *L. G. Dean*, Brit. Pat. 894885 (April 26th, 1962).

[100] *W. E. Hanford* and *K. J. Radimer*, U.S.-Pat. 2970092/3 (Jan. 31st, 1961).

[101] *K. J. Radimer*, U.S.-Pat. 2841544 (July 1st, 1958).

[102] *W. O. Forshey*, Brit. Pat. 885635 (Dec. 28th, 1961).

[103] *F. Olstowski*, U.S.-Pat. 3017336 (Jan. 16th, 1962).

[104] *K. J. Radimer*, U.S.-Pat. 3032488 (May 1st, 1962).

[105] *M. H. Macdonald* and *R. D. Hill*, J. inorg. nuclear Chem. *15*, 105 (1960).

[106] *G. L. Cunningham*, U.S.-Pat. 2867568 (Jan. 6th, 1959).

[107] *M. A. Weinberger*, *T. J. Mousseau*, and *O. Maass*, Canad. J. Chem. *36*, 1455 (1958).

[108] *W. H. Schlechter*, U.S.-Pat. 3033766 (May 8th, 1962).

[109] *L. J. Wittenberg*, J. Amer. ceram. Soc. *42*, 209 (1959).

melts of sodium carbonate with sulfur (Freiberg digestion).

In alkali metal hydroxide melts, the presence of oxygen and water vapor leads to the formation of peroxides [110], towards which neither the noble metals nor most ceramic materials (with the exception of thorium oxide) are resistant [111]. Melts of this type have long been known as oxygen carriers. They make possible oxidations using air, *e.g.* the oxidation of dissolved manganese oxides [112] which leads to potassium manganate(V) at 240 to 300 °C, or to potassium manganate(VI) which precipitates out and can be filtered off [113].

$$2\ MnO_2 + 6\ KOH + {}^1/_2\ O_2 \rightarrow 2\ K_3MnO_4 + 3\ H_2O \quad (4)$$

$$2\ K_3MnO_4 + {}^1/_2\ O_2 + H_2O \rightarrow 2\ K_2MnO_4 + 2\ KOH \quad (5)$$

From investigations on the oxidation states of manganese in fused alkali metal nitrates it was found that the addition of hydroxide promotes the formation of manganate(V), whereas only manganate(VI) is formed in the presence of peroxide [114].

If, instead of oxygen, ozone is used as the oxidizing agent in an alkali metal nitrate melt containing Np salts at 150 °C, hexavalent neptunium is formed (detected by spectroscopy) [115], and neptunium(VI) oxide can be isolated [116].

Typical reactions involving participation of the melt are the preparations of alkali metal and alkaline earth titanates from hydroxides or carbonates and titanium dioxide [116a], and of chloro- and bromoapatites from alkaline earth phosphates, arsenates, and vanadates in fused alkali metal halides [117]. While metaphosphates react with fluoride ions with cleavage of the P–O–P chain

$$(PO_3^-)_n + n\ F^- \rightarrow n\ PO_3F^{2-} \quad (6)$$

and with hexafluorophosphates to form difluorophosphates

$$2\ (PO_3^-)_n + n\ PF_6^- \rightarrow 3\ n\ PO_2F_2^- \quad (7)$$

the analogous reaction with chloride ions cannot be carried out [118]. Finally, various silver silicates can be prepared in molten silver nitrate by cation exchange

$$3\ \beta\text{-}Na_2Si_2O_5 + 6\ AgNO_3 \rightarrow Ag_4SiO_4 + Ag_2SiO_3 + 4\ SiO_2 + 6\ NaNO_3 \quad (8)$$

With the exception of α-$Na_2Si_2O_5$, all silicates with layer structures undergo this reaction [119].

[110] *H. Lux, R. Kuhn,* and *T. Niedermaier,* Z. anorg. allg. Chem. *298,* 285 (1959).

[111] *H. Lux, E. Renauer,* and *E. Betz,* Z. anorg. allg. Chem. *310,* 305 (1961).

[112] *H. Lux* and *T. Niedermaier,* Z. anorg. allg. Chem. *285,* 246 (1956).

[113] *M. B. Carus* and *A. H. Reidies,* U.S.-Pat. 2940821–5 (June 14th, 1960).

[114] *R. M. Benett* and *O. G. Holmes,* Canad. J. Chem. *41,* 108 (1963).

[115] *D. Cohen,* J. Amer. chem. Soc. *83,* 4094 (1961).

[116] *D. Cohen,* Inorg. Chem. *2,* 866 (1963).

[116a] *K. L. Berry,* U.S.-Pat. 2841470 (July 1st, 1958).

[117] *R. Klement* and *R. Harth,* Chem. Ber. *94,* 1452 (1961).

[118] *K. Bühler* and *W. Bues,* Z. anorg. allg. Chem. *308,* 62 (1961).

[119] *F. Wodtke* and *K.-H. Jost,* Z. anorg. allg. Chem. *314,* 341 (1962).

B. Acid-Base Reactions

The study of acid-base reactions and their kinetics in fused nitrates is of particular interest. The nitrate ion is slightly dissociated:

$$NO_3^- \rightleftharpoons NO_2^+ + O^{2-} \quad (9)$$

A relatively high concentration of nitryl ions is obtained by interception of the oxide with salts of strong acids, *e.g.* the readily soluble dichromates [120] or pyrosulfates [121]:

$$S_2O_7^{2-} + NO_3^- \rightleftharpoons NO_2^+ + 2\ SO_4^{2-} \quad (10)$$
$$Cr_2O_7^{2-} + NO_3^- \rightleftharpoons NO_2^+ + 2\ CrO_4^{2-}$$

The nitryl ions react further with nitrate ions or with added bromide ions:

$$NO_2^+ + NO_3^- \rightarrow 2\ NO_2 + {}^1/_2\ O_2 \quad (11)$$
$$NO_2^+ + Br^- \rightarrow NO_2 + {}^1/_2\ Br_2$$

Investigations have also been carried out on the reaction of bromates in the presence of divalent cobalt, copper, nickel, and zinc cations to form the corresponding metal oxides [122]:

$$6\ M^{2+} + 12\ BrO_3^- \rightarrow 6\ Br_2 + 15\ O_2 + 6\ MO \quad (12)$$

Bromates decompose in the presence of bromide ions [123]:

$$BrO_3^- + Br^- \rightarrow BrO_2^- + BrO^- \text{ (slow)}$$
$$BrO^- + BrO_3^- \rightarrow 2\ BrO_2^- \text{ (fast)} \quad (13)$$
$$BrO_2^- \rightarrow Br^- + O_2 \text{ (fast)}$$

Perchlorates decompose in a similar manner in fused sodium hydroxide; this reaction is accelerated by binding the oxygen as peroxide [124].

C. Halogenations

Molten salts are in many respects particularly suitable as solvents for halogenations. Apart from their stability towards hydrogen halides or halogens, they dissolve these substances as well as the reaction products which otherwise cover the surface. Thus the reaction of spent uranium-zirconium fuel elements with hydrogen fluoride to form the tetrafluorides of the two metals proceeds satisfactorily only in fluoride melts [9, 125]. If fluorine or chlorine trifluoride is passed into the melt, the UF_4 reacts further to form UF_6, which separates from the melt and, after repeated adsorption and desorption on sodium fluoride, can be led directly to the isotope separator. Zirconium and more than 99% of the fission products remain in the melt.

[120] *F. R. Duke* and *M. L. Iverson,* J. Amer. chem. Soc. *80,* 5061 (1958).

[121] *F. R. Duke* and *S. Yamamoto,* J. Amer. chem. Soc. *81,* 6378 (1959).

[122] *F. R. Duke* and *W. W. Lawrence,* J. Amer. chem. Soc. *83,* 1269 (1961).

[123] *F. R. Duke* and *E. A. Shute,* J. physic. Chem. *66,* 2114 (1962).

[124] *R. P. Seward* and *H. W. Otto,* J. physic. Chem. *65,* 2078 (1961).

[125] *R. P. Milford,* Ind. Engng. Chem. *50,* 187 (1957).

To avoid corrosion, chlorine was used in the lower-melting chloride systems. Here, uranium trichloride and zirconium tetrachloride are formed; the latter is evaporated, while all of the uranium remains in the melt and is extracted by electrolysis. Its separation from fission products is more difficult in this case (cf. Section IV), since *e.g.* plutonium is also present in the melt as K_2PuCl_6, *i.e.* in the less common tetravalent state [126].

Valence states which are otherwise difficult to obtain, *e.g.* of titanium and other transition elements, can be stabilized in a melt. In a solution of titanium metal in molten titanium halides more than 90% of the titanium is present in the divalent state, as the complex K_2TiCl_4 [127]. A particularly elegant method of preparing halides of divalent titanium [128], iron, and chromium [129] makes use of the fact that the products of chlorination are obtained in the molten state and that compounds of higher valence states are reduced by excess metal.

As in the case of uranium, the use of fused salts is advantageous when, in the chlorination of an alloy, large quantities of other volatile chlorination products are formed, which would otherwise block the reaction vessel. For example, in the preparation of silicon tetrachloride from ferrosilicon or from the silicon/copper mixture remaining from the Rochow synthesis of organochlorosilanes, a smooth and complete reaction is inhibited by the iron and copper chlorides formed. Addition of alkali metal chlorides gives a melt of non-volatile complexes in which the reaction proceeds to completion, the heavy metal chlorides formed in various valence states acting as chlorine carriers [43]. The resulting silicon tetrachloride is very pure. Fused salts can also be used as washing liquids for the separation of volatile halides which differ in their tendencies towards complex formation, *e.g.* for the absorption of iron or aluminum chloride from niobium pentachloride [130] or zirconium tetrachloride [131] vapors.

Volatile chlorides can be prepared directly from oxides by chlorination under reducing conditions. The oxides are generally dissolved or suspended in the presence of finely divided carbon, or carbon monoxide is simultaneously led into the melt to act as a reducing agent. Boron trichloride is prepared in a eutectic mixture of sodium, calcium, and barium chlorides in which 10 to 15% by weight of boron trioxide are dissolved [132]:

$$B_2O_3 + 3\,C + 3\,Cl_2 \rightarrow 2\,BCl_3 + 3\,CO \qquad (14)$$

The best yields are obtained at 800 °C. Carbon tetrachloride can also be used for this reaction [43]. Silicon tetrachloride is prepared directly from silicon dioxide by a similar method, while beryllium and thorium oxides react with carbon and chlorine to form complex chlorides which are soluble in the melt. The metals are then extracted by electrolysis [134].

It is also possible to obtain 97% of the titanium from ilmenite in the form of the volatile titanium tetrachloride by reductive chlorination in the melt at 500 °C, while the greater part of the iron remains bound as $NaFeCl_4$. With columbite the result is similar: iron and all of the uranium remain in the melt, while 90% of the niobium and tantalum are obtained as the volatile chlorides [135]. Elegant reductive chlorinations are achieved in fused alkali metal or alkaline earth chlorides by the use of anodes of the appropriate oxides and carbon [136].

Halogenations in fused salts can also be carried out by halogen transfer, *e.g.* between a halide and an element. Thus, halides of boron, aluminum, and silicon are produced by reaction of the element with silver or copper halides [137, 138]:

$$\begin{aligned} B(Al) + 3\,AgX &\rightarrow BX_3\,(AlX_3) + 3\,Ag \\ Si + 4\,CuX &\rightarrow SiX_4 + 4\,Cu \qquad X = Cl, Br, I \end{aligned} \qquad (15)$$

This procedure is particularly useful for the preparation of radioactive compounds. Although the reaction begins when the solid components are heated, the conversion in many cases becomes appreciable only when the temperature reaches the melting point of the halide. An example is the formation of boron trichloride using CuCl.

For compounds which are thermally stable, halogen exchange reactions in molten fluorides [139] offer advantages over the conventional methods of fluorination using fluorides of the transition elements (Ag, Hg, Cd, Co), which are difficult to obtain, or suspensions of solid fluorides. Chlorine compounds of sulfur, carbon, silicon, and phosphorus react between 300 and 550 °C in a LiF/NaF/KF melt or in the $ZnCl_2$/KCl eutectic containing potassium or calcium fluoride to give the fluorides, sometimes in good yields, *e.g.*

$$\begin{aligned} SO_2Cl_2(SOCl_2, COCl_2) + 2\,NaF &\rightarrow \\ SO_2F_2(SOF_2, COF_2) + 2\,NaCl & \\ CCl_4 + x\,NaF &\rightarrow CF_xCl_{4-x} + x\,NaCl \end{aligned} \qquad (16)$$

Carbonyl fluoride and sulfuryl fluoride (the latter free from thionyl fluoride) can be readily prepared by this method, without the use of elementary fluorine which is otherwise necessary. The alkali metal chlorides formed as by-products depress the melting point of the reaction medium. This halogen exchange was also used to prepare thiocarbonyl fluoride [140] in such quantities that it was possible to determine the physical properties of the colorless gas, record its spectra, determine its structure by

[126] *R. Benz* and *R. M. Douglass*, J. inorg. nuclear Chem. *23*, 134 (1961).

[127] *W. C. Kreye* and *H. H. Kellog*, J. electrochem. Soc. *104*, 504 (1957).

[128] *P. Ehrlich, H. J. Hein*, and *H. Kühnl*, Z. anorg. allg. Chem. *292*, 139 (1957).

[129] *H. Kühnl* and *W. Ernst*, Z. anorg. allg. Chem. *317*, 84 (1962).

[130] *C. A. Sutherland* and *A. G. White*, U.S.-Pat. 3085855 (April 16th, 1963).

[131] *R. V. Horringan* and *O. F. Sprague*, German Patent Application 1045998 (Dec. 11th, 1958).

[132] *M. Baccaredda* and *F. G. Nencetti*, Chim. e Ind. *42*, 1084 (1960).

[133] *A. W. Evans* and *K. Arkless*, German Patent Application 1123298 (Febr. 8th, 1962).

[134] *A. R. Gibson*, Brit. Pat. 856462 (Dec. 14th, 1960).

[135] *B. S. Mathur, V. S. Sastri*, and *Y. W. Golzhale*, J. sci. ind. Res. [New Delhi], Sect. D *21*, 5 (1962).

[136] *R. W. Ancrum* and *A. W. Evans*, Brit. Pat. 864538 (April 6th, 1961).

[137] *K. H. Lieser, H. W. Kohlschütter, D. Maulbecker*, and *H. Elias*, Z. anorg. allg. Chem. *313*, 193 (1962).

[138] *K. H. Lieser, H. Elias*, and *H. W. Kohlschütter*, Z. anorg. allg. Chem. *313*, 199 (1962).

[139] *W. Sundermeyer*, Z. anorg. allg. Chem. *314*, 100 (1962).

[140] *W. Sundermeyer* and *W. Meise*, Z. anorg. allg. Chem. *317*, 334 (1962).

electron diffraction [141], and to study its chemical behavior.

$$CSCl_2 + 2\,NaF \rightarrow CSF_2 + 2\,NaCl \quad (17)$$

Attention should be drawn to the reactions with chlorine and bromine yielding the difluorohalogenomethanesulfenyl halides, $F_2XC-S-X$, and to the possible industrial importance of the polymerization of CSF_2 to elastomeric products.

D. Halogen-Pseudohalogen Exchange

Exchange of halogen for pseudohalogen in solutions of alkali metal pseudohalides in fused salts leads to cyanides, cyanates, and thiocyanates of silicon and carbon [*] [142].

$$\begin{aligned} (CH_3)_3SiCl + KCN &\rightarrow (CH_3)_3SiCN + KCl \\ (CH_3)_2SiCl_2 + 2\,KOCN &\rightarrow (CH_3)_2Si(NCO)_2 + 2\,KCl \\ SiCl_4 + 4\,KSCN &\rightarrow Si(NCS)_4 + 4\,KCl \end{aligned} \quad (18)$$

The entire series of cyanates and thiocyanates $(CH_3)_xSiX_{4-x}$ (X = NCO, NCS) have been obtained, in some cases in very good yield. Advantages of this method are: (a) the starting materials are the more readily available alkali metal pseudohalides instead of the silver salts used in other methods; (b) the alkali metal pseudohalides are more readily soluble in melts than the potassium or silver salts are in organic solvents, and hence the reaction proceeds in the homogeneous phase. The corresponding reactions with halogenated hydrocarbons yield acetonitrile and ethyl thiocyanate:

$$\begin{aligned} CH_3Cl + KCN &\rightarrow CH_3CN + KCl \\ C_2H_5Cl + KSCN &\rightarrow C_2H_5SCN + KCl \end{aligned} \quad (19)$$

This is in contrast to the reaction with silver or copper cyanide, in which methyl isonitrile (CH_3CN) is formed. It was therefore assumed that the silicon pseudohalides of Equation (18), which were formerly regarded as isocompounds, contain the same anion as the alkali metal pseudohalides from which they are formed. This assumption has been confirmed in the case of trimethylcyanosilane [143]. The same method was used for the preparation of methylazidosilanes by reacting the corresponding methylchlorosilanes with a 1.0 to 20% suspension (or to some extent solution) of sodium azide in a $ZnCl_2$/KCl melt at 250 °C [144]:

$$(CH_3)_xSiCl_{4-x} + x\,NaN_3 \rightarrow (CH_3)_xSi(N_3)_{4-x} + x\,NaCl \quad (20)$$
$$x = 1, 2, 3$$

Phenylazidosilanes and (for the first time) mixed halogenated-pseudohalogenated silanes have also become available *via* trimethylazidosilane by exchange reactions.

Metal pseudohalides are obtainable in valence states which are difficult to achieve by other methods. Thus potassium tetracyanonickelate(0) can be prepared in accordance with Equation (21) in fused cyanide, as can

$$K_2Ni(CN)_4 + 2\,KCN \rightarrow K_4Ni(CN)_4 + (CN)_2 \quad (21)$$

potassium tetracyanonickelate(I) by reduction of tetracyanonickelate(II) with metallic nickel in the melt [145]. Similarly, cyanomanganates, cyanomolybdates, and cyanopalladates in various oxidation states are obtainable in fused salts by reduction with cyanide ions [146].

The industrial preparation of sodium cyanide illustrates how important the fused state can be for a good conversion. The reaction of sodium with ammonia in the presence of wood charcoal at 700 to 900 °C proceeds particularly smoothly if sodium cyanide has already been formed or has been added in advance. Sodium cyanide is a good solvent or suspending medium for all intermediates of the reaction which presumably proceeds in the following steps:

$$\begin{aligned} 2\,NH_3 + 2\,Na &\rightarrow 2\,NaNH_2 + H_2 \\ 2\,NaNH_2 + C &\rightarrow Na_2N_2C + 2\,H_2 \\ Na_2N_2C + C &\rightarrow 2\,NaCN \end{aligned} \quad (22)$$

A similar method is used for the preparation of calcium cyanide from calcium cyanamide, and of potassium cyanide by anion exchange between sodium cyanide and potassium chloride in the melt [147]. Alkali metal cyanates are prepared analogously. For example, sodium cyanate is obtained in 71 % yield at 530 °C by the reaction

$$CaCN_2 + Na_2CO_3 + CO_2 \rightarrow 2\,NaOCN + CaCO_3 \quad (23)$$

Potassium cyanide, either fused or dissolved in molten alkali metal halides, reacts quantitatively with oxygen at 400 °C to give potassium cyanate [43], while the reaction with chlorine yields cyanogen:

$$2\,KCN + Cl_2 \rightarrow (CN)_2 + 2\,KCl \quad (24)$$

Owing to the high temperature, however, the latter is 40% polymerized to paracyanogen. The assumption that cyanogen chloride occurs as an intermediate in Reaction (24) has been confirmed both by the reaction of cyanogen chloride with potassium cyanide in the melt

$$KCN + CNCl \rightarrow (CN)_2 + KCl \quad (25)$$

and by the almost exclusive formation of cyanogen chloride in the reaction of the cyanide with excess chlorine [43].

$$KCN + Cl_2 \rightarrow CNCl_2 + KCl \quad (26)$$

E. Preparation of Amides, Nitrides, Carbides, and Sulfides

The melt appears to have a catalytic effect in the preparation of alkali metal and alkaline earth amides from the metals and ammonia in molten alkali metal hydroxides

[141] This work was kindly carried out by Prof. *E. Rogowski*, Physikalisch-Technische Bundesanstalt Braunschweig (Germany).

[*] Unconvincing structural investigations of the silicon compounds of Eq. (18) were interpreted to indicate that these are isocyanates and isothiocyanates.

[142] *W. Sundermeyer*, Z. anorg. allg. Chem. *313*, 290 (1961).

[143] The author is grateful to Prof. *H. Hoyer*, Leverkusen (Germany) for his collaboration and discussions.

[144] *W. Sundermeyer*, Chem. Ber. *96*, 1293 (1963).

[145] *S. von Winbush, E. Griswold*, and *J. Kleinberg*, J. Amer. chem. Soc. *83*, 3197 (1961).

[146] *W. L. Magnuson, E. Griswold*, and *J. Kleinberg*, Inorg. Chem. *3*, 88 (1964).

[147] Ullmanns Encyklopädie der technischen Chemie. 3rd.Edit., Urban & Schwarzenberg, München 1954, Vol. 5, p. 648.

at 300 to 400 °C. In the industrial preparation of sodamide, the product serves as the solvent (as in the production of sodium cyanide) [148]. Boron nitride, which is stable at high temperatures, can be synthesized in an almost eutectic melt of sodium hydroxide and sodamide [149]:

$$B_2O_3 + 3\ NaNH_2 \rightarrow 2\ BN + NH_3 + 3\ NaOH \quad (27)$$

When prepared from boron trioxide and ammonia in the NaCl/KCl eutectic at 850 to 950 °C, the boron nitride floats on the surface of the melt, and can be isolated without wasting the melt by dissolving it in water [150]. As for nitrides, fused salts appear to be the only solvents suitable for the production of carbides. Reaction

$$MgCl_2 + CaC_2 \rightarrow MgC_2 + CaCl_2 \quad (28)$$

(28) again proceeds only upon liquefaction of the powdered mixture. The MgC_2 decomposes further into carbon and Mg_2C_3, which is only stable below 600 °C [151]. Thus, to obtain Mg_2C_3, hydrolysis of which yields mainly propyne [152], sodium chloride is added to the melt. Solutions of calcium carbide in alkali metal and alkaline earth halides can be used for the synthesis of titanium

$$TiO_2 + CaC_2 \rightarrow TiC + CaO + CO \quad (29)$$

carbide [153] and for the reduction of oxides and sulfides of high-melting metals (Cr, Ti, Zr) [154]. An interesting reaction takes place between calcium or aluminum carbide and alkali metal or alkaline earth fluorides in the presence of chlorine [155]:

$$CaC_2 + 2\ x\ NaF + 5\ Cl_2 \rightarrow 2\ F_xCCl_{4-x} + CaCl_2 + 2\ x\ NaCl \quad (30)$$

It appears to offer a new route to the perhalogenated fluorochloromethanes.

The high solubility of the alkali metal and alkaline earth sulfides in fused salts permits the preparation of many sulfides of transition elements, which are generally sparingly soluble and separate out in a highly crystalline form. Sulfide ions are oxidized to elementary sulfur by oxidizing agents such as Cu^{2+}, Fe^{3+}, Hg^{2+}, and iodine [62]:

$$4\ S^{2-} + 4\ Cu^{2+} \rightarrow 2\ Cu_2S + S_2 \quad (31)$$

In the resulting blue solution the sulfur is probably present in the diatomic form, and can be titrated to decolorization with a solution of potassium cyanide in the same

$$S + KCN \rightarrow KSCN \quad (32)$$

melt, as has been demonstrated for solutions of polysulfides in potassium thiocyanate [156]. Solutions containing sulfides can be used *e.g.* for the preparation of carbon oxide sulfide from phosgene

$$COCl_2 + K_2S \rightarrow COS + 2\ KCl \quad (33)$$

and for the preparation of bis(trimethylsilyl) sulfide from trimethylchlorosilane [157]:

$$2\ (CH_3)_3SiCl + K_2S \rightarrow (CH_3)_3Si{-}S{-}Si(CH_3)_3 + 2\ KCl \quad (34)$$

F. Hydrogenations

An example which illustrates the advantages of chemical reactions in ionic liquids is the synthesis of silicon- and boron hydrides [158]. It had formerly been necessary to use the expensive complex hydrides of aluminum and boron, since no solvents could be found for the reaction of the salt-like hydrides of the alkali metals and of the alkaline earths. However, these dissolve in fused salts, *e.g.* in a LiCl/KCl melt at 400 °C (cf. Section III). If silicon- or boron halides are passed through such a melt containing an alkali metal hydride, halogen-hydrogen interchange takes place:

$$4\ LiH + SiCl_4 \rightarrow SiH_4 + 4\ LiCl \quad (35)$$

If an electrolysis is carried out in the same melt using a cathode flushed with hydrogen, new lithium hydride is continuously formed. The overall equation of the reaction sequence (which would proceed explosively in the reverse direction) then is:

$$SiCl_4 + 2\ H_2 \rightarrow SiH_4 + 2\ Cl_2 \quad (36)$$

The chlorine which is produced electrolytically can be used again for the preparation of silicon tetrachloride. The suggestion [159] to carry out the reaction with a silicon or boron anode appears to be impracticable, since very pure anode materials would be needed. A similar process described can be used for the preparation of diborane and for the hydrogenation of partially alkylated silanes. Thus dimethylsilane, an important starting material for the preparation of dimethylchlorosilane, can be obtained from dimethyldichlorosilane.

It proved impossible to carry out the reaction continuously or discontinuously in one reaction vessel on the industrial scale [158, 160]; however, an apparatus consisting essentially of a three-branched tube [158] could be developed into an industrial plant which is used today [161] (see Fig. 2).

The lithium, which is electrolysed in a conventional cell at 400 °C, flows into the hydrogenation unit, which operates at about 600 °C to obtain a faster reaction. To suppress the thermal decomposition of the silicon- or boron hydride, the

[148] Gmelins Handbuch der Anorganischen Chemie. Verlag Chemie, Berlin 1928, Vol. 21, p. 253.

[149] *H. Tagawa* and *O. Itouji*, Bull. chem. Soc. Japan *35*, 1536 (1962).

[150] *L. M. Litz*, German Patent Application 1096884 (Jan. 12th, 1961).

[151] *A. Schneider* and *J. F. Cordes*, Z. anorg. allg. Chem. *279*, 94 (1955).

[152] *J. F. Cordes, H. Lüdemann*, and *K. Wintersberger*, Z. Naturforsch. *15b*, 677 (1960).

[153] *W. A. Barber*, U.S.-Pat. 3078149 (Febr. 19th, 1963).

[154] *J. Bouchard* and *P. Cotton*, German Patent Application 1037146 (Aug. 21st, 1958).

[155] *H. L. Roberts*, Brit. Pat. 874099 (Aug. 2nd, 1961).

[156] *H. Lux* and *H. Anslinger*, Chem. Ber. *94*, 1161 (1961).

[157] *M. Fild, W. Sundermeyer*, and *O. Glemser*, Chem. Ber. *97*, 620 (1964).

[158] *W. Sundermeyer*, German Patent Application 1080077 (Aug. 8th, 1957).

[159] *E. Enk* and *J. Nickl*, German Patent Application 1092890 (Nov. 17th, 1960).

[160] *W. Sundermeyer* and *O. Glemser*, Angew. Chem. *70*, 625 (1958).

[161] This work was carried out by Dr. *L. M. Litz*, Union Carbide Corporation, Parma, Ohio (U.S.A.), with great personal effort and great experience. The author is indebted to him for communicating the results.

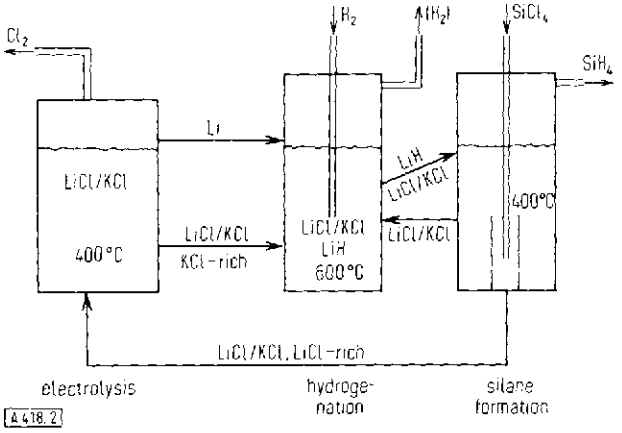


Fig. 2. Schematic representation of the silane synthesis of *Sundermeyer*.

third unit, *i.e.* the silane unit, again operates only at 400 °C. This has the further advantage that the solution containing the alkali metal hydride can be transported to the third stage simply by convection. The melt in which the lithium chloride has accumulated is recycled to the electrolysis unit. The process has been in use for several years in an unattended experimental plant [161], with more than 90 per cent conversion and almost quantitative yield [162]. Since the decomposition of trichlorosilane reaches an equilibrium and since monosilane can be easily purified and decomposed to yield silicon, this method is advantageous for the preparation of very pure silicon.

By a coincidence, the new process originated in the same laboratory from which *Friedrich Wöhler* reported the first preparation of monosilane exactly 100 years earlier [158, 163]. *Wöhler* also decomposed the silane by heat to obtain silicon, a sample of which is still held in the institute's collection in a tube labeled in *Wöhler*'s own handwriting (see Fig. 3).

Owing to the technical importance of the silanes and boranes, other methods are available for their preparation in fused salts. Whereas only traces of monosilane are obtained when silicon tetrachloride is reduced with hydrogen in the presence of aluminum in a $NaCl/AlCl_3$ melt at normal pressure [43], a conversion of 84% is

$$3\ SiCl_4 + 4\ Al + 6\ H_2 \rightarrow 3\ SiH_4 + 4\ AlCl_3 \quad (37)$$

achieved at 750 atm. Silicon dioxide can also be reduced in a vibrating autoclave at high pressures [164]:

$$3\ SiO_2 + 4\ Al + 2\ AlCl_3 + 6\ H_2 \rightarrow 3\ SiH_4 + 6\ (AlOCl) \quad (38)$$

Boron trioxide or borates undergo a similar reaction to yield diborane [165], which can also be prepared by the reaction of alkali metal borohydrides with Lewis acids, *e.g.* with hydrogen chloride, or better, boron halides in alkali metal chloride/aluminum chloride or alkali metal chloride/zinc chloride systems [166]:

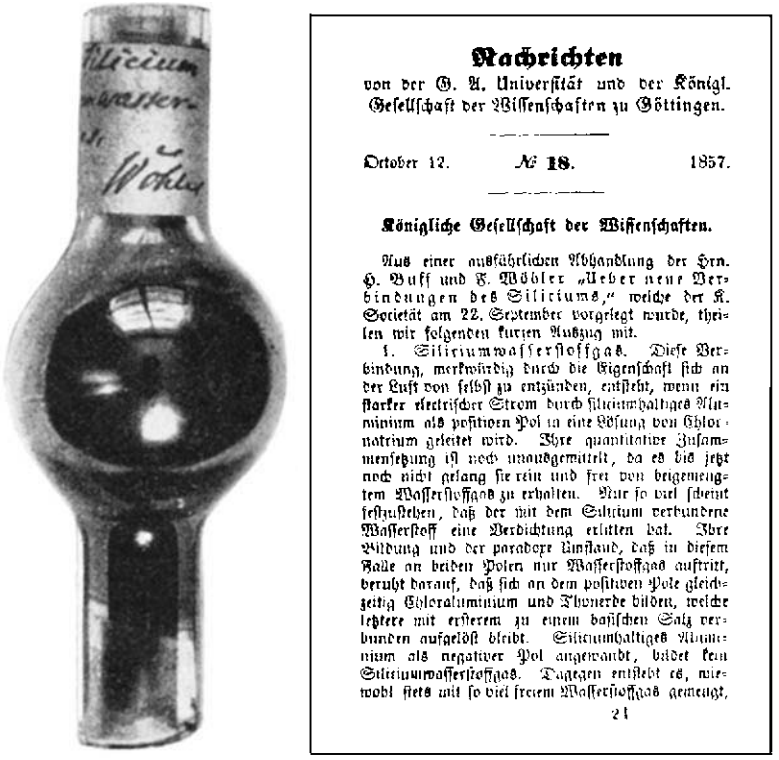
$$3\ NaBH_4 + BCl_3 \rightarrow 2\ B_2H_6 + 3\ NaCl \quad (39)$$

In another reaction the starting materials are the alkali metal borohydride and tin(II) chloride [167]. While diborane and hydrogen escape the melt without decomposing, the tin separates as a liquid:

$$2\ NaBH_4 + SnCl_2 \rightarrow Sn + 2\ NaCl + B_2H_6 + H_2 \quad (40)$$

Finally, some methods should be mentioned which proceed satisfactorily only in the melt and in which the end-product itself provides the melt. Lithium perchlorate, which is used as an oxidizing agent in rocket technology, is prepared according to Equation (41) and is then decanted in the

$$Li_2CO_3 + 2\ NH_4ClO_4 \rightarrow 2\ LiClO_4 + 2\ NH_3 + CO_2 + H_2O \quad (41)$$



Nachrichten

von der G. A. Universität und der Königl. Gesellschaft der Wissenschaften zu Göttingen.

October 12. № 18. 1857.

Königliche Gesellschaft der Wissenschaften.

Aus einer ausführlichen Abhandlung der Hrn. H. Buff und F. Wöhler „Ueber neue Verbindungen des Siliciums," welche der K. Societät am 22. September vorgelegt wurde, theilen wir folgenden kurzen Auszug mit.

1. Siliciumwasserstoffgas. Diese Verbindung, merkwürdig durch die Eigenschaft sich an der Luft von selbst zu entzünden, entsteht, wenn ein starker electrischer Strom durch siliciumhaltiges Aluminium als positiven Pol in eine Lösung von Chlornatrium geleitet wird. Ihre quantitative Zusammensetzung ist noch unausgemittelt, da es bis jetzt noch nicht gelang sie rein und frei von beigemengtem Wasserstoffgas zu erhalten. Nur so viel scheint festzustehen, daß der mit dem Silicium verbundene Wasserstoff eine Verdichtung erlitten hat. Ihre Bildung und der paradoxe Umstand, daß in diesem Falle an beiden Polen nur Wasserstoffgas auftritt, beruht darauf, daß sich an dem positiven Pole gleichzeitig Chloraluminium und Thonerde bilden, welche letztere mit ersterem zu einem basischen Salz verbunden aufgelöst bleibt. Siliciumhaltiges Aluminium als negativer Pol angewandt, bildet kein Siliciumwasserstoffgas. Dagegen entsteht es, mögleich stets mit so viel freiem Wasserstoffgas gemengt,

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Fig. 3. Silicon obtained by *Wöhler* in 1857 by thermal decomposition of silane.

[162] Monosilane can now be produced at one third of the former cost. The present experimental plant could supply the entire U.S. market for high-purity silicon.

[163] *F. Wöhler*, Nachr. königl. Ges. Wiss. Göttingen, Oktober 12th, 1857.

[164] *H. L. Jackson, F. D. Marsh*, and *E. L. Muetterties*, Inorg. Chem. *2*, 43 (1963).

[165] *A. L. McClelland*, U.S.-Pat. 3088804 (May 7th, 1963).

[166] *J. P. Faust*, U.S.-Pat. 3019083 (Jan. 30th, 1962).

[167] *W. Jeffers*, Chem. and Ind. *1961*, 431.

molten state [168]. Lithium nitrate can be prepared in a similar manner from ammonium nitrate [169]. Ammonium beryllium fluoride is decomposed to form beryllium fluoride by introducing it into molten beryllium fluoride at 900 °C [170]:

$$(NH_4)_2BeF_4 \rightarrow BeF_2 + 2\ NH_4F \quad (42)$$

G. Reactions in Suspensions of Metals

Relatively little is known about reactions with suspensions or solutions of metals in fused salts. A number of quaternary systems, consisting of two metals and their halides, and their equilibria in alkali metal chloride melts have been investigated. These equilibria are often strongly displaced towards the "right", *e.g.* in the violent reaction (43) of zinc with various metal chlorides. Spectroscopically pure lead or cadmium separate out [171]. Lead is also displaced from lead chloride by cadmium.

$$PbCl_2 + Zn \rightarrow Pb + ZnCl_2 \quad (43)$$
$$CdCl_2 + Zn \rightarrow Cd + ZnCl_2$$

The reaction of mercury(II) chloride with zinc begins with a spontaneous rise in temperature of the powder and becomes explosive at the melting point. The same is reported for the reaction of aluminum with zinc chloride [172]. The reactions of tin(II) chloride with zinc [173] and of tin(IV) chloride with aluminum [43] also proceed vigorously in fused salts, with separation of metallic tin.

The fact that the reactions often proceed to completion is generally due to the removal of one component as a separate liquid phase or as a vapor. For example, when calcium is added to a lithium chloride/potassium chloride melt, alkali metals distil off [43]. These can also be liberated from alkali metal fluorides by magnesium and calcium [174], and by uranium, zirconium, and yttrium.

The reduction with metals is used industrially in the production of titanium. Titanium tetrachloride is blown into melts of alkali metal chlorides or alkaline earth chlorides containing sodium [175] or lithium [176]. The titanium is obtained as a fine powder or as a sponge. If the reaction is carried out with magnesium, the product is a magnesium-titanium alloy, which is subsequently separated into its components above 750 °C [177]. Niobium and tantalum are obtained in a similar manner from the double fluorides, using sodium [178].

$$K_2TaF_7 + 5\ Na \rightarrow 2\ KF + 5\ NaF + Ta \quad (44)$$

Uranium [179] and zirconium are displaced from their chlorides by aluminum. If the zirconium is only partially reduced, it can be separated from the unreacted hafnium tetrachloride [180].

The "subchloride process" for the electrothermal production of aluminum is likely to achieve great technical importance [181]. It involves the endothermic reaction of aluminum with gaseous aluminum chloride, or a sodium chloride/aluminum chloride melt, to form aluminum subchloride. At 1200 °C, the equilibrium lies 98 % to the right [182].

$$2\ Al + AlCl_3 \rightleftharpoons 3\ AlCl \quad (45)$$

If the subchloride vapor is brought into contact with liquid aluminum or with the above melt in a separate reaction vessel at 700 °C, the reaction is reversed and pure aluminum separates out. A particular advantage of this process is that the subchloride can also be produced from compounds with a high aluminum content or from alloys formed *e.g.* by reduction of bauxite with coke [183] or by direct electrolysis of bauxite in a cryolite melt, thus avoiding the Bayer digestion process. A very large quantity of the aluminum can be extracted from an alloy in this manner, before appreciable quantities of other metals are entrained, since AlCl reacts with foreign metal chlorides as shown in Equation (46) [184].

$$MnCl_2 + AlCl \rightarrow Mn + AlCl_3 \quad (46)$$

Whereas the reaction (47) of aluminum oxide with carbon and aluminum chloride in a sodium chloride/aluminum

$$Al_2O_3 + AlCl_3 + 3\ C \rightarrow 3\ AlCl + 3\ CO \quad (47)$$

chloride melt, with subsequent separation of aluminum is difficult to carry out, aluminum oxide can be reacted with phosgene in an alkali metal chloride/aluminum chloride melt at lower temperatures (550 to 900 °C):

$$Al_2O_3 + 3\ COCl_2 \rightarrow 2\ AlCl_3 + 3\ CO_2 \quad (48)$$

The aluminum chloride formed sublimes out of the melt. This reaction is best carried out in a fluidized bed [185] and is a first example of a reaction catalysed by fused salts.

VI. Fused Salts as Catalysts

In many respects, fused electrolytes are particularly suitable media also for organic reactions. Owing to the high thermal conductivity, the heat of reaction is rapidly dissipated, whereas local overheating and consequent autocatalytic decomposition is often unavoidable on solid supports. Moreover, catalytically active material remains permanently active and is not removed with the reaction products. Finally, the melt is generally immiscible with decomposition products, which are therefore easily removed, whereas the large surface of solid sup-

[168] *D. R. Stern*, U.S.-Pat. 2929680 (March 22nd, 1960).

[169] *D. R. Stern*, U.S.-Pat. 2959463 (Nov. 8th, 1960).

[170] *A. R. S. Gough* and *E. W. Bennet*, Brit. Pat. 833808 (April 27th, 1960).

[171] *J. I. Jelagina* and *A. P. Palkin*, Zh. Neorg. Khim. *2*, 873 (1957).

[172] *A. P. Palkin* and *O. K. Belussow*, Zh. Neorg. Khim. *2*, 1620 (1957).

[173] *G. G. Urazow* and *M. A. Sokolowa*, Izv. Akad. Nauk U.S.S.R., Otdel. khim Nauk *1940*, 739.

[174] *I. M. Dubrowin* and *A. K. Jewssejew*, Atomnaya Energiya *9*, 414 (1960).

[175] *J. Smolenski*, *J. C. Hannam*, and *A. L. Leach*, J. appl. Chem. *8*, 375 (1958).

[176] *M. P. Neipert* and *R. D. Blue*, Brit. Pat. 863428 (March 22nd, 1961).

[177] *W. Schaller*, *A. Ehringfeld*, and *P. Tillmann*, German Patent Application 1061081 (July 9th, 1959).

[178] German Patent Application 1141794 (Dec. 27th, 1962), National Research Corp.

[179] *R. H. Moore*, *J. R. Morrey*, and *E. E. Voiland*, J. physic. Chem. *67*, 744 (1963).

[180] *I. E. Newnham*, U.S.-Pat. 2916350 (Dec. 8th, 1959).

[181] Review: *E. Herrmann*, Aluminium *37*, 143, 215 (1961).

[182] *P. Weiß*, Z. Erzbergbau Metallhüttenwes. *3*, 241 (1950).

[183] *F. W. Southam*, Belg. Pat. 621068 (Febr. 4th, 1963).

[184] *J. P. McGeer*, Belg. Pat. 621069 (Febr. 4th, 1963).

[185] *J. Hille* and *W. Dürrwächter*, Angew. Chem. *72*, 850 (1960).

ports may become blocked and ineffective. Frequently, reactions in ionic melts yield products which are different from those obtained on solid catalysts, owing to the polarizing forces of the melt.

It is thought that the mechanism of the catalytic action of ionic melts is similar to that of the corresponding metals [186]. In the metals, we have a lattice of positively charged atoms with freely moving electrons, whereas an ionic melt contains cations "diluted" with anions. A similar "dilution" is observed in many activated solid catalysts. Owing to the varying distances between the cations in the melt, however, more products are likely to be formed here than on solid catalysts with fixed lattice distances.

The melting point of the catalytically active salt must be as low as possible, and in any case lower than 500 °C. High catalytic activities are shown by the purely ionic salts, which have high melting points even in binary or ternary systems, and in particular by salts whose cations occur in two or more valence states; these are generally salts of the transition metals. Since some of these are strongly covalent, *i.e.* form "molecular melts", they are mixed with alkali metal or alkaline earth halides; the original molecular structures then dissolve to form complex ions (solvation). The salt must also be able to form an intermediate or addition compound with the reactants.

A. Catalytic Chlorination

The chlorination of hydrocarbons is generally accompanied by the evolution of considerable heat, which can lead to local overheating and hence to unsuccessful reactions. Advantages of using a melt are the high solubility of chlorine, and a close control of the reaction temperature. Controlled partial chlorinations can therefore be carried out with no danger of explosion, owing to the high dilution.

The reaction of acetylene with chlorine (1:1), using carbon tetrachloride as a diluent, at 175 to 250 °C in an $NaCl/AlCl_3$ melt containing iron(III) chloride yields a mixture of ethylene chloride, tetrachloroethylene, and carbon tetrachloride [187], while ethylene chloride reacts at 400 to 480 °C to form 1,1-dichloroethylene (20 %), 1,2-dichloroethylene (22 %), trichloroethylene (29 %), and other chlorinated products. If the ratio of ethylene chloride to chlorine is reduced to between 0.55:1 and 0.75:1, the principal product at about 350 °C is 1,1,2-trichloroethane (about 50 %) [188]. Ethane and chlorine (1:3) react at 400 °C in a sodium chloride/aluminum chloride melt containing $CuCl_2$ to give ethyl chloride (46 %), vinyl chloride (22 %) (by elimination of HCl from 1,1- or 1,2-dichloroethane), and methyl chloride (4 %) [189]. The chlorination of benzene at 200 to 250 °C in an $NaCl/AlCl_3/FeCl_3$ melt is more specific. Monochlorobenzene is formed with an 88 % conversion and an equally high yield when gaseous benzene and chlorine are introduced into the melt. Only about 10 % of more highly chlorinated products, mainly dichlorobenzene, are formed. The lower the temperature and the shorter the contact time, the higher is the ratio of monosubstituted to polysubstituted products [190, 191].

Since the vapor-phase chlorination of methane to form methyl chloride is difficult to control, the reaction was tried in fused salts (potassium hydrogen sulfate, zinc chloride, and alkali metal and alkaline earth chlorides with relatively large quantities of iron(III) chloride or copper(II) chloride).

At 320 °C and a molar ratio $CH_4:Cl_2 = 2:1$, methyl chloride is obtained in 50 % yield, together with very small quantities of methylene chloride and chloroform [192]. The chlorination can also be carried out in potassium chloride/copper chloride (70 mole-% of CuCl) if up to 48 % of the copper(I) chloride is chlorinated to copper(II) chloride; this then acts as a mild chlorinating agent [193]:

$$CH_4 + 2\ CuCl_2 \rightarrow CH_3Cl + Cu_2Cl_2 + HCl \quad (49)$$

The bath can be regenerated by bubbling in chlorine or hydrogen chloride and oxygen. With less than 20 mole-% of copper(II) chloride, the conversion remains small; this is explained by the fact that, in a melt containing 30 mole-% of potassium chloride, up to 21.4 mole-% of the copper(II) chloride are bound as K_2CuCl_4 (very low partial pressure of chlorine over melts containing less than 20 mole-% of $CuCl_2$). Investigations on the ternary system $KCl/CuCl/CuCl_2$ and the partial pressure of chlorine over the melt have led to the conclusion that the chlorine is made available by Reaction (50) [194].

$$Cu^{2+} + CuCl_4^{2-} \rightarrow Cu_2Cl_2 + Cl_2 \quad (50)$$

An unsatisfactory feature of all chlorinations of organic substances is that half of the chlorine used is lost as hydrogen chloride. This can be avoided, particularly in the reactions in alkali metal chloride/copper chloride or alkali metal chloride/ferric chloride systems, by mixing oxygen with the chlorine during the reaction [Equation (51)] or by using hydrogen chloride and oxygen right from the beginning [Reaction (52)].

$$CH_4 + x/2\ Cl_2 + x/4\ O_2 \rightarrow CH_{4-x}Cl_x + x/2\ H_2O \quad (51)$$

$$CH_4 + x\ HCl + x/2\ O_2 \rightarrow CH_{4-x}Cl_x + x\ H_2O \quad (52)$$

However, this direct oxidative chlorination at 400 to 550 °C yields 40 % of carbon tetrachloride, 40 % of chloroform, 15 % of methylene chloride, and only 5 % of methyl chloride. The two-step process, involving chlorination with copper(II) chloride and regeneration of the melt with hydrogen chloride and oxygen, is therefore more favorable [195, 196]. Another example of oxidative chlorination, this time with a copper chloride/potassium chloride melt on a solid support in a fluidized bed, is the reaction of ethylene at 300 to 500 °C, which yields 53 % of tetrachloroethylene, 23 % of trichloroethylene, 9 % of pentachloroethane, and 5 % of dichloroethylene [197]. If ethylene, hydrogen chloride, and oxygen are used in the ratio of 2:2:1, a 61 % yield of vinyl chloride is obtained [198]:

$$H_2C{=}CH_2 + HCl + {}^1/_2\ O_2 \rightarrow H_2C{=}CHCl + H_2O \quad (53)$$

Vinyl chloride is also obtained on oxidative chlorination of ethane [199]:

$$C_2H_6 + HCl + O_2 \rightarrow H_2C{=}CHCl + 2\ H_2O \quad (54)$$

[186] *N. E. Norman* and *H. F. Johnstone*, Ind. Engng. Chem. *43*, 1553 (1951).

[187] *J. H. Reilly*, U.S.-Pat. 2140551 (Dez. 20th, 1938).

[188] *J. H. Reilly*, U.S.-Pat. 2140548/9 (Dec. 20th, 1938).

[189] *J. H. Reilly*, U.S.-Pat. 2140547 (Dec. 20th, 1938).

[190] *J. H. Reilly*, U.S.-Pat. 2140550 (Dec. 20th, 1938).

[191] *O. Glemser* and *K. Kleine-Weischede*, Liebigs Ann. Chem. *659*, 17 (1962).

[192] German Pat. 393550 (April 5th, 1924), Holzverkohlungs-Industrie AG.

[193] *E. Gorin*, *C. M. Fontana*, and *A. G. Kidder*, Ind. Engng. Chem. *40*, 2128 (1948).

[194] *C. M. Fontana*, *E. Gorin*, *G. A. Kidder*, and *C. S. Meredith*, Ind. Engng. Chem. *44*, 363 (1952).

[195] *E. Gorin*, U.S.-Pat. 2498546 (Febr. 21st, 1950).

[196] *W. T. Wdowitschenko* et al., Gazovaya Prom. *5*, 37 (1960).

[197] *L. E. Bohl*, Belg. Pat. 602842 (Aug. 16th, 1961).

[198] Belg. Pat. 614467 (Aug. 27th, 1962), ICI Australia and New Zealand Ltd.

[199] *W. K. Snead* and *R. H. Chandley*, Belg. Pat. 617586 (Aug. 31st, 1962).

The addition of alkali metal chlorides as "activators" to copper or zinc chlorides on a support was frequently described. Here a molten phase is formed in which the reaction proceeds with a good conversion; also, the vapor pressure of the catalytically active salt is reduced.

The mechanism of the oxidative chlorination has been investigated in detail. When air is led through a potassium chloride/copper(I) chloride melt, up to 75 % of the oxygen is absorbed [200] and Cu_2OCl_2 is formed at 350 to 400 °C:

$$2\ CuCl + {}^1/_2\ O_2 \rightarrow CuO{\cdot}CuCl_2 \qquad (55)$$

This compound, which can be isolated, is partly dissolved in the melt. If the temperature of the melt is raised to 450 to 525 °C, chlorine-free oxygen is liberated; this provides a method of extracting oxygen from the air [201]. On reaction with hydrogen chloride $CuO{\cdot}CuCl_2$ forms water and copper(II) chloride:

$$CuO{\cdot}CuCl_2 + 2\ HCl \rightarrow 2\ CuCl_2 + H_2O \qquad (56)$$

Summation of the two Equations (55) and (56) gives Equation (57) for the Deacon process:

$$2\ HCl + {}^1/_2\ O_2 \rightleftharpoons H_2O + Cl_2 \qquad (57)$$

The Deacon process using copper salts as catalysts is particularly susceptible to exhaustion of the catalyst owing to migration of the salt from the support (which can be compensated by continuous evaporation of a copper(II) chloride melt). It is therefore not surprising that the possibility of using fused salts as catalysts has been intensely investigated [203].

The problem here (as in experiments with solid catalysts and with fused salts on solid supports) is that the reaction is an equilibrium which permits a conversion of only 65 to 75 % at the required temperatures of 350 to 400 °C. This conversion is only achieved in a few cases, mainly when alkali metal chloride/copper(II) chloride, alkali metal chloride/iron(III) chloride, or chromium-, manganese- or rare earth chloride melts are used as catalysts. A property common to chromium, manganese, and the rare earths is their ability to form stable oxide chlorides. Optimum conversion is readily achieved in fused salts by good contact between the gases and the liquid phase (use of an aerating stirrer) [43, 142]. However, the residual gas always contains 20 to 25 % of hydrogen chloride and oxygen, and this makes isolation of the chlorine difficult.

These difficulties are avoided if the Deacon process is carried out in two steps [204]. Oxygen (air) and hydrogen chloride are bubbled into a copper chloride/potassium chloride melt at 350 to 425 °C. Water and copper(II) chloride are formed via $CuO{\cdot}CuCl_2$. When the $CuCl_2$ concentration in the melt reaches 45 to 75 %, the melt is heated at 500 to 800 °C in a separate chamber, whereupon pure chlorine is liberated, with regeneration of copper(I) chloride. The ratio of hydrogen chloride to absorbed oxygen should be as close as possible to 4:1, since the oxide chloride separates out, if the concentration of this intermediate exceeds 30 mole-%. The potassium chloride content should also be maintained at or below 30 mole-%. Otherwise too much copper(II) chloride is bound as a complex and is not available for decomposition in the second step.

Instead of isolating chlorine by raising the temperature, hydrocarbons can also be introduced in the second step of the Deacon process, or phosgene can be produced from carbon monoxide [205]:

$$CO + 2\ HCl + {}^1/_2\ O_2 \rightarrow COCl_2 + H_2O \qquad (58)$$

Recent investigations have shown that the oxidation potential of iron(III) ions in the melt (in contrast to aqueous solutions) is practically the same as that of copper(II) ions [206]. This explains the use of iron(III) ions as catalysts in the Deacon process. The optimum conversion of 70 % is achieved in an iron(III) chloride/potassium chloride melt at 430 °C [207].

Catalytically active fused salts can be used as solvents for esterification and ether cleavage reactions [208]. Methanol is quantitatively converted to methyl chloride by hydrogen chloride, without the need for other substances to remove the water. Only traces of dimethyl ether are formed during the reaction. Dimethyl ether which is formed in the industrial methanol synthesis, and for which uses are difficult to find, can be cleaved to methyl chloride by hydrogen chloride in a zinc chloride/potassium chloride melt. The conversion is 90 %.

$$H_3C{-}O{-}CH_3 + 2\ HCl \rightarrow 2\ CH_3Cl + H_2O \qquad (59)$$

The reaction of diethyl ether with hydrogen chloride in an $AlCl_3$/KCl/NaCl melt to form ethyl chloride has been reported [209]. However, it was found that it is the reaction with aluminum chloride which leads to ethyl chloride [208]:

$$3\ H_5C_2{-}O{-}C_2H_5 + 2\ AlCl_3 \rightarrow Al_2O_3 + 6\ C_2H_5Cl \qquad (60)$$

The hydrolysis of methylchlorosilanes to produce methylpolysiloxanes gives rise to the formation of large quantities of hydrochloric acid. On the other hand, if *e.g.* dimethylchlorosilane is reacted with methanol in a melt containing zinc chloride, the desired dimethylcyclosiloxane is obtained in 80 % yield, in addition to methyl chloride which is required for the Rochow synthesis of methylchlorosilanes [208]:

$$(CH_3)_2SiCl_2 + 2\ CH_3OH \rightarrow [(CH_3)_2SiO] + 2\ CH_3Cl + H_2O \qquad (61)$$

The reaction of dimethyldichlorosilane with dimethyl ether is less satisfactory.

The Rochow synthesis, which is generally carried out in fluidized beds nowadays, has also been investigated in various fused salts, in the hope of obtaining a more favorable ratio of dimethyldichlorosilane to other methylchlorosilanes. Silicon powder was reacted with methyl chloride in a $ZnCl_2$/KCl/NaCl melt at 290 °C, using 10 % of copper powder and 0.5 % of zinc powder as catalysts [43, 210]. The yields of dimethyldichlorosilane did not come up to expectations, in spite of the quantitative consumption of silicon. The attempt

[200] *C. M. Fontana, E. Gorin, G. A. Kidder*, and *R. E. Kinney*, Ind. Engng. Chem. *44*, 369, 373 (1952).

[201] *C. M. Fontana*, U.S.-Pat. 2447323 (Aug. 17th, 1948).

[202] *F. Wolf, F. Runge*, and *R. Korn*, Z. anorg. allg. Chem. *304*, 48 (1960).

[203] The author is grateful to Dipl.-Chem. *A. Kettrup* for his help with the difficult task of collecting about 20 patents which suggest 41 elements as catalysts, as well as various procedures.

[204] *E. Gorin*, U.S.-Pat. 2418931 (April, 15th, 1947).

[205] *E. Gorin* and *C. B. Miles*, U.S.-Pat. 2444289 (June 29th, 1948).

[206] *I. Slama*, Collect. czechoslov. chem. Commun. *28*, 518 (1963).

[207] *H. Krekeler* and *H. Schlecht*, German Pat. 857633 (Jan. 31st, 1952).

[208] *W. Sundermeyer*, Chem. Ber. *97*, 1069 (1964).

[209] *J. L. Amos*, U.S.-Pat. 2140500 (Dec. 20th, 1938).

to methylate silicon by reaction of the Si–H bond with methyl chloride was unsuccessful. Instead, chlorosilane and methane were formed in the copper chloride/potassium chloride melt [43]:

$$SiH_4 + CH_3Cl \begin{cases} \xrightarrow{\Delta} CH_3SiH_2Cl + H_2 \\ \rightarrow SiH_3Cl + CH_4 \end{cases} \quad (62)$$

Chlorosilanes were formerly prepared in sealed tubes at high pressures because of the volatility of the aluminum chloride catalyst. They can now be produced continuously and at normal pressure by two methods, in a $NaCl/AlCl_3$ melt. If a mixture of monosilane and hydrogen chloride (1:1) is led into the melt at 120 °C, 80% of monochlorosilane is obtained together with other chlorosilanes [211]:

$$SiH_4 + HCl \rightarrow SiH_3Cl + H_2 \quad (63)$$

To avoid evolution of hydrogen from the valuable Si–H compounds, the commutation under otherwise identical conditions is preferable:

$$SiH_4 + SiCl_4 \rightarrow 2\ SiH_2Cl_2 \quad (64)$$

Alkylated silanes can also be reacted in this way. This provides a simple and extremely favorable method of preparing dimethylchlorosilane, which is used for the synthesis of α,ω-hydridopolysiloxanes [43, 212]:

$$(CH_3)_2SiH_2 + (CH_3)_2SiCl_2 \rightarrow 2\ (CH_3)_2SiHCl \quad (65)$$

The Friedel-Crafts hydrocarbon synthesis can also be carried out in melts containing aluminum chloride, *e.g.* the reaction of benzene with ethyl chloride or ethyl bromide at 150–170 °C to yield ethylbenzene; however, large amounts of tarry products are formed [191, 213].

B. Catalytic Eliminations and Additions

Elimination and addition reactions generally proceed satisfactorily in a zinc chloride/potassium chloride melt. The preparation of vinyl chloride by thermal dehydrohalogenation of 1,1- and 1,2-dichloroethanes has recently attracted attention at the expense of the hydrohalogenation of acetylene on activated charcoal loaded with mercury salts. Heating difficulties are avoided when fused salts are used. A further advantage of fused salts is the stabilization of the catalyst.

If 1,1-dichloroethane is passed through a $ZnCl_2/KCl$ or $ZnCl_2/CnCl$ melt at 330 °C, vinyl chloride is obtained in 97% yield and 77% conversion [214]. The conversion obtained with 1,2-dichloroethane is lower (about 50%). To avoid formation of acetylene compounds, 5% by weight of mercury(II) chloride must be added. The addition of hydrogen chloride to acetylene also proceeds in 89% yield in this melt. By a combination of both steps 2 moles of vinyl chloride can be obtained from one mole of acetylene and one mole of 1,1-dichloroethane:

$$HC{\equiv}CH + Cl_2HC{-}CH_3 \rightarrow 2\ H_2C{=}CHCl \quad (66)$$

Moreover, butene can be produced with a 77% conversion by elimination of hydrogen chloride from n-butyl chloride in a zinc chloride/copper(I) chloride melt at 400 °C [191]. Examples of the hydrochlorination of olefins are also known, such as the addition of HCl onto ethylene, which gives an 82% yield of ethyl chloride in a $NaCl/KCl/AlCl_3$ melt at 100 °C. The remainder of the ethylene polymerizes.

Olefins can be prepared by elimination of water from alcohols; the reaction proceeds most readily with tertiary alcohols. Ethanol reacts at 350 °C in molten copper(I) chloride to form ethylene [186], while the same reaction in molten $NaCl/ZnCl_2$ is more specific, giving a yield of 98% [191]. Propylene and butene have also been prepared in this way.

Perchloroethylene is obtained by dehydrogenation of symmetrical tetrachloroethane at 300 to 500 °C in a copper chloride/zinc chloride melt [215]:

$$Cl_2HC{-}CHCl_2 + {}^1/_2\ O_2 \rightarrow Cl_2C{=}CCl_2 + H_2O \quad (67)$$

If the oxygen supply is insufficient, trichloroethylene is also formed by elimination of hydrogen chloride [216]. Another way to prepare trichloroethylene is the reaction of tetrachloroethylene with hydrogen at 300 °C [217]:

$$Cl_2C{=}CCl_2 + H_2 \rightarrow Cl_2C{=}CHCl + HCl \quad (68)$$

C. Miscellaneous Reactions

About 25 patents have been granted for methods of isomerizing n-paraffins to branched-chain compounds. Melts are used in which compounds of the type of Friedel-Crafts catalysts are dissolved, *e.g.* an alkali metal chloride/aluminum chloride melt with an excess of aluminum chloride [218]. Additions of antimony chloride [219], zinc chloride [220], or nickel and cobalt chlorides, as well as other chlorides of subgroup VIII elements also serve their purpose [221]. The reaction is generally carried out below 200 °C. The longer the carbon chain of the n-paraffin, the lower is the temperature chosen, since otherwise undesirable cracking occurs. In the case of hydrocarbons with more than five C-atoms, the reaction is carried out below 80 °C. It has been found particularly useful to add a small quantity of hydrogen chloride [222]; for example, the isomerization of n-butane to isobutane then proceeds at 141 °C with a 50% conversion. This process is of interest for increasing the octane rating of petroleum fractions.

[210] *W. Schmidt* and *K. Jost*, German Pat. 920187 (April 15th, 1954).

[211] *W. Sundermeyer* and *O. Glemser*, Angew. Chem. *70*, 628 (1958).

[212] *W. Sundermeyer*, Lecture, IUPAC-Congress, London, September 1963.

[213] *W. Sundermeyer* and *O. Glemser*, Angew. Chem. *70*, 629 (1958).

[214] *W. Sundermeyer*, *O. Glemser*, and *K. Kleine-Weischede*, Chem. Ber. *95*, 1829 (1962).

[215] *R. Earl Feathers* and *R. H. Rogerson*, U.S.-Pat. 2914575 (Sept. 27th, 1956).

[216] *A. C. Ellsworth* and *R. M. Vancamp*, U.S.-Pat. 2951103 (Sept. 4th, 1958).

[217] Belg. Pat. 616504 (Aug. 16th, 1962), Uddeholms AB.

[218] *H. A. Cheney*, U.S.-Pat. 2342073 (Febr. 15th, 1944.)

[219] *J. Anderson*, *S. H. McAllister*, and *W. E. Roses*, U.S.-Pat. 2387868 (Oct. 30th, 1945).

[220] *C. C. Crawford* and *W. E. Ross*, U.S.-Pat. 2394752 (Febr. 12th, 1946).

[221] *H. A. Cheney*, U.S.-Pat. 2279292 (April 14th, 1942).

[222] *T. B. Hudson* and *J. D. Upham*, U.S.-Pat. 2439301 (April 6th, 1948).

The nitration of paraffins proceeds more readily in fused nitrates than in the vapor phase. Propane and nitric acid react at 372–444 °C to give nitropropane with an 11% conversion; this is due to both the efficient temperature control and to the catalytic effect of the melt [223]. However, the reaction of organic substances in fused nitrates always leads to fairly large quantities of various oxidation products [43].

Finally, fused salts have also been used for reactions with acetylene. Here again the rapid dissipation of the heat of reaction, which would otherwise cause decomposition to carbon and hydrogen, is of advantage. Acyclic oligomers, such as monovinylacetylene (80%), and higher-boiling products (15%), are formed from acetylene in a copper(I) chloride/amine hydrochloride melt [224]. Benzene (40%), toluene (10%), xylene (10%), and naphthalene (20%), are obtained, together with 30% of tars and carbon, at 500 to 600 °C in melts containing zinc chloride (and only in these) [225]. Acetylene has been reacted with ammonia at 440 to 550 °C, again in an alkali metal chloride/zinc chloride melt, in an attempt to synthesize pyridine derivatives; however, acetonitrile was obtained in 60% yield [226].

[223] *D. C. Coldiron, L. F. Albright*, and *L. G. Alexander*, Ind. Engng. Chem. *50*, 991 (1958).

[224] *H. Vollmann* and *B. Schacke*, U.S.-Pat. 2161645 (June 6th, 1939).

[225] *P. C. Johnson* and *S. Swann*, Ind. Engng. Chem. *38*, 990 (1946).

[226] *R. S. Hanmer* and *S. Swann*, Ind. Engng. Chem. *41*, 325 (1949).

VII. Conclusion

In view of the large number of publications on fused salts [10], and particularly on their physicochemical properties, the present paper can only be almost complete in the intended field, *i.e.* the use of ionic liquids in preparative chemistry. Very informative papers have been published on the manipulation of melts [227], corrosion problems, isotope separation, electrophoresis, polarography, Raman and infrared recording techniques, chromatography, gas chromatography (with a melt as the stationary phase), and analyses using fused salts as solvents [228, 229].

Ionic liquids, which still represent a wide and new scientific territory, will take their place alongside nonpolar and water-like solvents, and, like these, will frequently be the best solvents for given preparations.

I am sincerely grateful to the Director of the Anorganisch-Chemisches Institut, Prof. O. Glemser, and to Farbenfabriken Bayer in Leverkusen (Germany) for their generous support of my work, and particularly to Dr. F. Freund, Göttingen, for valuable and critical discussions.

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Translated by Express Translation Service, London

[227] *J. D. Corbett* and *F. R. Duke* in *H. B. Jonassen* and *A. Weissberger*: Technique of Inorganic Chemistry. Interscience Publishers, New York 1964.

[228] *M. Blander* (Editor): Molten Salt Chemistry. Interscience Publishers, New York 1964.

[229] *B. R. Sundheim* (Editor): Fused Salts; Series in Advanced Chemistry. McGraw-Hill, New York 1964.

COMMUNICATIONS

Synthesis of Cyclopropane Compounds from Triethyl Phosphoenolpyruvate or α-Halogenoacrylic Esters

By Prof. Dr. Ulrich Schmidt

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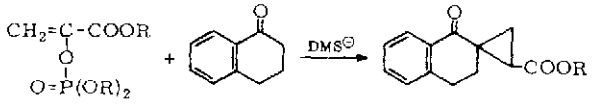
Triethyl phosphoenolpyruvate *(1)* is obtained by a Perkow reaction [1] between ethyl bromopyruvate and triethyl phosphite (85% yield, b.p. 95–100 °C/0.1 mm, $n_D^{20} = 1.4342$). It reacts in the presence of one mole of base (the dimethylsulfinyl carbanion [2] or t-butoxide) with methylene compounds to give cyclopropane derivatives. With tetralone, for example, an 80% yield of spiro-[2-ethoxycarbonylcyclopropane-1,2'-tetralone] *(2)*, m.p. 86.5–87.5 °C, is obtained.



(1), R = C_2H_5 *(2)*

Reaction between *(1)* and acetophenone or acetoacetic ester yields 60% ethyl 2-benzoylcyclopropanecarboxylate *(3)* [b.p. 110 °C/0.1 mm, $n_D^{20} = 1.5242$, m.p. of dinitrophenylhydrazone 173–174 °C] or 40% diethyl 2-acetylcyclopropane-1,2-dicarboxylate [b.p. 82–87 °C/0.1 mm, $n_D^{20} = 1.4668$].

Procedure: A solution of 2.5 g of sodium hydride in 50 ml of dimethylsulfoxide [2] is added dropwise under nitrogen to a mixture of 25 g of triethyl phosphoenolpyruvate and 15 g of α-tetralone, keeping the temperature of the reaction mixture at 45 °C. After 30 min, the mixture is poured into 500 ml of water. Extraction with chloroform and processing of the chloroform extract affords 80% *(2)*, which is purified by recrystallization from ethanol or by vacuum distillation (0.01 mm) in a sausage flask at a bath temperature of 180 °C.

This new cyclopropane sythesis probably proceeds by a Michael addition followed by a 1,3-elimination and is stereospecific as regards the formation of *(2)* and *(3)*. Only one isomer of *(2)* is formed (homogeneous on thin-layer chromatograms) which on saponification produces only one isomer of the carboxylic acid *(2)*, R = H, m.p. 117 °C. The carbonyl and ethoxycarbonyl groups in *(2)* are probably in *trans*-relationship, since no intramolecular hydrogen bond can be detected by infrared spectroscopy in the free acid. Compound *(3)* is also homogeneous in gas chromatograms. Hydrolysis affords the low-melting isomer of 2-benzoylcyclopropanecarboxylic acid [3]. Gas chromatography of *(4)* yields two isomers in a ratio of 2:1.

Analogous cyclopropane syntheses can be carried out with α-halogenoacrylic esters. Thus, for example, *(2)* is formed in 30% yield from ethyl α-chloroacrylate and tetralone.

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[1] Perkow reaction of bromopyruvic acid and triethyl phosphite: *V. M. Clark* and *A. J. Kirby*, Biochim. biophysica Acta *78* (4), 732 (1963).

[2] *E. J. Corey*, J. Amer. chem. Soc. *84*, 866 (1962).

[3] *C. H. F. Allen* and *H. W. J. Cressman*, J. Amer. chem. Soc. *55*, 2953 (1933).

Substitution Reactions with Photochemically Produced Acyl Radicals [1]

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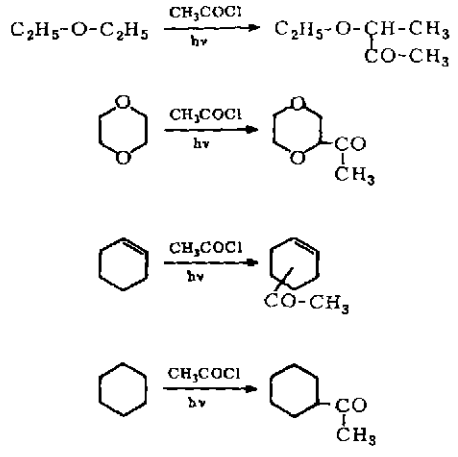
Acyl chlorides are split into acyl and chlorine radicals by light of wavelength 254 mμ. Since the dissociation energy of the chlorine-hydrogen bond is considerably larger than that of the acyl-hydrogen bond, substitution of the substrate by acyl radicals is observed on irradiation of acid chlorides. On irradiation of acetyl chloride the following reactions take place:



A few percent of aldehyde and diacetyl are always found, the latter being formed by combination of acetyl radicals. After irradiation of acetyl chloride in cyclohexane free chlorine was present in the reaction mixture. Ethers are substituted with particular ease.

With a large (five- to ten-fold) excess of substrate the yields are 10–20 %. Recovery of the starting material increases the yield to 30–50 %.

Example: Acetylchloride (30 g) in 170 ml ether was irradiated for 24 hours with a low-pressure mercury lamp (10 watts at 254 mμ). Distillation produced 9 g of 3-ethoxybutan-2-one (b.p. 62–64 °C/80 mm, n_D^{20} = 1.3970; dinitrophenylhydrazone: m.p. 86–87 °C).

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[1] 3rd Communication on Photochemical Reactions of Carboxylic Acid Derivates. – 2nd Communication: *U. Schmidt*, Angew. Chem. 77, 169 (1965); Angew. Chem. internat. Edit. 4, 146 (1965).

Synthesis of 3-Phenyl-, 3,4-Diphenyl-, and 3-(β-Naphthyl)-1,2,5-thiadiazole

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None of the methods known for preparing 1,2,5-thiadiazoles [1] is suitable for obtaining their aryl derivatives.

We have found that 3-phenyl-1,2,5-thiadiazole *(1)*, m.p. 43 to 44 °C is formed on refluxing S_4N_4 with ethylbenzene for 6 h in a molar ratio of 1:5. The product is purified by distillation at 90 °C/0.9 mm and recrystallization from petroleum ether. The yield is 12.6% based on the S_4N_4 consumed. 3,4-Diphenyl-1,2,5-thiadiazole *(2)*, m.p. 85–86 °C, is obtained analogously in 6.5% yield from dibenzyl and S_4N_4. Similarly, 3-(β-naphthyl)-1,2,5-thiadiazole *(3)*, m.p. 84–85 °C, is formed in 9% yield from β-ethylnaphthalene and S_4N_4. The product *(3)* is isolated by chromatography on a column of Al_2O_3 (40 cm long and 1.15 cm diameter for a charge prepared from 6 g of S_4N_4) with petroleum ether (b.p. 45–60 °C) as eluent; *(3)* occurs in the 14–47th of 25 ml fractions taken from the column and is purified by recrystallization from petroleum ether. Compound *(2)* is purified analogously.

Ultraviolet spectra of the products in iso-octane show the following maxima:

(1): λ_{max} = 228 mμ (ε = 9800); 280 (13500) [2]

(2): λ_{max} = 214 mμ (ε = 23800); 250 (10600); 295 (13100)

(3): λ_{max} = 212 mμ (ε = 24300); 236 (38300); 257 (13000); 269 (16100); 278 (19300); 293 (19000); 304 (21100); 324 (5160); 340 (2070).

Oxidation of *(1)* with hot alkaline permanganate affords over 80% benzoic acid. Reduction of *(1)* with sodium in alcohol yields α,β-diaminoethylbenzene. The NMR spectrum of *(1)* has signals at 7.25–7.45 and 7.80–8.00 ppm (phenyl protons) and at 8.77 ppm (proton on C-4) relative to tetramethylsilane as internal standard. Reduction of *(2)* with sodium in ethanol gives rise to *meso*-α,α'-diphenylethylenediamine, m. p. 120 to 121 °C.

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[1] *F. H. Marquardt*, Univ. Microfilms, Ann Arbor, Mich. (U.S.A.), No. Mic. 60-6303; *D. C. Sen*, J. Indian chem. Soc. 15, 537 (1938); *R. D. West*, U.S.-Patent 3115497 (1963); Österreichische Stickstoffwerke, Austrian Patent 230885 (1963); *J. M. Ross* and *W. C. Smith*, J. Amer. chem. Soc. 86, 2861 (1964).

[2] Maximum with fine structure.

Synthesis of o-Dihalogenobenzenes from Benzenediazonium-2-carboxylate

By Dr. L. Friedman and F. M. Logullo

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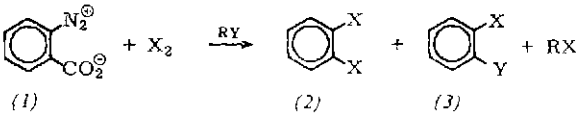
Benzenediazonium-2-carboxylate *(1)* [1,2] and an equimolar quantity of halogen in a solvent (see Table) were refluxed with stirring until gas evolution ceased. Most of the reactions were complete in less than 30 minutes. *o*-Dihalgenobenzenes were identified by gas chromatography and infrared spectroscopy. Yields were determined by quantitative gas chromatography.



(1) *(2)* *(3)*

RY = solvent

X_2	RY	Yield [%]		
		(2), X=Br	*(2)*, X=I	*(3)*, X=I, Y=Cl
Br_2	CCl_4	29		
Br_2	$CHCl_3$	26		
Br_2	CH_2Cl_2	55		
Br_2	$Cl(CH_2)_2Cl$	59 [a]		
ICl	$CHCl_3$			15
ICl	$Cl(CH_2)_2Cl$			32
I_2	CCl_4		28	0.1
I_2	$CHCl_3$		67	2
I_2	CH_2Cl_2		41	8
I_2	$Cl(CH_2)_2Cl$		50	22

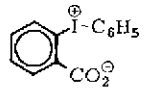
[a] *o*-C_6H_4BrCl (6 %) was also formed.

In addition to *o*-dihalogenobenzenes acidic products were obtained. Formation of monohalogenobenzenes was not observed.

Compound *(1)* and iodine in 1,2-dimethoxyethane gave *o*-iodoanisole (2 %), *o*-diiodobenzene (36 %), 1-(*o*-iodophenyl)-2-methoxyethane (40 %), and methyl iodide.

Reaction of 4-iodo-, 4-chloro-, and 4-nitrobenzenediazonium-2-carboxylate [2] with iodine in chloroform gave 1,2,4-triiodobenzene (69 %), 3,4-diiodochlorobenzene (76 %), and 3,4-diiodonitrobenzene (27 %).

Diphenyliodonium-2-carboxylate *(4)* [3] and iodine in *o*-dichlorobenzene reacted to give *o*-diiodobenzene (60 %).



(4)

Aprotic diazotization [4] of anthranilic acid and its 5- and 3-methyl derivatives in the presence of iodine gave *o*-diiodobenzene (53 %), 3,4-diiodotoluene (30 %), and 2,3-diiodotoluene (55 %), respectively.

The intermediacy of dehydrobenzene in these reactions is indicated by the fact that 4- and 5-chlorobenzenediazonium-2-carboxylate [2] with iodine monochloride forms the same mixture (37:63) of 2,4- and 2,5-dichloroiodobenzene (76 and 40 % yields, respectively).

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German version: Angew. Chem. 77, 217 (1965)

[1] *M. Stiles, R. G. Miller*, and *U. Burckhardt*, J. Amer. chem. Soc. *85*, 1792 (1963).

[2] *L. Friedman, D. F. Lindow*, and *F. M. Logullo*, unpublished work.

[3] *E. LeGoff*, J. Amer. chem. Soc. *84*, 3786 (1962). The compound contains one equivalent of water (*L. F. Fieser*, personal comunication).

[4] *L. Friedman* and *F. M. Logullo*, J. Amer. chem. Soc. *85*, 1549 (1963).

Oxidative Phosphorylation Following Addition of Inorganic Phosphate onto Compounds with a C=N$^{\oplus}$ Double Bond

By Professor Dr. V. M. Clark [*],
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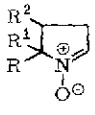
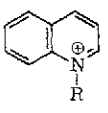
University Chemical Laboratory, Cambridge (England)

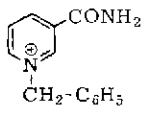
Compounds of the type *(1)–(3)* containing an sp^2 hybridized carbon atom bonded to a planar nitrogen atom bearing a formal positive charge react with tris(tetra-n-butylammonium) or tris(trimethylsulfoxonium) orthophosphate at room temperature in anhydrous solvents to form adducts, which can be detected by ultraviolet spectroscopy (see Table).



(1)



(2)



(3)

Starting material	λmax [mμ]	Solvent	λmax of adduct [mμ] after 24 h
(1a), R=R^2=H, R^1=C$_2$H$_5$ [1]	245	Dioxane	[a]
(1b), R=R^1=CH$_3$, R^2=H [1]	244	Dioxane	[a]
(1c), R=R^1=R^2=CH$_3$ [1]	247	Dioxane	[a]
(2a), R=O$^{\ominus}$ [2]	248, 347	Dioxane	[a]
(2b), R=CH$_3$	317	Acetonitrile	331, 538, 584
(3)	263	Ethanol	290–300

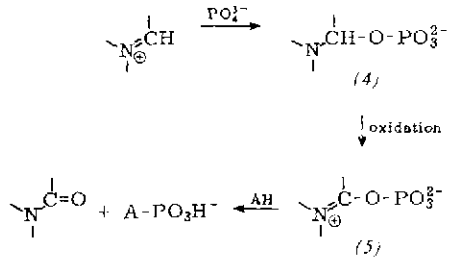
[a] The solution absorbs at the same wavelength as the initial solution but with less than 10 % of the original intensity.

Some of the changes in absorption are complete within one hour. Adducts with similar spectroscopic characteristics are formed from *(1)–(3)* with other inorganic anions [1, 3].

The phosphate adducts have not yet been isolated. It appears that adduct formation with the Δ^1-pyrroline *N*-oxides *(1)* is reversible, since dilution of the solutions with anhydrous solvent or with water restores the original ultraviolet absorption.

If a twofold excess of orthophosphate is used during adduct formation and if the solution is subsequently oxidized, *e.g.* with bromine or permanganate at room temperature, pyrophosphate can be detected in 25 % yield (estimated by the method of [4]). If only one equivalent of orthophosphate is used for adduct formation, other substrates can be phosphorylated by oxidation of the adducts. For example, bis-(tetra-n-butylammonium)phenyl phosphate is phosphorylated by the orthophosphate adduct of *(1b)* with $KMnO_4$ as oxidizing agent to give a 25 % yield of phenyl pyrophosphate. Similarly, addition of bromine to a solution of the orthophosphate adduct of *(3)* in ethanol afforded a 10 % yield of ethyl phosphate.

These phosphorylation reactions can be formulated as follows (cf. [5]):



(4) *(5)*

Imidoyl phosphates analogous to *(5)* are known as phosphorylating agents [6]. A nicotine-adenine-dinucleotide derivative corresponding to *(4)* has been isolated from mitochondria [7].

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[1] *R. Bonnett, R. F. C. Brown, V. M. Clark, I. O. Sutherland*, and *A. R. Todd*, J. chem. Soc. (London) *1959*, 2094.

[2] *M. Colonna* and *A. Risaliti*, Gazz. chim. ital. *83*, 58 (1953).

[3] *K. Wallenfels* and *H. Schüly*, Liebigs Ann. Chem. *621*, 106 (1959).

[4] *D. A. Usher*, J. Chromatogr. *12*, 252 (1963).

[5] *J. A. Barltrop, P. W. Grubb*, and *B. Hesp*, Nature (London) *199*, 759 (1963).

[6] *V. M. Clark, D. W. Hutchinson, A. J. Kirby*, and *S. G. Warren*, Angew. Chem. *76*, 704 (1964); Angew. Chem. internat. Edit. *3*, 678 (1964), and references [55] – [67] in both publications.

[7] *D. E. Griffiths*, Federat. Proc. *22*, 1064 (1963).

^{17}O-Hyperfine Structure in the ESR Spectrum of [^{17}O]-2,4,6-Triphenylphenoxyl

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In connection with investigations of deuterated and ^{13}C-labelled 2,4,6-triphenylphenoxyls [1] aimed at determining the distribution of the unpaired electron throughout the molecule, we have prepared [^{17}O]-2,4,6-triphenylphenoxyl as the first ^{17}O-labelled free radical with a C–O bond [2].

2,4,6-Triphenylbenzenediazonium fluoroborate was treated with $H_2{}^{17}O$ containing about 13 atom-% ^{17}O [3] in a little methanol (to enhance solubility). The [^{17}O]-2,4,6-triphenylphenol obtained was then dehydrogenated to the phenoxyl radical. The ratio of the intensities of the ^{17}O-HFS lines in the

ESR spectrum of the labelled radical to that of the main signal obtained from the unlabelled compound indicates a degree of enrichment of 13 atom-% ^{17}O in the labelled phenoxyl. Thus, no isotope dilution has occurred during its synthesis.

In the ESR spectrum, four of the six HFS lines expected [I(^{17}O) = 5/2] are readily differentiated; the remaining two are masked by the main signal from the unlabelled radical. The ^{17}O-splitting constant is a(^{17}O) = 9.7 gauss, a value which indicates a considerable spin density ρ on the oxygen atom. A simple HMO calculation gave $\rho_O = 0.174$ [4].

In order to be able to calculate the spin density on the oxygen from the splitting constant, more data on ^{17}O-labelled C–O radicals are required, particularly because the influence of the spin density at the neighboring atom [5] upon the coupling constant of the oxygen cannot be estimated at present.

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German version: Angew. Chem. 77, 217 (1965)

[1] *K. Dimroth, F. Kalk, R. Sell,* and *K. Schlömer,* Liebigs Ann. Chem. *624,* 51 (1959); *K. Dimroth, A. Berndt,* and *F. Bär,* unpublished work.

[2] The ^{17}O-hyperfine structure in the ESR spectrum of an organic free radical has so far been measured only for di-s-butylnitroxyl: *J. C. Baird,* J. chem. Physics *37,* 1879 (1962).

[3] We are indebted to Professor *D. Samuel,* Rehovoth (Israel), for his generous gift of the $H_2{}^{17}O$.

[4] *A. Schweig,* Marburg/Lahn, unpublished work.

[5] *M. Karplus* and *G. K. Fraenkel,* J. chem. Physics *35,* 1312 (1961); *P. H. Rieger* and *G. K. Fraenkel,* ibid. *37,* 2795 (1962); *R. L. Ward,* J. Amer. chem. Soc. *84,* 332 (1962); *A. Carrington* and *J. dos Santos Veiga,* Molecular Physics *5,* 21 (1962); *P. H. Rieger* and *G. K. Fraenkel,* J. chem. Physics *40,* 609 (1963); *C. A. McDowell* and *K. F. G. Paulus,* Molecular Physics *7,* 541 (1963/64).

Preparation of 1-Bromo-2-chloroethane and 1-Chloro-2-iodoethane

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Tris-(β-chloroethyl) phosphite, which is readily prepared from ethylene oxide and PCl_3 [1], undergoes a smooth Arbusow reaction with benzyl bromide to give 1-bromo-2-chloroethane. An equimolar mixture of benzyl bromide and tris-(β-chloroethyl) phosphite is warmed slowly with stirring to 120 °C, when an exothermal reaction commences. The reaction mixture is then heated for 3 h at 140 °C. The product is distilled off at 150 mm and separated by fractional distillation from traces of 1,2-dichloroethane; 83–85% yields of 1-bromo-2-chloroethane, b.p. 106 °C, are obtained.

With methyl iodide instead of benzyl bromide, the exothermal reaction begins at 70 °C, and after heating the mixture for 1 h at 80–90 °C, an 85% yield of 1-chloro-2-iodoethane, b.p. 140 °C, is obtained.

These procedures are less laborious and give better yields than those used to date [2]. No reaction takes place with potassium fluoride instead of benzyl bromide.

Received: January 11th, 1965 [Z 892/718 IE]
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[1] *Houben-Weyl*: Methoden der Organischen Chemie. Thieme-Verlag, Stuttgart 1964, Vol. XII/2, p. 69; German Patent Application D 45706 IVb/120, Deutsche Advance Produktion GmbH.

[2] *Houben-Weyl*: Methoden der Organischen Chemie. Thieme-Verlag, Stuttgart 1960, Vol. V/4, p. 150; *E. L. Gefter* and *M. J. Kabachnik,* Izvest. Acad. Nauk U.S.S.R., Otdel. khim. Nauk *1957,* 194; Chem. Abstr. *51,* 11238d (1957).

N-Substituted 4H-1,3-Oxazinium Salts

By Dr. Richard R. Schmidt

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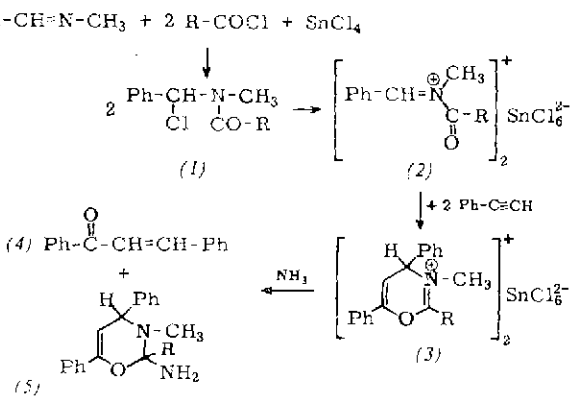
The surprising ease with which bis-(2,6-diphenyl-4*H*-1,3-oxazinium) hexachlorostannate is formed from *N*-chloromethylbenzamide, phenylacetylene, and stannic chloride [1] encouraged us to synthesize the corresponding *N*-substituted compounds *(3)* from *N*-methylbenzylideneimine, acyl halides, phenylacetylene, and stannic chloride.

The components were dissolved in anhydrous chloroform or ethylene dichloride and were mixed at room temperature in the above order. The mixture was boiled for 2 hours. On cooling, the *N*-methyl-4*H*-1,3-oxazinium salts *(3)* crystallized out and were filtered off. The structures of the products were proved by their reaction with ammonia: treatment of *(3d)* with concentrated ammonia produces *(4)* and *(5)*, whereas with dilute ammonia, only *(5)* is formed.

The formation of pyrylium salts from acyl halides, phenylacetylene, and stannic chloride [2] or of *N*-substituted phthalimidines from *N*-methylbenzylideneimine and acyl halides [3] was not observed. The reaction proceedes *via* the *N*-acyl-*N*-(α-halogenoalkyl)methylamines *(1)* [4] and the *N*-methyl-*N*-acyl-*N*-benzylideneiminium salts *(2)* formed from *(1)* and stannic chloride. 1,4-Addition of phenylacetylene onto *(2)* then affords *(3)*.



	R	M.p. (decomp.) [°C]	Yield [%]
(3a)	Phenyl	210–215	39
(3b)	*p*-Tolyl	205–215	41
(3c)	*p*-Chlorophenyl	218	37
(3d)	Methyl	225–235	92

Received: January 13th, 1965 [Z 893/719 IE]
German version: Angew. Chem. 77, 218 (1965)

[1] *R. R. Schmidt,* Chem. Ber., in the press.

[2] *R. R. Schmidt,* Angew. Chem. *76,* 437 (1964); Angew. Chem. internat. Edit. *3,* 387 (1964).

[3] *T. Cohen* and *J. Lipowitz,* J. Amer. chem. Soc. *86,* 2514 (1964).

[4] *H. Böhme* and *K. Harte,* Chem. Ber. *96,* 600 (1963).

Synthesis and Properties of Red Tantalum Nitride Ta_3N_5

By Prof. Dr. G. Brauer and Dr. J. R. Weidlein

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We have produced Ta_3N_5 [1] from pure tanatalum pentoxide and extremely pure ammonia (2–4 l/h) at 860–920 °C. The reaction of 1–2 g of oxide is complete only after 36–120 h and

only if titanium turnings are present to act as getter for the oxygen. The titanium metal probably also catalyses the decomposition of ammonia in the immediate vicinity of the reacting oxide. As the oxygen in the pentoxide is replaced by nitrogen, the color changes *via* dark green, bright green, yellow-brown, and red-brown to the red color of the oxygen-free nitride Ta_3N_5.

Ta_3N_5 is stable up to about 950 °C under NH_3 at normal pressure. On heating *in vacuo*, it starts to lose nitrogen at about 500 °C and decomposes into black tantalum nitride TaN [2].

Ta_3N_5 has a tetragonal crystal lattice with the lattice constants a = 10.265 Å and c = 3,898 Å; its density measured pyknometrically is 9.85 g/cm³; the unit cell contains four Ta_3N_5 formula units.

Received: January 14th, 1965 [Z 895/721 IE]
German version: Angew. Chem. *77*, 218 (1965)

[1] *H. Funk* and *H. Böhland*, Z. anorg. allg. Chem. *334*, 155 (1964), also described a synthesis of Ta_3N_5.

[2] *G. Brauer* and *K. H. Zapp*, Z. anorg. allg. Chem. *277*, 129 (1954); *N. Schönberg*, Acta chem. scand. *8*, 199 (1954).

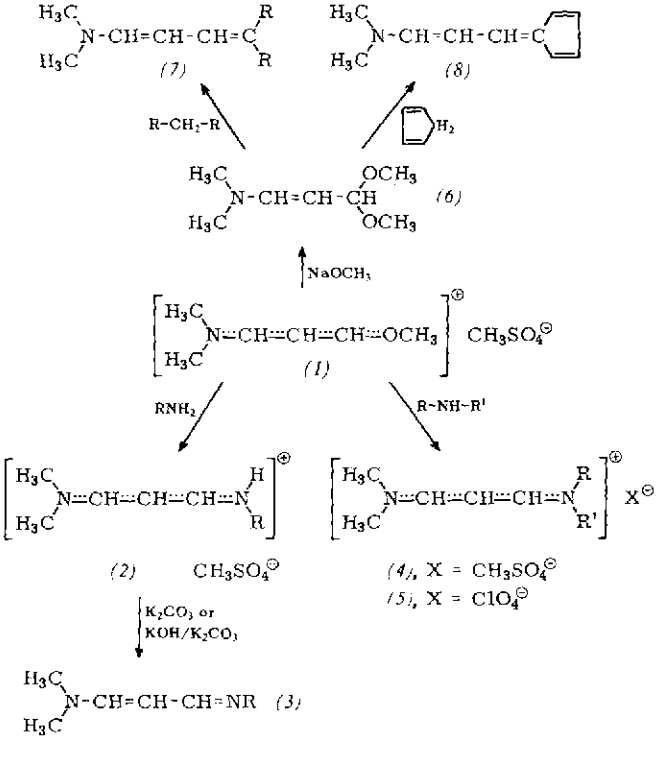
Synthesis and Reactions of Vinylogous Amide Acetals and Vinylogous Amidines

By Prof. Dr. H. Bredereck, Dr. F. Effenberger, and Dipl.-Chem. D. Zeyfang

Institut für Organische Chemie der Technischen Hochschule Stuttgart (Germany)

Dimethyl sulfate reacts smoothly, sometimes exothermally, with β-(*N*,*N*-dimethylamino)acrolein to give the adduct *(1)* [1–3], which smoothly reacts with nucleophilic reagents, even at room temperature.

With primary amines, the salts *(2)* [R = CH_3: m.p. 78–80 °C, 46% yield; R = C_6H_5: m.p. 138–140 °C, 53% yield; R = α-pyridyl: oil, n_D^{20} = 1.6330] are formed. Treatment of *(2)* with a solution of potassium carbonate or of potassium hydroxide/potassium carbonate liberates the vinylogous amidines *(3)* [R = CH_3: b.p. 90–96 °C/13 mm, picrate: m.p. 140–142 °C; 29% yield; R = C_6H_5: m.p. 62–65 °C, 43% yield; R = α-pyridyl: m.p. 113–115 °C, 48% yield].



The reaction of *(1)* with secondary amines leads to the methyl sulfates *(4)*, which do not crystallize well. However, treatment of *(4)* with a concentrated solution of sodium perchlorate [3,4] produces analytically pure perchlorates *(5)* [R = R' = CH_3: m.p. 119 °C, 68% yield; R = C_6H_5, R' = CH_3: m.p. 143–146 °C, 62% yield].

The reaction of *(1)* with sodium methoxide gives rise to β-(*N*,*N*-dimethylamino)acrolein dimethylacetal *(6)* [b.p. 78 °C/15 mm, n_D^{20} = 1.4521, 62% yield], which condenses readily with compounds containing an activated methylene group (*e.g.* malonodinitrile or diethyl malonate) to give butadiene derivatives *(7)* [R = CN: m.p. 130–134 °C, 53% yield; R = $COOC_2H_5$: m.p. 100–102 °C, 38% yield] or with cyclopentadiene to give 60% (β-dimethylaminovinyl)fulvene *(8)*, m.p. 70–72 °C [5].

Received: January 14th, 1965 [Z 894/720 IE]
German version: Angew. Chem. *77*, 219 (1965)

[1] German Patent Application B 65348 IVb/12o (December 27th, 1961), inventors: *H. Bredereck*, *F. Effenberger*, and *G. Simchen*.

[2] *H. Bredereck*, *F. Effenberger*, and *G. Simchen*, Chem. Ber. *96*, 1350 (1963).

[3] *G. Simchen*, Ph. D. Thesis, Technische Hochschule Stuttgart, 1962.

[4] *Z. Arnold* and *A. Holy*, Coll. czechoslov. chem. Commun. *28*, 2040 (1963).

[5] *Z. Arnold* and *J. Zemlička*, Coll. czechoslov. chem. Commun. *25*, 1302 (1960).

5,6-Dimethylbenzo[a]calicene

By Doz. Dr. H. Prinzbach, Dipl.-Chem. D. Seip, and Dipl.-Chem. Ulf Fischer

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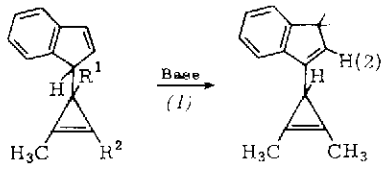
In the series of hydrocarbons with a cyclic, cross-conjugated π-bond system, so far cyclopropenylidenecyclopentadiene (calicene) could not be synthesized. We have prepared a monobenzo derivative *(5)* of this system by the following route [1].

Treatment of 30 mmoles of indenylmagnesium bromide with 20 mmoles of dimethylcyclopropenylium fluoroborate in tetrahydrofuran at 20 °C leads to a 5:1 mixture of *(1)* and *(2)*, b.p. 68–70 °C/0.01 mm, in 35% yield. The structure of *(1)* was proved *inter alia* by its infrared spectrum (C=C absorption at 1850 cm^{-1}) and NMR spectrum [2.81 τ (4 H, M); 3.33; 3.63 (AB quartet, J = 5.5 cps); 6.84 (1 H, M); 8.61 (1 H, D, J = 5.5 cps); and 8.02 (6 H, S)], by its isomerization to *(3)* [NMR: 2.80 τ (4 H, M); 4.10 (1 H, D, J = 2.1 cps); 6.83 (2 H, D, J = 2.1 cps); 7.58 (1 H, S); and 7.93 (6 H, S)], and by the formation of its crystalline derivatives *(6)*.

The dehydrogenation of *(1)* to *(4)* is effected with triphenylmethyl fluoroborate in chloroform at 0 °C for 30 min in 50 to 55% yield. Compound *(4)* forms colorless crystals, m.p. 98 to 99 °C, with λ_{max} in 70% $HClO_4$ at 309 mμ (ε = 2450) and 230 (17800). Its NMR in CF_3COOD has signals at 1.68 τ (T, J = 1.8 cps); 2.10–2.70 (M); 6.02 (broad singlet); and 6.86 (S) in area ratios of 1:4:2:6. In accordance with the coupling expected of *(4)*, the H(2) triplet converges to a sharp singlet, and the half-width of the methylene signal is reduced by half [2], when *(4)* is irradiated with the methylene or H(2) resonance frequency, respectively.

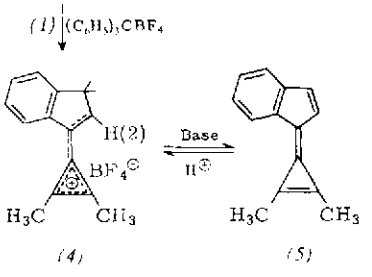
Compound *(4)* is a very weak acid; no isotopic exchange of the methylene protons can be detected when *(4)* is left for several days in CF_3COOD. Accordingly, *(4)* is stable for a few hours in 2% $HClO_4$. Treatment of *(4)* with a five- to ten-fold excess of trimethylamine or pyridine at 10 °C converts it in 95% yield into 5,6-dimethylbenzo[*a*]calicene *(5)*, which exists only in dilute solution but which can be characterized by reconverting it into *(4)* by protonation. Hydrocarbon *(5)*

has λ_{max} in ether at 336 mμ (ε approx. 4400) and 267 (ε approx. 8300), in chloroform at 343 (ε approx. 5000), and in n-hexane at 335 mμ (ε approx. 4100). In accordance with the



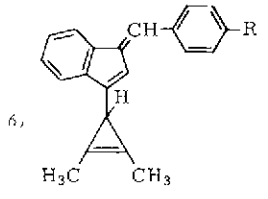
(3)

(1), R^1 = H, R^2 = CH_3
(2), R^1 = CH_3, R^2 = H



(4) (5)

weak acidity of *(4)*, compound *(5)* is a strong base: it is extracted in the form of *(4)* from its solution in chloroform by only 15% $HClO_4$.



(6)

The 6-phenyl-4-cyclopropenylbenzo[*b*]fulvenes *(6)* obtained from *(2)* by condensation with 4-substituted benzaldehydes (R = Cl, CH_3O) are not isomerized to the corresponding benzocalicene derivatives [1] under conditions which allowed the prototropic conversion of the analogous cycloheptatrienylbenzofulvenes into the benzosesquifulvalenes [3]. Since no hydrogen-deuterium exchange was observed in the three-membered ring of *(6)* in CH_3OD/CH_3ONa, it need not be thermodynamic reasons that are responsible for the lack of reaction.

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German version: Angew. Chem. 77, 258 (1965)

[1] *D. Seip*, Ph. D. Thesis, Universität Freiburg/Brsg., 1965.
[2] *A. Melera* and *U. Scheidegger*, Varian Laboratory, Zurich (Switzerland).
[3] *H. Prinzbach* and *D. Seip*, Angew. Chem. 73, 169 (1961).

Synthesis of 1-Dicyanomethylenephenalene and 1-(Ethoxycarbonylcyanomethylene)phenalene

By Doz. Dr. H. Prinzbach and Dipl.-Chem. V. Freudenberger

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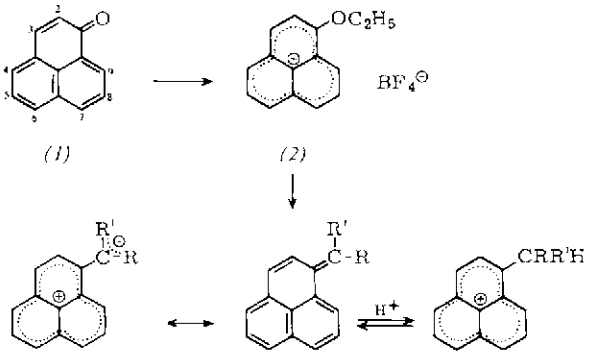
For methylenephenalene *(3)*, R = R' = H ("phenafulvene"), as for its vinylogues heptafulvene and triafulvene, a dipolar resonance structure *(4)* is included in the quantum-mechanical description of the ground state. We have prepared the first stable derivatives of *(3)* by two routes.

1. Phenalen-1-one *(1)* [1] is alkylated in CH_2Cl_2 at 40 °C with an equimolar amount of triethyloxonium fluoroborate, giving 80–90% of the ethyloxonium fluoroborate *(2)*, m.p. 170 to 171 °C (decomp.), λ_{max} in acetonitrile = 408 mμ (ε = 14400), NMR spectrum in nitromethane: 8.18 τ [T, CH_3]; 5.0 [Q, CH_2]; 2.30 [H(2), D, J_{2-3} = 9.3 cps]; 2.1–1.0 [H(3)-H(8), M]; and 0.96 [H(9), Q, J_{9-8} = 7.5 cps]; its ultraviolet and NMR spectra correspond largely to those of protonated *(1)* in CF_3COOH.

The salt *(2)* reacts with either sodiomalonodinitrile or sodiocyanoacetic ester in tetrahydrofuran at 20 °C to form *(3a)* or *(3b)* by elimination of ethanol.



(1) (2)

(4) (3a), R = R' = CN (5)
(3b), R(R') = CN, R'(R) = $CO_2C_2H_5$

1-Dicyanomethylenephenalene *(3a)* forms violet-red needles, m.p. 236 °C; its infrared spectrum has C = C absorptions at 1577 and 1626 cm^{-1} and $\nu_{C\equiv N}$ at 2208 cm^{-1}; its NMR spectrum in [$^2H_6$]-dimethyl sulfoxide has signals at 2.64 τ [H(2), D, J_{2-3} = 9.0 cps]; 2.3–1.5 [H(3)-H(8), M]; and 0.78 [H(9), Q, J_{9-8} = 7.5 cps]; it has λ_{max} in iso-octane at 451 mμ, in acetonitrile at 472 (ε = 18800), and in ethanol at 476 (19000). The NMR and ultraviolet spectra reveal that, like 8,8-dicyanoheptafulvene [2] and the 4,4-dicyanotriafulvenes [3], *(3a)* is not detectably protonated in CF_3COOH.

1-(Ethoxycarbonylcyanomethylene)phenalene *(3b)* is an approximately 1:1 mixture of the *cis*- and *trans*-isomers and forms dark red needles, m.p. 135–137 °C; the infrared spectrum has C=C absorptions at 1570 and 1626 cm^{-1}, $\nu_{C=O}$ at 1695 cm^{-1}, and $\nu_{C\equiv N}$ at 2193 cm^{-1}; NMR signals are observed in $CDCl_3$ at 8.59/8.53 τ [T, CH_3]; 5.89/5.65 [Q, CH_2]; 2.9–1.9 [H(2)-H(8), M]; and 0.76 [H(9), D, J_{9-8} = 7.5 cps]; λ_{max} in iso-octane is at 463 mμ, in acetonitrile at 482 (ε = 11900), and in ethanol at 492 (11400). Compound *(3b)* is a stronger base than *(3a)*, and in CF_3COOH the equilibrium *(3)* ⇌ *(5)* lies largely on the side of the conjugate acid *(5)*, judging from ultraviolet spectra.

2. Low yields of *(3a)* and *(3b)* are also obtained by direct condensation of *(1)* in acetic anhydride at 100 °C, with malonodinitrile and ethyl cyanoacetate, respectively.

The distribution of the π-electrons in *(3a)* and *(3b)* estimated from the NMR data imply polarization of the molecules as indicated in *(4)*.

Received: January 14th and February 1st, 1965 [Z 909/733 IE]
German version: Angew. Chem. 77 (1965), in the press.

[1] *G. Lock* and *G. Gergely*, Ber. dtsch. chem. Ges. 77, 461 (1944).
[2] *K. Hafner, H. W. Riedel*, and *H. Danielisz*, Angew. Chem. 75, 344 (1963); Angew. Chem. internat. Edit. 2, 215 (1963); *H. Prinzbach*, Habilitation Thesis, Universität Freiburg/Brsg., 1962.
[3] *E. D. Bergmann* and *I. Agranat*, J. Amer. chem. Soc. 86, 3587 (1964); *A. S. Kende* and *P. T. Izzo*, ibid. 86, 3587 (1964).

ESR-Spectroscopic Detection of a [^{33}S]-Sulfur Radical

By Dr. W. Rundel and Dr. K. Scheffler

Chemisches Institut der Universität Tübingen (Germany)

Free radicals can be detected by electron spin resonance spectroscopy in solutions of 2,4,6-tri-t-butylthiophenol *(1)* after irradiation with ultraviolet light; the radicals are stable

for some time at room temperature ($t^1/_2$ *ca.* 30 min). The g factor of 2.0104 and the absence of any hyperfine structure in the ESR spectrum indicate that the unpaired electron is located largely on the sulfur atom [1]. Participation of the sulfur in the free radical state should be recognizable from the hyperfine structure in the ESR-spectrum of the radical labelled with ^{33}S [2].

Using a sample of *(1)* containing 11.5 % ^{33}S, we found in addition to the main ESR signal (g = 2.0103 ± 0.0001) a symmetrically distributed weaker quartet due to the interaction of the unpaired electron with the nuclear magnetic ^{33}S isotope. The intensity ratio of the signals was 100:12, corresponding to the ratio $^{33}S/^{32}+^{34}S$ (value calculated from the isotope ratio:100:13). The quartet had a splitting constant a(^{33}S) of 14.75 gauss at a line width of 2.8 gauss. This proves that *(1)* is a genuine sulfur radical, most probably the tri-t-butylphenyl sulfide radical [3].

To measure the ESR spectrum exactly, a solution in benzene of labelled *(1)* and dibenzoyl peroxide was heated to 80 °C. Under these conditions, a relatively large stationary concentration of the radicals is available for a long time [4].

Received: January 15th, 1965 [Z 896/722 IE]
German version: Angew. Chem. 77, 220 (1965)

[1] *W. Rundel* and *K. Scheffler*, Z. Naturforsch. *18b*, 984 (1963).

[2] Funds for purchasing the sulfur isotope were provided by the Deutsche Forschungsgemeinschaft.

[3] Further experiments with a ^{13}C-labelled benzene ring are in progress to prove that the radicals are not formed from liberated sulfur.

[4] Subsequent processing of the mixture yielded some unchanged *(1)* plus bis(tri-t-butylphenyl) disulfide and benzoic acid.

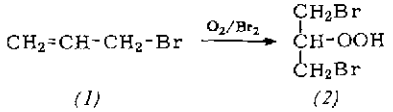
Synthesis of Halogenoalkyl Hydroperoxides by "Bromine-Induced Autoxidation" of Allyl Halides

By Prof. Dr. A. Rieche, Dr. Manfred Schulz, and Dipl.-Chem. K. Kirschke

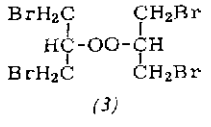
Institut für Organische Chemie der Deutschen Akademie der Wissenschaften zu Berlin, Berlin-Adlershof (Germany)

According to *Bockemüller* and *Pfeuffer* [1], the simultaneous action of oxygen and bromine on a solution in benzene of allyl bromide *(1)* at room temperature in diffuse daylight produces the tetrabromodialkyl peroxide *(3)*.

However, we have found that the reaction does not really lead to *(3)*, but to 1,3-dibromo-2-propyl hydroperoxide *(2)*, b.p. 66 °C/0.1 mm, n_D^{25} = 1.5493 [2]. Apart from *(2)*, no other peroxide could be detected either by paper- or thin-layer chromatography.

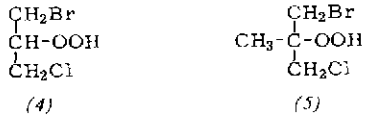


(1) *(2)*



(3)

Conversion of *(2)* into *(3)* could not be accomplished. Both the reaction of *(2)* with acids and thermolysis of *(2)* yielded 1,3-dibromoacetone. Reduction of *(2)* with KI/acetic acid or $LiAlH_4$ afforded 1,3-dibromopropan-2-ol.



(4) *(5)*

Oxidation of allyl chloride under analogous conditions led to 1-bromo-3-chloro-2-propyl hydroperoxide *(4)*, b.p. 61 °C/0.1 mm.

Similarly, methallyl chloride gave rise to α-bromomethyl-α-chloromethylethyl hydroperoxide *(5)*, b.p. 56 °C/0.25 mm.

Received: January 18th, 1965 [Z 897/723 IE]
German version: Angew. Chem. 77, 219 (1965)

[1] *W. Bockemüller* and *L. Pfeuffer*, Liebigs Ann. Chem. *537*, 178 (1939).

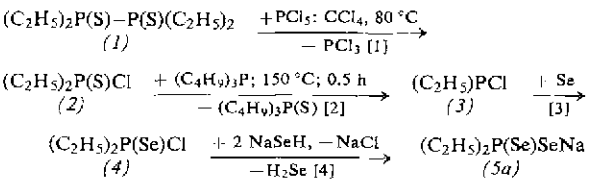
[2] Use of moist oxygen promotes the reaction leading to *(2)*. 1,2,3-Tribromopropane is formed in addition to *(2)*.

Synthesis of Diethyldiselenophosphinic Acid and Its Salts and Esters

By Prof. Dr. W. Kuchen and Dipl.-Chem. B. Knop

Institut für Anorganische und Elektrochemie der Technischen Hochschule Aachen (Germany)

Sodium diethyldiselenophosphinate *(5a)* has been prepared in 80 % yield [based on *(4)*] by the following route.



In order to obtain *(5a)* from *(4)*, a stoichiometric amount of hydrogen selenide was passed into a solution of sodium ethoxide in alcohol, which was then cooled in ice, *(4)* being added dropwise afterwards.

Dissolution of *(5a)* in acetone/H_2O (95:5 v/v) and reprecipitation with ligroin yielded the hydrate $(C_2H_5)_2P(Se)SeNa \cdot 2H_2O$ *(5b)* in the form of stable colorless needles, m.p. 129–130 °C.

When *(5b)* was passed over a stronly acidic cation exchanger [Ionenaustauscher I from E. Merck, Darmstadt (Germany)], aqueous solutions of diethyldiselenophosphinic acid $(C_2H_5)_2P(Se)SeH$ *(5)* were obtained which could be kept for about 24 h at room temperature in the dark, but which decomposed rapidly in diffuse daylight with precipitation of elemental selenium.

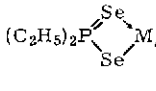
Treatment of *(5b)* with HCl gas in benzene at 0 °C also produced the free acid *(5)* in the form of a yellow oil; however, because of the lability of *(5)*, this preparation is not pure. It decomposes rapidly to bis(diethylselenophosphoryl) selenide *(6)*, colorless platelets, m.p. 65 °C, and orange-red bis(diethylselenophosphoryl) triselenide *(7)*, m.p. 135–137 °C [5]. Compound *(6)* was also made by heating *(4)* with *(5a)* in benzene.

$(C_2H_5)_2P(Se)-(Se)_n-P(Se)(C_2H_5)_2$

(6), n = 1; *(7)*, n = 3

When *(5b)* is refluxed with alkyl bromides, alkyl diethyldiselenophosphinates are produced, *e.g.* the ethyl ester, b.p. 105 °C/0.13 mm, n_D^{20} = 1.6193, and the n-propyl ester, b.p. 98 °C/0.1 mm, n_D^{20} = 1.6037.

Intramolecular coordination compounds of formula *(8)* are precipitated from aqueous solutions of various metal salts by addition of *(5b)*.



(8)

Complexes of this type include the zinc(II) salt, m.p. 151 °C, the cadmium(II) salt, m.p. 158 °C, the lemon-yellow lead(II) salt, m.p. 157–158 °C, the brown-red palladium(II) salt, m.p.

197 °C, the vermilion-red bismuth(III) salt, m.p. 132 °C, the bright yellow indium(III) salt, m.p. 146 °C, and the pale yellow thallium(I) salt, m.p. 129 °C.

Potentiometric determination [6] of the apparent dissociation constants in 80 % aqueous isopropanol at 20 °C gave the following sequence for the strengths of the various phosphinic acids:

$(C_2H_5)_2P(S)OH$ [pK 4.98] ≪ $(C_2H_5)_2P(S)SH$ [pK 2.60]

$(C_2H_5)_2P(S)SeH$ [pK 2.29] ≈ $(C_2H_5)_2P(Se)SeH$ [pK 2.18]

Received: January 19th, 1965 [Z 899/725 IE]
German version: Angew. Chem. 77, 259 (1965)

[1] By analogy to the preparation of $(C_3H_7)_2P(S)Cl$, cf. *W. Kuchen, H. Buchwald, K. Strolenberg*, and *J. Metten*, Liebigs Ann. Chem. *652*, 28 (1962).

[2] See *H. Ulmer, L. C. D. Groenweghe*, and *L. Maier*, J. inorg. nucl. Chem. *20*, 82 (1961).

[3] *A. Markowska* and *J. Michalski*, Roczniki Chem. *34*, 1675 (1960); Chem. Abstr. *56*, 7346 (1962).

[4] Reaction in analogy with the preparation of $(C_2H_5)_2P(S)SNa$ by *T. A. Mastryukova, A. E. Shipov*, and *M. J. Kabachnik*, Zhur. obshch. Khim. *31*, 507 (1961); Chem. Abstr. *55*, 22101 (1961).

[5] The molecular weight could not yet be determined because solutions of this substance decompose rapidly.

[6] *H. Hertel*, Diploma Thesis, Technische Hochschule Aachen, 1965.

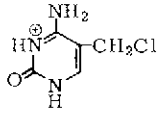
Synthesis and Properties of 5-Chloromethylcytosine

By Priv.-Doz. Dr. Dr. R. Brossmer and E. Röhm

Max-Planck-Institut für Medizinische Forschung, Institut für Chemie, Heidelberg (Germany)

Up to the present, reactive chloromethyl derivatives of naturally occurring pyrimidine bases were known only in the uracil series.

When 5-hydroxymethylcytosine or its hydrochloride is heated with thionyl chloride in tetrahydrothiophene 1,1-dioxide [1], the hydrochloride of 5-chloromethylcytosine *(1)* is obtained in 95 % yield as slightly grey crystals, m.p. above 300 °C.



$Cl^{\ominus}$ *(1)*

For reasons of analogy and on the basis of the infrared spectra, we assume that the basic nitrogen atom of the ring is protonated. On account of its high reactivity, the free base of *(1)* is rather difficult to isolate. Proof of structure *(1)* is supplied by the elemental analysis, by its chemical reactions, and by its infrared spectrum [the 7 strongest bands in order of decreasing intensity occur at 1665, 1725, 2855 (part of a group of bands at 3280–2740), 1215, 1235, 1600, and 760 cm^{-1}; the band at 1025 cm^{-1} typical of the alcohol is not observed].

Under mild conditions the allylic chlorine atom can be displaced with compounds containing a nucleophilic group. Ethers, thioethers, amines, or esters are formed in mostly good yields [2]. Ethers, for example, are produced by heating *(1)* in an alcohol or phenol or by treating *(1)* with alkali metal alkoxides or phenoxides. Many amines react with *(1)* even at room temperature in acetone. In this manner, many substances can be linked *via* the methylene bridge to the cytosine nucleus, wich can act as a low molecular-weight mobile carrier.

Received: January 20th, 1965; supplemented: February 1st, 1965
German version: Angew. Chem. 77, 260 (1965) [Z 911/735 IE]

[1] This solvent (Sulfonal from Shell) has proved to be extremely valuable for other reactions as well. Its properties (strongly polar, chemically inert, heat-stable, miscible with water and organic solvents) make it appear suitable for use in various fields of nucleic acid chemistry.

[2] Reported at the Fall Meeting of the Deutsche Gesellschaft für Physiologische Chemie in Köln (Germany), October 22nd to 24th, 1964.

Crystal Structure of Strontium Disilicide

By Dipl. Chem. K. Janzon, Dr. H. Schäfer, and Prof. Dr. Armin Weiss

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In calcium disilicide $CaSi_2$, the silicon atoms are linked together in a two-dimensionally infinite, corrugated net of hexagons [1]. In contrast, in barium disilicide $BaSi_2$ [2], sodium silicide NaSi [3], and potassium silicide KSi [4], isolated Si_4 tetrahedra occur.

In strontium disilicide $SrSi_2$, the silicon atoms form a three-dimensional framework. The shortest Si–Si distances are 2.41 Å and thus comparable with those in elemental silicon (2.34 Å). The Si–Si–Si angles are 113° 2′ each, *i.e.* very close to the angles in a regular tetrahedron. As the electronegativity of the Group II elements decreases, the shortest Si–Si distance falls off from 2.48 Å in $CaSi_2$ via 2.41 Å in $SrSi_2$ to 2.34–2.37 Å in $BaSi_2$. Despite the differences in the structural framework of the silicon in these three compounds, each silicon atom is linked directly to three neighboring silicons. Each strontium atom in $SrSi_2$ is surrounded by six silicon neighbors at distances of 3.21 Å and two further silicons at 3.43 Å.

Crystallographic data for $SrSi_2$:

Cubic pentagonal-icositetrahedral, space group O^6–$P4_232$, a = 6.540 ± 0.002 Å; d_m = 3.40 ± 0.05 g/cm³; d_x = 3.42 g/cm³.

The unit cell contains four Sr atoms, which occupy the 4a positions, and eight silicon atoms in the 8c positions of the space group with x = 0.428. The minimum for the discrepancy index R is very unsharp as a function of x_{Si}.

x_{Si}	0.420	0.422	0.424	0.426	0.428	0.430	0.434
R	0.14_3	0.12_8	0.11_4	0.10_9	0.10_8	0.11_4	0.16_5

Hence the parameter x cannot be given with very great accuracy. When x = 0.428, R for the series (hk0) becomes 0.10_8, for the series (hk1) 0.09_2, and for the series (hk2) 0.11_4. In work with the $Cu_{K\alpha}$ radiation, "Umweganregung" is observed.

Received: January 21st, 1965 [Z 900/742 IE]
German version: Angew. Chem. 77, 258 (1965)

[1] *I. Böhm* and *O. Hassel*, Z. anorg. allg. Chem. *160*, 152 (1927).

[2] *H. Schäfer, K. Janzon*, and *A. Weiss*, Angew. Chem. *75*, 451 (1963); Angew. Chem. internat. Edit. *2*, 393 (1963).

[3] *J. Witte* and *H. G. Schnering*, Z. anorg. allg. Chem. *327*, 260 (1964).

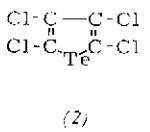
[4] *E. Busmann*, Naturwissenschaften *47*, 82 (1960); Z. anorg. allg. Chem. *313*, 90 (1961).

Preparation of Tetrachlorotellurophene and Tetrachloroselenophene

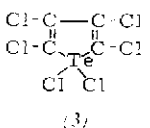
By Dr. W. Mack

Consortium für elektrochemische Industrie GmbH., München (Germany)

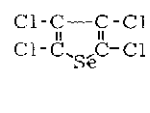
The ring system of tellurophene was so far known only from the synthesis of its tetraphenyl derivative [1]. We have now prepared tetrachlorotellurophene *(2)* by the reaction of hexachloro-1,3-butadiene *(1)* with tellurium.



(2)



(3)



(5)

Finely pulverized tellurium (0.3 mole) is shaken for 40 h at 250 °C with 0.1 mole of *(1)*. The tellurium tetrachloride formed

is removed with concentrated hydrochloric acid. Distillation of the organic phase affords 13.1 g (14%) of *(2)*, b.p. 31 °C/0.02 mm, yellow needles, m.p. 49 °C from methanol. It has λ_{max} = 295 mμ, log ε = 4.05 in cyclohexane, and infrared absorptions at 695 (m), 805 (s), 1000 (m), 1230 (s), and 1490 (m) cm^{-1} [2].

The new compound readily absorbs 1 mole of chlorine, being converted quantitatively into hexachlorotellurophene *(3)*, bright yellow crystals, m.p. 200 °C. When a suspension of *(3)* in benzene is shaken with aqueous sodium hydrogen sulfite, it is reconverted quantitatively into *(2)*.

In contrast to *(2)*, the hexachloro derivative *(3)* is decomposed rapidly by aqueous alkali to 1,2,3,4-tetrachloro-1,3-butadiene *(4)*, tellurous acid, and alkali chloride. This ring cleavage and the elemental analyses prove the structures of *(2)* and *(3)*. In view of its formation from *(3)*, it appears that *(4)*, m.p. 51 °C, n_D^{60} = 1.5438 [3], has the *cis,cis*-configuration [4].

The hitherto unknown tetrachloroselenophene *(5)* can be prepared by a synthesis analogous to that of *(2)* [5]. Selenium (0.3 mole) is shaken for 20 h at 250 °C with 0.3 mole of *(1)*. The reaction mixture is poured into acetone to reduce the Se_2Cl_2 formed. Distillation then affords 25.8 g (32%) of *(5)*, b.p. 127 °C/15 mm, colorless needles, m.p. 35 °C from ethanol. Compound *(5)* has λ_{max} = 266 mμ, log ε = 3.97 in cyclohexane, and infrared absorptions at 740 (s), 843 (s), 1033 (m), 1270 (m), and 1510 (m) cm^{-1} [2].

Received: January 27th, 1965 [Z 906/730 IE]
German version: Angew. Chem. 77, 260 (1965)

[1] *E. A. Braye*, *W. Hübel*, and *J. Caplier*, J. Amer. chem. Soc. *83*, 4406 (1961); *Ch. Courtot* and *Mohammed-Gholi Bastani*, C. R. hebd. Séances Acad. Sci. *203*, 197 (1936); Chem. Abstr. *30*, 7107^5 (1936).

[2] m = medium; s = strong.

[3] *A. Roedig* and *R. Kloss*, Liebigs Ann. Chem. *612*, 1 (1958).

[4] In this connection, cf. *H. H. Freedman*, J. org. Chemistry *27*, 2298 (1962).

[5] According to *H. Suginome* and *S. Umezowa*, Bull. chem. Soc. Japan *11*, 157 (1936); Chem. Abstr. *30*, 5981^9 (1936), the compound described by *H. V. A. Briscoe* and *I. B. Peel*, J. chem. Soc. (London) *1928*, 1747, as tetrachloroselenophene does not actually possess this structure.

Isonitrilocyclopentadienyl Complexes of Lanthanides

By Prof. Dr. E. O. Fischer and Dipl.-Chem. Hartmut Fischer

Anorganisch-Chemisches Laboratorium der Technischen Hochschule München (Germany)

The reaction of tricyclopentadienyl compounds of lanthanides with cyclohexyl isonitrile at 20 °C in benzene leads to novel complexes of formula $M(C_5H_5)_3CNC_6H_{11}$. These are the first compounds in which isonitriles are linked to rare-earth metals and in which a stable metal-carbon σ-bond is formed with such metals.

So far we have isolated green $Yb(C_5H_5)_3CNC_6H_{11}$, m.p. 167 °C *(1)*, yellow $Ho(C_5H_5)_3CNC_6H_{11}$, m.p. 165 °C *(2)*, and colorless $Tb(C_5H_5)_3CNC_6H_{11}$, m.p. 162 °C *(3)* in analytical purity. The crystalline substances can be sublimed *in vacuo* and dissolve well in benzene and ethers, but are only slightly soluble in pentane and hexane. They are thermally stable and decompose only above 240 °C. The action of oxygen and water results in rapid decomposition.

The infrared spectra (recorded in Nujol/Hostaflon mulls) of the three compounds are very similar, and show, as expected, one sharp ν_{CN} band at 2205 cm^{-1} (the ν_{CN} band of the free ligand lies at 2130 cm^{-1}). Further bands occur at 3077, 1449, 1014, and 787/759 cm^{-1}, and have been assigned to ν_{CH}, ω_{CC}, δ_{CH}, and γ_{CH} vibrations of the symmetrical five-membered ring.

All three compounds are paramagnetic; their magnetic moments were measured by the susceptibility method in benzene using NMR methods [1,2]. The values obtained for μ_{eff} were 4.5 B.M. for *(1)*, 10.6 B.M. for *(2)*, and 10.1 B.M. for *(3)*.

Received: February 2nd, 1965 [Z 907/731 IE]
German version: Angew. Chem. 77, 261 (1965)

[1] *D. E. Evans*, J. chem. Soc. (London) *1959*, 2003.

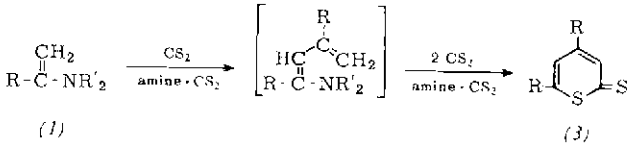
[2] *H. P. Fritz* and *K. E. Schwarzhans*, J. organomet. Chemistry *1*, 208 (1964).

α-Dithiopyrones from Enamines and Carbon Disulfide [1]

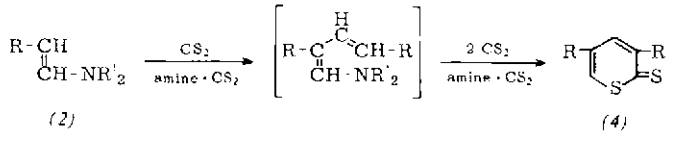
By Prof. Dr. Roland Mayer and Dipl.-Chem. J. Wehl

Institut für Organische Chemie der Technischen Universität Dresden (Germany)

Carbon disulfide reacts with enamines of type *(1)* or *(2)* at room temperature and atmospheric pressure to give α-dithiopyrones. 2-Aminoalkenes *(1)* generally yield 4,6-disubstituted derivatives *(3)*, while 1-aminoalkenes yield 3,5-disubstituted products *(4)*. The yields vary widely but are usually over 50%.



(1) *(3)*



(2) *(4)*

The dienamines indicated as intermediates react analogously if their steric configuration is correct. Thus, the parent compound α-dithiopyrone [2] can be prepared from 1-amino-1,3-butadiene [3].

Example: In order to prepare 4,6-diphenyl-α-dithiopyrone *(3)*, R = C_6H_5, 100 g of 1-pyrrolidinyl-1-phenylethylene *(1)*, R = C_6H_5, NR'_2 = pyrrolidinyl, are dissolved in 200 ml of anhydrous dioxane, and 200 ml of carbon disulfide are added with stirring over 10 min, initially at a temperature of 60 °C. The mixture is stirred for 1 h, the excess CS_2 is distilled off, and 200 ml of a 1:4 mixture of methanol and water are stirred in. The product *(3)* is then extracted from the dark red mass with chloroform. The yield is 60–68 g or 74–84% of shiny red needles, m.p. 113 °C from dioxane/methanol, λ_{max} in ethanol at 245 mμ (log ε = 4.16), 308 (4.17), 477 (3.64).

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German version: Angew. Chem. 77, 261 (1965)

[1] Sulfur Heterocycles and their Precursors, Part 50. – Part 47: *J. Faust* and *R. Mayer*, Liebigs Ann. Chem., in the press. – Parts 48 [*R. Mayer* and *J. Wehl*, Angew. Chem. *76*, 861 (1964); Angew. Chem. internat. Edit. *3*, 705 (1964)] and 49 [*P. Rosmus* and *R. Mayer*, Z. Chem. *4*, 426 (1964)] are not indicated as such.

[2] *R. Mayer* and *P. Fischer*, Chem. Ber. *95*, 1307 (1962).

[3] *R. Mayer* and *G. Laban*, unpublished results.

Synthesis of Cyclopropanols from β-Chloroethyl Cyclopropyl Ethers

By Dr. J. Paust and Prof. Dr. U. Schöllkopf

Organisch-Chemisches Institut der Universität Göttingen (Germany)

If β-chloroethyl dichloromethyl ether [1] is treated with methyl-lithium/lithium iodide [2] in the presence of olefins [3], β-chloroethyl cyclopropyl ethers are obtained. These ethers can be readily converted into cyclopropanols by two routes [4]: a) by dehydrochlorination with base and

subsequent acidic hydrolysis of the resulting cyclopropyl vinyl ethers, or b) by cleavage with butyl-lithium and hydrolysis of the resulting lithium cyclopropoxides.

Olefin	Cyclopropanol	B.p. [°C/mm]	Yield [%] [a]
Isobutene	2,2-Dimethyl-	65–70/80	a) 71 b) 92
Tetramethyl-ethylene	2,2,3,3-Tetramethyl-	54–56/13	a) 61 b) 90
Cyclohexene	*exo/endo*-7-hydroxy-bicyclo[4,1,0]heptane	83–86/13	a) 57 b) 94
Cyclooctene	*exo/endo*-9-Hydroxy-bicyclo[6,1,0]nonane	75–79/0.6	b) 91

[a] Based on β-chloroethyl cyclopropyl ether.

7-Hydroxybicyclo[4,1,0]heptane

By Method a): Potassium hydroxide (80 g) is melted on an oil bath at 250 °C, and 20 g of *exo/endo*-7-bicyclo[4,1,0]-heptyl β-chloroethyl ether are added dropwise with stirring over 45 min. The resultant vinyl ether is distilled off over a fractionating column 15 cm long (63 % yield, b.p. 56–59 °C/13 mm). This product is added dropwise over 10 min to a mixture of 150 ml of glycol dimethyl ether and 150 ml of 0.3 N sulfuric acid at 50 °C. The solution is neutralized with sodium hydrogen carbonate and extracted with ether.

By Method b): 130 ml of a 1 N solution of butyl-lithium in ether are added dropwise at room temperature to a solution of 10 g of *exo/endo*-7-bicyclo[4,1,0]heptyl β-chloroethyl ether in 50 ml of ether until the Gilman test [5] becomes positive. The reaction mixture is poured into 400 ml of a saturated solution of sodium hydrogen carbonate, and the product is extracted with ether.

Received: February 10th, 1965 [Z 915/739 IE]
German version: Angew. Chem. 77, 262 (1965)

[1] Prepared according to *H. Gross, A. Rieche*, and *E. Höft*, Chem. Ber. *91*, 654 (1958).

[2] Prepared from methyl iodide and lithium according to *H. Gilman, E. A. Zöllinger*, and *W. M. Selby*, J. Amer. chem. Soc. *55*, 1252 (1933).

[3] *U. Schöllkopf* and *J. Faust*, Angew. Chem. *75*, 670 (1963); Angew. Chem. internat. Edit. *2*, 397 (1963).

[4] For other syntheses of cyclopropanols see *C. H. De Puy, G. M. Dappen, K. H. Eilers*, and *R. A. Klein*, J. org. Chemistry *29*, 2813 (1964), where further references are given.

[5] *H. Gilman* and *F. Schulze*, J. Amer. chem. Soc. *47*, 2002 (1925).

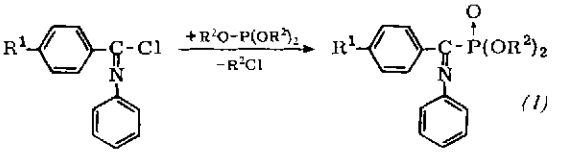
Synthesis of N-Phenyliminobenzylphosphonates and Benzoylphosphonates by Michaelis-Arbusow Reaction of Aromatic Imidoyl Chlorides

By Prof. Dr. G. Hilgetag, Dipl.-Chem. K. Zieloff, and Dr. H. Paul

II. Chemisches Institut der Humboldt Universität zu Berlin (Germany)

The reaction of *N*-phenylbenzimidoyl chlorides with trialkyl phosphites produces good yields of dialkyl phenyliminobenzylphosphonates *(1)*.

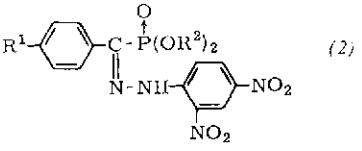
Triethyl-, tri-n-propyl-, tri-isopropyl-, and tri-n-butyl phosphites react with *N*-phenylbenzimidoyl chloride or its *p*-chloro, *p*-bromo, *p*-methoxy, and *p*-nitro derivatives at 130–160 °C. A temperature of 110–130 °C suffices for the reaction with trimethyl phosphite. The azomethines *(1)* are yellow oils, but only compounds *(1a)–(1e)* could be obtained analytically pure by vacuum distillation.



(1)

	R^1	R^2	M.p. [°C/mm]	n_D^{20}	Yield [%]
(1a)	H	C_2H_5	151–152/0.1	1.5626	75
(1b)	H	C_3H_7	157.5–158/0.03	1.5558	65
(1c)	H	C_4H_9	170–171/0.04	1.5460	74
(1d)	CH_3	C_2H_5	159/0.03	1.5661	63
(1e)	Cl	C_2H_5	155/0.005	1.5742	74

Without exception, the phenyliminobenzylphosphonates *(1)* could be hydrolysed with dilute sulfuric acid at 50 °C to give aniline and the corresponding benzoylphosphonates, which were isolated as their 2,4-dinitrophenylhydrazones *(2)*.



(2)

R^2	M.p. [°C]	R^2	M.p. [°C]
$R^1 = H$		$R^1 = OCH_3$	
CH_3	189.5–191	CH_3	198–200
C_2H_5	171–172	C_2H_5	177–178
C_3H_7	142.5–145.5	C_3H_7	113.5–115
i-C_3H_7	150–152	i-C_3H_7	140.5–141.5
C_4H_9	113–114.5	C_4H_9	139.5–140.5
$R^1 = CH_3$		$R^1 = Cl$	
CH_3	190–192	CH_3	190–192
C_2H_5	180–181	C_2H_5	203.5–206.5
C_3H_7	132–133	C_3H_7	154–156
C_4H_9	117–118	C_4H_9	137.5–139
$R^1 = Br$		$R^1 = NO_2$	
CH_3	198.5–200	CH_3	221–224 (decomp.)
C_2H_5	201–203	C_2H_5	176–177.5
C_3H_7	131.5–133.5	C_3H_7	177–179
i-C_3H_7	148–150	i-C_3H_7	174 (decomp.)
C_4H_9	116.5–118	C_4H_9	127.5–129

N-Methylbenzimidoyl chloride reacts analogously with trialkyl phosphites to give pale greenish-yellow azomethines, from which 2,4-dinitrophenylhydrazones *(2)*, R^1 = H, can be obtained in a one-stage reaction by hydrolysis and condensation with 2,4-dinitrophenylhydrazine in aqueous ethanol containing sulfuric acid.

These investigations show that the Michaelis-Arbusow reaction can be applied to any *N*-substituted aromatic benzimidoyl chloride. To our knowledge only one example [1] of this type of reaction has so far been published.

Received: February 5th, 1965 [Z 912/736 IE]
German version: Angew. Chem. 77, 261 (1965)

[1] *N. Kreutzkamp* and *G. Cordes*, Liebigs Ann. Chem. *623*, 103 (1959).

Coordination Chemistry

The 8th International Conference on Coordination Chemistry was organized by the Verein Österreichischer Chemiker (*A. Maschka*) and was held in Vienna (Austria) from September 7th to 11th, 1964 under the chairmanship of *V. Gutmann*. There were 850 participants from 34 countries, and the 155 lectures and discussions were dedicated to three major problems: the nature of the chemical bond in coordination compounds, novel coordination compounds, and new results and methods in coordination chemistry in solution [1].

Plenary Lectures [2]:

New Approaches to the Theory of Complex Ions and Their Physical Foundations

H. Hartmann, Frankfurt/Main (Germany)

A "united atom model" for complex compounds has been developed which affords information beyond the limitations of the ligand field theory (crystal field theory) with reasonable calculatory effort, provided the mathematical operations are carried out precisely, and which is still applicable even when MO–LCAO calculations fail owing to non-orthogonality of the functions belonging to the various centers involved. In this model, use is made of hydrogen-like single-center functions which correspond in their symmetry and in the nature and number of their nodal surfaces to MO–LCAO multicenter functions. In the Hamiltonian operator, a term c/r_2 is included for correction; the only parameters used are a variation parameter ($Z_{effective}$) and a free parameter (c in the term c/r_2). This model gives very close agreement with experimental data for Ti(III) and V(III) complexes.

Metal-Metal Interactions in Coordination Compounds

L. Lewis, Manchester (England)

Compounds with metal-metal bonds between the same elements have so far been found for all transition elements with the exceptions of zinc and metals of the scandium group. Here the elements occur in any oxidation state from +5 to −1 and with electronic configurations (of the electrons not bonded to ligands or anions) d^1–d^1 to d^9–d^9 and s^1–s^1; d^6–d^6 is never observed. They also occur in the most diversified structural arrangements, *e.g.* Mo in $[\overset{+5}{Mo}(OC_6H_5)_3Cl_2]_2$ (d^1–d^1), $[\overset{+4}{Mo}O_2]_x$ (d^2–d^2), $[\overset{+3}{Mo}_2Cl_9]^{3-}$ (d^3–d^3), $[\overset{+2}{Mo}Cl_2]_x$ (d^4–d^4), $[\overset{+1}{Mo}(\pi\text{–}C_5H_5)(CO)_3]_2$ (d^5–d^5), and $[\overset{-1}{Mo}_2(CO)_{10}]^{2-}$ (d^7–d^7). The tendency for M–M bonds to be formed is greater in the second and third periods of transition elements as well as in higher groups of transition elements and at lower states of oxidation of the elements. Frequently there are ligand bridges in addition to the M–M bonds. Occasionally structural units are observed where 3, 4, 5, or 6 metal atoms are intercombined and remain together even in solution. Thus, for example, there are always 3 atoms of rhenium at the corners of the equilateral triangle in the entities $[ReCl_3]_n$, $[(R_3P)_3Re_3Cl_9]$, $[Re_3Cl_{11}]^{3-}$, and $[Re_3Cl_{12}]^{3-}$. A M≡M triple bond is postulated in the diamagnetic ion $[W_2Cl_9]^{3-}$ since the W–W distance (2.40 Å) here is much shorter than in tungsten metal (2.74 Å). M–M quadruple bonds even occur in $[Cr(CH_3COO)_2]_2$ and in the diagmagnetic ion $[Re_2Cl_8]^{2-}$, where the Re–Re distance (2.27 Å) is extremely short and overlap of d_{z^2} (= σ), d_{xz} and d_{yz} (= π), and d_{xy} (= δ) orbitals occurs.

The number of compounds with σ-M–M bonds between two different metals is still relatively small. The combinations observed are V–Au, W–Mo, W–Au, Mo–Fe, Mn–Re, Mn–Fe, Mn–Co, Mn–Cu, Mn–Au, Fe–Co, Fe–Ni, Fe–Cu, Fe–Ag, Fe–Au, Fe–Hg, Co–Cu, Co–Ag, Co–Au, Rh–Hg, Ir–Hg, Pd–Pt, and Pt–Cu. Atoms with a $d^{10}s^1$ configuration form particularly strong bonds. Thus, the bond energy for Au–Au is 51.5 kcal/mole, for Cu–Au 54.5, for Ag–Au 47.6, for Cr–Au 50.4, and for Sn–Au 57.5 kcal/mole. σ-Metal-metal bonds can be strongly influenced by back-donation from the metals to ligands and from ligands to the metals, by π-M–M bonds, by repulsion effects from non-bonding orbitals, and by steric requirements. Metal-metal bonds are best recognized by combination of Raman and infrared spectroscopy (M–M frequencies lie below 200 cm^{-1}), X-ray structural analysis, and magnetic measurements. There is considerable variance in the lengths of the bonds observed to date for individual elements depending on the strengths of the bonds in question.

Tetrahedral and Octahedral Cationic Chelates of Main Group Elements

E. L. Muetterties, Wilmington, Del. (U.S.A.)

Salts such as $[L_2BH_2]^{\oplus}X^{\ominus}$ with ligands L = R_2S, R_3N, R_3P, and R_3As can be prepared according to Equations (a) and (b)

$$LBH_3 + LH^{\oplus}X^{\ominus} \rightarrow H_2 + [L_2BH_2]^{\oplus}X^{\ominus} \quad (a)$$

$$[L_2BH_2]^{\oplus} + 2\,L' \rightarrow 2\,L + [L'_2BH_2]^{\oplus} \quad (b)$$

as well as by the reaction of LBH_3 with B_2H_6, which leads with evolution of hydrogen to $[L_2BH_2]^{\oplus}$ $[B_{12}H_{11}L]^{\ominus}$. Compounds of the type $[L_2BH_2]^{\oplus}OH^{\ominus}$ are strong bases, $[L_2BH_2]^{\oplus}Cl^{\ominus}$ are strong electrolytes. The cation $[(R_3N)_2BH_2]^{\oplus}$ is remarkably stable. It is not attacked by concentrated sulfuric, hydrochloric, or nitric acid, alkalies, $Au^{3\oplus}$, 30 % H_2O_2 up to 100 °C, I_2, or Friedel-Crafts reagents. When heated at 100 °C with *aqua regia*, the complex is converted without decomposition into $[(R_3N)_2BHCl]^{\oplus}$. Its salts decompose according to Equation (c) below 180 °C in the presence of small, compact anions (X = Cl, Br, or N_3).

$$[(R_3N)_2BH_2]^{\oplus}X^{\ominus} \rightarrow R_3NBXH_2 + NR_3 \quad (c)$$

Amine exchange occurs above 150 °C, *e.g.* according to Equation (d).

$$[(R_3N)_2BH_2]^{\oplus} + R_2NC_2H_4NR_2 \rightarrow [(R_2NC_2H_4NR_2)BH_2]^{\oplus} + 2\,NR_3 \quad (d)$$

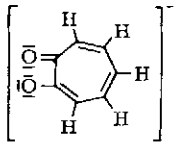
For theoretical reasons, this can be preceded only by a dissociation equilibrium [Equation (e)].

$$[(R_3N)_2BH_2]^{\oplus} \rightleftharpoons [H_2BNR_3]^{\oplus} + NR_3 \quad (e)$$

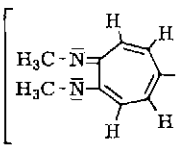
Substitution of the hydrogen atoms can be achieved only by means of radical reactions. Thus, $[(R_3N)_2BH_2]^{\oplus}$ reacts with fluorine in aqueous solution to give $[(R_3N)_2BF_2]^{\ominus}$, with FSO_2OOSO_2F to give $[(R_3N)_2B(OSO_2F)_2]^{\oplus}$, and with ICl to give $[(R_3N)_2BCl_2]^{\oplus}$. The stability of the other complexes decreases in the series $R_3N > R_3P > R_3As > R_2S$.

[1] Abbreviations used in this report are: El = atom of an element, L = ligand, M = metal, R = organic ligand, THF = tetrahydrofuran, s* = s/p hybrid orbitals.

[2] Complete and partially extended versions of the plenary lectures will be published in the Journal of Pure and Applied Chemistry.



(1)



(2)

The anions $(C_7H_5O_2)^{\ominus}$ *(1)* and $(C_9H_{11}N_2)^{\ominus}$ *(2)* derived from tropolone and its methylaminomethylimino derivative, respectively, give rise to pseudotetrahedral (D_{2d}) cations $(C_7H_5O_2)_2B^{\oplus}$ and $(C_9H_{11}N_2)_2B^{\oplus}$. The salt $(C_7H_5O_2)_2B^{\oplus}Br^{\ominus}$ is a strong 1:1 electrolyte, $(C_9H_{11}N_2)_2B^{\ominus}OH^{\ominus}$ is a strong base. Salts of the pseudo-octahedral ions $(C_9H_{11}N_2)_3El^{\oplus}$ with El = Si, Ge, or Sn are also strong electrolytes. On the other hand, $(C_7H_5O_2)_3SnCl$ and $(C_7H_5O_2)_3SnC_6H_5$ – which can be sublimed – are non-electrolytes with seven-coordinated tin. Experiments with ^{18}OH have revealed that hydrolysis of $(C_7H_5O_2)_3El^{\oplus}$ proceeds primarily by substitution on the ligands and not by attack of the central atom. Other ions produced included $(C_7H_5O_2)_3P^{2\oplus}$ (from PCl_5 and 3 $C_7H_6O_2$), $(C_7H_5O_2)_2As(OH)_2^{\oplus}$ and the eightfold coordinated compounds $(C_7H_5O_2)_4Nb^{\oplus}Cl^{\ominus}$ and $(C_7H_5O_2)_4Ta^{\oplus}Cl^{\ominus}$. Hydrolysis of $(C_7H_5O_2)_4Nb^{\oplus}$ yields $(C_7H_5O_2)_3NbO$, but $(C_7H_5O_2)_4Ta^{\oplus}$ is not markedly hydrolysed even at 140 °C.

The Role of Organometallic Compounds in the Development of Coordination Chemistry

F. G. A. Stone, Bristol (England)

Starting from π-$C_5H_5V(CO)_4$, $Fe(CO)_5$, $HMn(CO)_5$, and $NaMn(CO)_5$, complex compounds containing metal-carbon bonds were prepared whose investigation led to the discovery of novel classes of compounds and which have brought decisive advances in the development of coordination chemistry and organometallic chemistry. Thus, $C_5H_5V(CO)_4$ reacts with cycloheptatriene to give a π-aromatic complex $(C_7H_7)V(C_5H_5)$ in which V has the oxidation state zero. The weakly paramagnetic compound $[\pi$-$C_5H_5V(SCH_3)_2]_2$, which is also prepared via $C_5H_5V(CO)_4$, is a binuclear complex with four $S(CH_3)$ bridges and strong V–V bonds. Paramagnetism occurs within the thermic range. Iron pentacarbonyl is substituted even at room temperature according to Equation (f) to give σ-perfluoroalkyliron complexes (n = 1, 2, or 3).

$$Fe(CO)_5 + C_nF_{2n+1}I \rightarrow CO + C_nF_{2n+1}Fe(CO)_4 \qquad (f)$$

π-$C_5H_5Co(CO)$ $(C_nF_{2n+1})I$ or π-$C_5H_5Ni(CO)$ (C_nF_{2n+1}), for example, can be prepared analogously. $Fe(CO)_5$ reacts with dibutyldivinyltin to give $[(C_4H_9)_2SnFe(CO)_4]_2$. $Mn(CO)_4NO$ is a compound that is isosteric with $Fe(CO)_5$ and has a trigonal bipyramidal structure; it is a deep red diamagnetic liquid which decomposes on exposure to air and whose vapors are similar to those of bromine. It is formed from $HMn(CO)_5$ and p-CH_3–$C_6H_4SO_2$–NCH_3–NO in ether at 25 °C in the dark. Tetrafluoroethylene adds onto $HMn(CO)_5$ in pentane at 20 °C and 2 atm to give $H(CF_2)_2Mn(CO)_5$. Analogous reactions were achieved with the carbonyl hydrides of W, Re, and Fe and with $RMn(CO)_5$ (R = CH_3 or C_6H_5) on the one hand and with $ClFC{=}CF_2$, $Cl_2C{=}CF_2$, and $F_3C{-}C{\equiv}C{-}CF_3$ on the other. $NaMn(CO)_5$ reacts with π-$C_5H_5Fe(CO)_2I$ or $Re(CO)_5Cl$ to give π-$C_5H_5(CO)_2Fe$–$Mn(CO)_5$ or $(CO)_5Re$–$Mn(CO)_5$, *i.e.* carbonyl complexes with a covalent hetero-metal-metal bond. With perfluoroalkylcarbonyl chlorides it reacts to give compounds of the type $C_nF_{2n+1}COMn(CO)_5$, which on heating decompose into CO and $C_nF_{2n+1}Mn(CO)_5$. An analogous reaction takes place according to Equation (g).

$$2\ C_3F_7COCl + Na_2Fe(CO)_4 \rightarrow 2\ NaCl + 2\ CO + (C_3F_7)_2Fe(CO)_4 \qquad (g)$$

σ-Perfluoroalkylmetal complexes are generally very stable and have confirmed the theoretical predictions by *Orgel* that additional CO valence frequencies should appear in the infrared spectra of carbonyl complexes with distorted symmetry owing to splitting of the E bands and appearance of an additional B_1 band.

Intermediates in the Electrode Reactions of Coordination Compounds

A. A. Vlček, Prague (Czechoslovakia)

Redox processes at inert polarized electrodes differ from those occurring with redox reagents in homogenous solution. They sometimes take a different course, and in the case of complex ions, often proceed via a number of chemical transformations not occasioned by redox processes, *e.g.* alterations of the type or number of ligands attached to the complex.

$$D_1 \rightleftharpoons D_2 \rightleftharpoons \ldots D_n \xrightarrow{+e^-} D_n^- \rightleftharpoons \ldots D_z^-$$

Only the particle with the greatest redox activity (D_n) reacts at the electrode. If the rates of the subsequent chemical transformations $D_n^- \rightarrow D_z^-$ are slow, it is possible to detect otherwise unrecognizable intermediates by polarography at a dropping mercury electrode and even occasionally to prepare the species by electrolysis. Thus, $[Mn(dipy)_3]^{2\oplus}$ is reduced at −1.5 volt in 1 M alcoholic LiCl to stable $[Mn(dipy)_3]^{\oplus}$, which had hitherto never been isolated in the form of salts; beyond −1.6 volt reduction of the dipyridyl ligands begins. On homogeneous reduction in aqueous systems, $[Ni(CN)_4]^{2\ominus}$ leads to $[Ni_2(CN)_6]^{4\ominus}$, and in liquid ammonia to $[Ni(CN)_4]^{4\ominus}$. It can be concluded from electrode processes that it is always the complex of nickel with the oxidation state zero that is formed first and that this is rapidly oxidized by water to give $[Ni_2(CN)_6]^{4\ominus}$. The primary product of electrode reduction of $[Cr(CN)_5NO]^{3\ominus}$ is $[Cr(CN)_5NO]^{4\ominus}$, which can be isolated as such by electrolysis in 0.1 M NaOH; however, below pH 9.5 the species is decomposed by addition of two protons or because further reduction occurs. Rapid oxidation of $[Co(dipy)_3]^{\oplus}$ in the presence of catalytic amounts of $[Cr(CN)_5NO]^{3\ominus}$ in homogeneous solution proceeds via the steps shown in Equations (h) and (i).

$$[Co(dipy)_3]^{\oplus} + [Cr(CN)_5NO]^{3\ominus} \rightarrow [Co(dipy)_3]^{2\ominus} + [Cr(CN)_5NO]^{4\ominus} \qquad (h)$$

$$[Cr(CN)_5NO]^{4\ominus} + H^{\oplus} \rightarrow [Cr(CN)_5NO]^{3\ominus} + H \qquad (i)$$

From the Research Reports [3]:

The major accent of preparative and synthetic coordination chemistry still lies on the field of carbonyl, π-aromatic, and π-olefin complexes, although increasing attention is being paid to the corresponding σ-compounds. New aspects worthy of inclusion in textbooks have appeared in the preparation of σ-metal-metal compounds and also in the detection of multiple bonds in oxo complexes of transition metals (*e.g.* in $\rangle VO$ or $\rangle CrO_2$), whose structures (*e.g.* $\rangle \overset{\oplus}{V}{\equiv}\overset{\oplus}{O}$ analogous to $\overset{\ominus}{C}{\equiv}\overset{\oplus}{O}$) explains their stability even towards protons. X-ray structural analysis and magnetic measurements (together with ESR and NMR spectroscopy) are still the most important aids for elucidating the details of the structures of coordination compounds; novel possibilities are offered by application of the Mössbauer effect [*E. Fluck*, Heidelberg (Germany); *I. Danon*, Rio de Janeiro (Brazil)]. In the following, a short review will be given of the most important results of preparative and synthetic coordination chemistry reported.

[3] Cf. *V. Gutmann*: Proceedings of the 8th International Conference on Coordination Chemistry. Springer, Vienna-New York 1964.

Metal-Metal Compounds

Metal-metal bonds occur in pure metals (Cu), metallic alloys (Cu/Zn), and salt-like alloys ($Cs^{\oplus}Au^{\ominus}$), as well as in compounds of transition metals with low states of oxidation ("$MoCl_2$" ~ $[Mo_6Cl_{12}]$; Ta_6Cl_{14}), in s*-donor compounds ($[Pt(SnCl_3)_4]^{2\ominus}$) and d-donor compounds (Ni-diacetyldioxime), and finally in distinctly covalent σ-bonding species such as s*/s* (Hg_2Cl_2), s*/d ($[(C_6H_5)_3PAuMn(CO)_5]$), and d/d ($[Mn_2(CO)_{10}]$). Classes of compounds prepared for the first time were $L{\cdot}M{-}M'(CO)_n$, pale yellow to clear brown solids with melting points between 80 and 200 °C (L = $(C_6H_5)_3P\rightarrow$, $H_3C{-}C[CH_2As(CH_3)_2]_3\rightrightarrows$, $H_3C{-}As[C_6H_4{-}O{-}As(CH_3)_2]_2\rightrightarrows$; M = Cu, Ag, or Au; M' = V, W, Mn, Fe, or Co; and n = 4,5, or 6) [*R. S. Nyholm*, London (England)], and $L_3X_2M{-}HgX'$ and $L_2X_3M'{-}HgX'$ (L = $(C_6H_5)_2AsCH_3$ or $(C_6H_5)_3P$; M = Rh or Os; M' = Ir; X = Cl, Br, or CO; and X' = F, Cl, Br, I, CN, or SCN) [*K. Vrieze*, London (England)].

Crystallographic analysis of $(C_6H_5)_3P\rightarrow Au{\cdot}Mn(CO)_5$ indicated a linear P–Au–Mn arrangement with an Au–Mn distance of 2.47 Å (r_{Au} = 1.2 and r_{Mn} = 1.27 Å), whereas the bonding radius of the Mn in $Mn_2(CO)_{10}$ is 1.46 Å and in $(C_6H_5)_2Sn[Mn(CO)_5]_2$ is 1,31 Å; here the two Sn–Mn distances are both 2.70 Å [*H. M. Powell*, Oxford (England)]. In the violet crystals of composition $K_{1,6}Pt(C_2O_4)_2{\cdot}2.5\ H_2O$ (Pt–Pt = 2.76 Å) and $K_2Pt(CN)_4Cl_{0,2}$ (Pt–Pt = 2.83 Å), the Pt–Pt distances are unusually short [*K. Krogmann*, Stuttgart (Germany)]. Investigations of the structures of the cations $[M_6X_{12}]^{2\ominus}$, where M = Nb or Ta and X = Cl or Br, revealed an octahedral arrangement of the equivalent metal atoms – formally 2 $M^{3\oplus}$ and 4 $M^{2\ominus}$ is expected – with strong M–M bonds [*M. B. Robin*, Murray Hill, N.J. (U.S.A.)]. Molybdenum(II) chloride reacts with pyridine or $(C_6H_5)_3P$ to give the non - electrolytes $(Mo_6Cl_8)Cl_4L_2$ and the electrolytes $[(Mo_6Cl_8)Cl_3L_3]Cl$ and $[(Mo_6Cl_8)Cl_2L_2(ROH)_2]Cl_2$ [*C. J. Wilkins*, Christchurch (New Zealand)].

Carbonyl Compounds

Vanadium hexacarbonyl reacts with benzene with liberation of 2 moles of CO to form $[V(CO)_4C_6H_6][V(CO)_6]$, which can be converted into the compounds $[V(CO)C_6H_6]PF_6$ and $[V(CO)_4C_6H_6][B(C_6H_5)_4]$ [*E. Calderazzo*, Geneva (Switzerland)]. Trimeric $[Mn(CO)_4]_3$ and polynuclear derivatives $[M(CO)_4]_x$ where M = Mn, Tc, or Re were formed during attempts to prepare $M(CO)_5H$ [*H. Kaesz*, Los Angeles, Calif. (U.S.A.)]. New hydrides and carbonyl hydrides of iridium were obtained by *L. Malatesta*, Milan (Italy): H_3IrL_2 (m.p. 145°C), H_3IrL_2py (m.p. 134°C), $HIr(CO)L_2$, and $H_3Ir(CO)L_2$ with the isomers *cis,cis-*, and *trans*-H, and *cis*-L, where L = $(C_6H_5)_3P$. Carbonyl acetylene complexes of tungsten such as $(RC{\equiv}CR')_3W(CO)$ with R and R' = CH_3, C_2H_5, and C_6H_5 [*D. Tate*, Akron, Ohio (U.S.A.)], of iron such as $(RC{\equiv}CR')Fe(CO)_4$ (yellow), $(RC{\equiv}CR)_2Fe_2(CO)_6$, $(RC{\equiv}CR)_3Fe_2(CO)_6$, $(RC{\equiv}CR)_2COFe_2(CO)_6$, $(RC{\equiv}CR')Fe_2(CO)_7$ (dark-green), and $(RC{\equiv}CR')Fe_3(CO)_9$ [*C. Hoogzand*, Brussels (Belgium)], and of cobalt such as $[(CH_3)_3C{-}C{\equiv}CH]$, $(HC{\equiv}CH)Co_2(CO)_4$, and $(HC{\equiv}CH)Co_2(CO)_9$ [*O. S. Mills*, Manchester (England)] were prepared and their occasionally unusual constitutions elucidated. *M. Tsutsui*, New York, N.Y. (U.S.A.) treated estrone with $Cr(CO)_6$ and acetylergosterol as well as vitamin A acetate with $Fe_3(CO)_{12}$ and succeeded in isolating the derivatives estrone-$Cr(CO)_3$, acetylergosterol-$Fe(CO)_3$, and vitamin A acetate-$Fe(CO)_3$. The reaction of $Co_2(CO)_8$ with S_8 led depending on the Co : S ratio to $Co_3(CO)_9S$, $Co_3(CO)_7S_2$, or $[Co_2(CO)_5S]_n$ [*L. Marko*, Veszprem (Hungary)]. $(CO)_5Mn{-}SCN$ can be prepared from $(CO)_5MnNa$ with ClSCN and rearranges within 5 min at 25 °C in acetonitrile to its bond isomer $(CO)_5Mn{-}NCS$, but is reformed from the latter in suspension in Nujol within 5 h at 25 °C [*A. Wojcicki*, Columbus, Ohio (U.S.A.)]. $NaMo(CO)_3(C_5H_5)$ reacts with CH_3SCH_2Cl in THF at 25 °C to form $CH_3SCH_2Mo(CO)_3(C_5H_5)$ which on irradiation with ultraviolet light is transformed into $CH_3SCH_2Mo(CO)_3(C_5H_5)$; both compounds are yellow and melt at 66–67 °C, and both are supposed to involve π-bonds over the $CH_2{=}S{-}CH_3$ moieties. $(CH_3S)Fe(CO)_2(C_5H_5)$, m.p. 67–69 °C, is a monomer without sulfur bridges [*R. B. King*, Pittsburgh, Pa. (U.S.A.)]. *J. A. Ibers*, Upton, N.Y. (U.S.A.) succeeded *in elucidating the details* of the structures of the crystalline carrier of molecular oxygen $(O_2)IrCl(CO)[(P(C_6H_5)_3]_2$, which can be prepared from its components and is comparable with the O_2/oxyhemoglobin complex, and of the analogous complex $(SO_2)IrCl(CO)[P(C_6H_5)_3]_2$.

π- and σ-Complexes with Aromatics and Olefins

The reaction of triphenylcyclopropenyl bromide with $Ni(CO)_4$ in methanol leads to red crystals of the bromine-bridged binuclear complex $\{[\pi{-}(C_6H_5)_3C_3]Ni(CO)Br\}_2$ [*S. F. A. Kettle*, Sheffield (England)]. π-Tetraphenylcyclobutadienepalladium dibromide is obtained via diphenylacetylene and is substituted by triphenylphosphine to form octaphenylcubane according to Equation (k).

$$2\ [\pi{-}(C_6H_5)_4C_4]PdBr_2 + 4\ (C_6H_5)_3P \rightarrow 2\ [(C_6H_5)_3P]_2PdBr_2 + (C_6H_5)_8C_8 \quad (k)$$

Ligand exchange occurs with $[(C_6H_5)_3P]_2NiBr_2$ to form $[(C_6H_5)_3P]_2PdBr_2$ and $[(C_6H_5)_4C_4]NiBr_2$, and it reacts with $Fe(CO)_5$ to form $[(C_6H_5)_4C_4]Fe(CO)_3$ and with $(C_5H_5)Fe(CO)_2Br$ by transfer of the cyclopentadienyl group to yield $\{[(C_6H_5)_4C_4]Pd(C_5H_5)\}^{\oplus}FeBr_4^{\ominus}$ [*P. M. Maitlis*, Hamilton, Ont. (Canada)].

The complex $C_{13}H_{17}Ni(C_5H_5)$ formed from NaC_5H_5 and $[(CH_3)_4C_4]NiCl_2$ was recognized by X-ray structural analysis to be π-cyclopentadienyl-1,2,3,4-tetramethyl-1-cyclopenta-1',3'-dienocyclobutenylnickel(II), a representative of a completely new type of compound [*L. Dahl*, Madison, Wisc. (U.S.A.)]. The reaction of $ZrCl_3$ with cyclopentadiene at 200 °C leads to $(\pi{-}C_5H_5)ZrCl_3$. $ZrCl_4$ reacts with NaC_5H_5 to form yellow $(\pi{-}C_5H_5)_4Zr$. The $[(\pi{-}C_5H_5)_2ZrCl]_2$ formed from "$(C_5H_5)_2ZrCl_2$" and aniline reforms the "$(C_5H_5)_2ZrCl_2$" with HCl without liberation of hydrogen, hence there must be a hidden proton somewhere in this compound [*A. F. Reid*, Melbourne (Australia)]. *F. Jellinek*, Groningen (Holland) succeeded in preparing purple colored $(C_5H_5)_2Ti(C_3H_5)$, m.p. 118 °C, and a similar complex $(C_5H_5)_2Ti(CH_2C_6H_5)$. *M. Cais*, Haifa (Israel) reported on some metal complexes of the pentalene system, *e.g.* $[(C_8H_6)Mn(CO)_3]^{\oplus}X^{\ominus}$. Crystalline olefin complexes of silver of general formula $[Ag(RR'C{=}CR'R)]^{\oplus}BF_4^{\ominus}$ have π-bond character [*H. W. Quinn*, Sarna (Canada)]. The chlorine-bridged complex $[Cl_2Pd_2(\pi{-}C_4H_6Cl)_2]$ obtained from $PdCl_2(C_6H_5CN)_2$ and butadiene reacts rapidly with alcohols to yield $[Cl_2Pd_2(\pi{-}C_4H_6OR)_2]$. The complex $[Cl_2Pd_2(C_3H_4Cl)_2]$ can be prepared analogously with allene. Na_2PdCl_4 and allene form the π-complex $[Cl_2Pd_2(C_6H_8Cl)_2]$ [*S. Robinson*, Leeds (England)]. *Dahl* found that $[(\pi{-}C_3H_5)PdCl]_2$ crystallizes in the space group $C_{2h}{-}2/m$. The reactions with hydrogen and with sodium acetate of the [(diolefin) (ROH)PdCl] complexes which have a π-allyl structure were described by *E. J. Smutny*, Emeryville, Calif. (U.S.A.). Unstable complexes of allene and transition metals are highly active and selective catalysts for converting butadiene into cyclodecatriene, 4-methyl-1,3,6-heptatriene, or 1,2-polybutadiene, and for polymerizing ethylene in solution [*G. Wilke*, Mülheim/Ruhr (Germany)]. *S. F. Mason*, Exeter (England) reported on some σ-π-complexes of cobalt and iron, *e.g.* tricarbonyloctafluoro-1,3-cyclohexadienyliron, and *E. Kurras*, Jena (Germany) described σ-π-allylchromium complexes and the dark violet compound $Li_4[V(\sigma{-}C_6H_5)_6]$.

Complex and Addition Compounds of Main Group Elements

The methylammonium *N*-methylboranocarbamate formed according to Equation (I) from methylamine and borane carbonyl is converted by 2 moles of KOH in refluxing alcohol

$$2\,CH_3NH_2 + H_3BCO \rightarrow [CH_3NH_3]\,[CH_3NH{-}CO{-}BH_3] \quad (I)$$

via elimination of 2 moles of methylamine and 1 mole of water into fine crystals of dipotassium boranocarbonate $K^{\oplus}[^{\ominus}O{-}CO{-}\overset{\ominus}{B}H_3]K^{\oplus}$ which decomposes only on heating above 400 °C, which is converted into the hydrogen carbonate $K^{\oplus}[HO{-}CO{-}\overset{\ominus}{B}H_3]$ by titration with acids, and which forms coordination compounds with transition metals [*R. W. Parry*, Ann Arbor, Mich. (U.S.A.)]. The preparation of a yellow crystalline sublimable borazole addition compound $[-(CH_3)BN(CH_3)-]_3TiCl_4$ which dissolves readily in benzene was achieved by *H. Nöth*, Munich (Germany). Aminoborane forms soluble 1:1 complexes with iodine in inert solvents [*J. J. Lagowski*, Austin, Tex. (U.S.A.)]. Acetonitrile and tetramethyldiborane $[R_2BH]_2$ combine to form two isomers of the type $[H_3C{-}CH{=}N{-}B(CH_3)_2]_2$ of m.p. 76 and ca. −5 °C. Analogously, compounds of general formula $[RR'C{-}NAlR'_2]_2$ are formed from RCN and AlR'_3 at 150–250 °C [*K. Wade*, Durham (England).

B. J. Aylett, London (England) reported on silyl iodide addition products, *e.g.* $H_3SiI(py)_2$ and $H_3SiI(dipy)$, and their reactions. Novel complexes of aluminum and gallium with coordination number 4 were isolated by *H. Schmidbaur*, Marburg/Lahn (Germany) in compounds of the types $[-(R_3Si)O\text{-}AlR'_2-]_2$, $Na[R'_2Al(OSiR_3)_2]$, and $K[Ga(OSiR_3)_4]$; he also succeeded in preparing complexes of lithium with the coordination number 2 in the form of the compounds $M[Li(OSiR_3)_2]$, where M = Na (m.p. 233–235 °C) and K (m.p. 258–262 °C). *H. Bürger*, Graz (Austria) investigated transition metal bistrimethylsilylamides $M[N(SiR_3)_2]_n$, where M = Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Cd, or Hg, which are mostly intensely colored liquids or crystals and are distillable or sublimate. From their infrared spectra and behavior toward Lewis bases it can be seen when and whether the lone pair of electrons on the nitrogen form π-bonds with the silicon or with the metal atom. Tetra- and pentafluoroorganylsilicates such as $[(C_2H_5)_4N]\,[CH_3SiF_4]$, $K_2[CH_3SiF_5]$, and $(NH_4)_4[F_5Si{-}CHCl{-}SiF_5]$ were prepared for the first time by *R. Müller*, Dresden-Radebeul (Germany) and are suitable as intermediates for separating methylchlorosilanes produced by direct synthesis, as carburating agents, or for the production of organomercury compounds. *M. Onyszchuk*, Montreal (Canada) managed to add two oxa rings $[-O(CH_2)_n-]_{ring}$ with n = 2, 3, 4, or 5 each onto SiF_4 and GeF_4, and simultaneously obtained $SiF_4[O(CH_3)_2]_2$, $GeF_4(CH_3OH)_2$, $GeF_4[OC(CH_3)_2]_2$, and $GeF_4O(CH_2)_4O$. The GeF_4 adducts are considerably more stable than the SiF_4 adducts. Some specially substituted phosphines and phosphites were examined in their capacity as complex-forming ligands, and compounds such as $(CO)_3Ni \leftarrow PR_2{-}B(NR'_2)_2$ or the cyclic derivative $[\rightarrow Ni(CO)_2 \leftarrow PR_2{-}B(NR_2){-}B(NR_2){-}R_2P \rightarrow]_{ring}$ (*Nöth*), octahedral complexes of Re(0), Re(II), Re(III), and Re(V), *e.g.* $[(R_2PCH_2CH_2PR_2)_2ReX_2]^{\oplus}X^{\ominus}$ [*E. S. Stern*, Runcorn (England)] or $Ni[\leftarrow P(OCH_2)_3C{-}CH_3]_4$ [*J. G. Verkade*, Ames, Iowa (U.S.A.)] were obtained. *K. Issleib*, Halle/Saale (Germany) synthesized such unusual compounds as $P[FeP(C_6H_5)_2]_3$, $P[Ti(PR_2)_2]_3$, or the cyclic complex $[-Fe{-}PR{-}PR{-}PR{-}PR-]_{ring}$. X-ray structural analysis of $K_4[As_2O_2F_8]$ indicated the space group $P2_1/n{-}C5_{2h}$ and the presence of a four-membered AsO ring [*W. Haase*, Jena (Germany)]. XeF_6 can be made to form complexes with Lewis acids; the colorless solids F_6XeBF_3, m.p. 90 °C, F_6XeAsF_5, and $F_6Xe(SbF_5)_2$ were isolated. They are extremely hygroscopic and react with moisture to form highly explosive XeO_3. Structures such as $F_6Xe \cdot BF_3$, $F_5Xe^{\oplus}AsF_6^{\ominus}$, and $F_4Xe(F_2SbF_4)_2$ came up for consideration [*H. Selig*, Argonne Ill. (U.S.A.)].

Miscellaneous

W. Beck, Munich (Germany) prepared some new fulminato complexes $M(CNO)_x$ (with M–C bonds), *e.g.* $HPt(CNO)(PR_3)_2$, $Ni(CNO)_2(PR_3)_2$, $Hg(CNO)_2(PR_3)_2$, the extremely stable category of compounds $(C_6H_5)_3El(CNO)$, where El = C, Si, Ge, Sn, or Pb, and the explosive complexes $(CH_3)_2Tl(CNO)$ and $(C_3H_7)_3Pb(CNO)$. *G. W. A. Fowles*, Southampton (England) reported on addition compounds of the type X_4TiL_2, X_3TiL_2, and Cl_3VL_2 in which X = Cl or Br, L = SR_2, and R = CH_3, C_2H_5, or $(CH_3)_2CH-$. *J. C. Carter*, Pittsburgh, Pa. (U.S.A.) obtained a labile complex $(C_5H_5)_2Ti(B_{10}H_{13})_2$ from $(C_5H_5)_2TiCl_2$ and $NaB_{10}H_{13}$. Dipole measurements on the compounds $[Cl_3ReNC_6H_5(PR_3)_3]$ and $[Cl_3ReO(PR_3)_3]$ suggested strong $\pi\text{-}\overset{\ominus}{R}e\equiv\overset{\oplus}{O}|$ and $\pi\text{-}\overset{\ominus}{R}e\equiv\overset{\oplus}{N}$ bonds, comparable with $\overset{\ominus}{C}\equiv\overset{\oplus}{O}$ or $\overset{\ominus}{C}\equiv\overset{\oplus}{N}{-}C_6H_5$ [*J. Chatt*, Welwyn (England)]. $Fe(dipy)_3$ has formally iron of zero valence and is obtained as deep green to black crystals from the reaction of $[Fe(dipy)_3]I_2$ and $Li_2(dipy)$ in THF or of $FeCl_3$ with dipyridyl and $Li_2(dipy)$; it dissolves in benzene to give a violet solution and is very sensitive to air and moisture [*S. Herzog*, Greifswald (Germany)].

[VB 874/178 IE]

German version: Angew. Chem. 77, 263 (1965)

Symposium on Macromolecular Compounds

The 3rd Symposium on Macromolecular Compounds took place at Zurich (Switzerland) on October 16th and 17th, 1964, the main subject of this year's discussion being additives to synthetic polymers.

From the lectures:

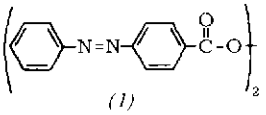
L. Dulog (Mainz, Germany) reported on the primary step in autoxidation. As ageing of synthetic polymers is mainly due to autoxidation, the initiation of this process is of interest. The primary step consists of a direct reaction of molecular oxygen with the organic compound. It precedes any autocatalytic oxidation which is initiated by peroxides present in the substrate. The primary reaction could be observed by analysing very small conversions in the autoxidation of n-butyl methacrylate and of tetralin. Some deviations from the usual kinetic relations were found. The mechanism could be derived from the kinetics of the autoxidation of styrene, indene, deuterated indene, and 1,1-dimethylindene. The primary step of the autoxidation was found to be a dehydrogenation of the organic compound by molecular oxygen, yielding free radicals.

H. Hartel (Troisdorf, Germany) dealt with inhibitors of the styrene polymerization. More than 100 inhibitors (quinones and their derivatives, nitroso compounds, phenols, amines, and hydrazines) were tested in concentrations of 10^{-2} mole-%. At 90 °C, the time of induction, *i.e.* the time elapsing before polymerization starts, was measured in relation to the inhibitor concentration. The results allowed some conclusions

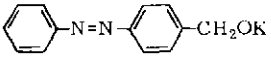
regarding the connection between inhibiting effect and chemical structure: The inhibiting effect of quinones decreases from *o*- to *p*-quinones, with the number of alkyl or halogen substituents, with the chain length of the alkyl groups, and with the number of rings. Introduction of hydroxy groups causes an increase of the inhibiting effect, provided that at least one position of the quinone ring is not substituted. The introduction of nitro groups into phenols (particularly at position 2), of nitroso groups, and of additional hydroxy groups increases the inhibiting effect, whereas aldehyde, keto, and halogen substituents have the opposite effect. Amino groups prolong the induction time only slightly less than hydroxy groups in the same position. Nitroso compounds inhibit more strongly than analogous phenols.

H. W. Schnecko (Mainz, Germany) reported on the polymerization of acrylonitrile with small amounts of silver nitrate in the solid state or in solution. The reaction which was examined in a homogeneous system (dimethylformamide as solvent) seems to involve a radical mechanism. An investigation into the part which the solvent plays, showed that the combination of amines with silver nitrate gives rise to very active catalysts which are far more active than pure $AgNO_3$ and approximately as active as redox catalysts. A stable complex between the monomer and silver nitrate has, so far, not been found. The action of silver nitrate on polyacrylonitrile causes considerable changes of properties which particularly affect the rate of ageing at higher temperatures.

H. Kämmerer (Mainz, Germany) discussed the introduction into polymers of unusual groups and in particular groups which can be determined colorimetrically in order to allow the elucidation of the polymer structure or of the mechanism of polymerization. The quantitative determination of such groups is carried out by extinction measurements. The groups should, therefore, possess strong absorptions which obey the Lambert-Beer law and are different from those of the polymer. Thus azo groups, which were introduced during the radical polymerization of styrene *via* the peroxide *(1)* or during polymerisation of ethylene oxide *via* the alcoholate *(2)*, could be analysed with at least the same degree of accuracy as radioactive groups.



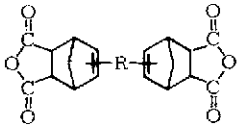
(1)



(2)

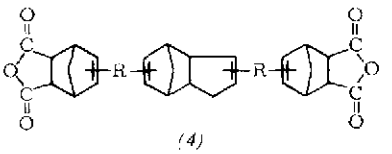
From a colorimetric determination of end groups in polystyrene, the minimum molecular weight, or in some cases the average molecular weight can be calculated with certain assumptions. According to present results, it should be possible to determine molecular weights up to 10^7. Copolymerizations, as well as transfer and cross-linking reactions can also be detected using this method.

A. Renner (Basel, Switzerland) gave a report on new bis-diene addition products as hardening agents for epoxide resins. For example, the reaction of bis-cyclopentadienyl com-



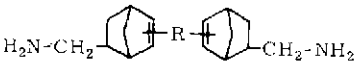
(3)

pounds with maleic anhydride yields dianhydrides *(3)* of tetracarboxylic acids. At a molar ratio of 1:1, tetracarboxylic acid dianhydrides *(4)* are formed possessing a dicyclopentadienylene group which can be opened.



(4)

These dianhydrides react with epoxide resins and polyvalent dienophiles, *e. g.* unsaturated polyesters, to form crosslinked products which can be used as metal binders.



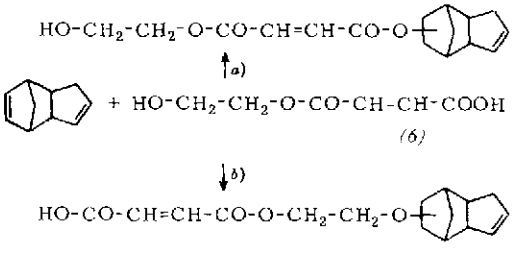
(5)

Amine hardeners of formula *(5)* are obtained from dienes and acrylonitrile by diene synthesis, followed by catalytic hydrogenation of the dinitriles. These hardeners, when used as additives to liquid epoxide resins of the bisphenol type, yield solid products of good mechanical properties.

R. Zimmermann and *F. Reiners*, Wiesbaden-Biebrich (Germany) discussed the structure and properties of polyesters modified with dicyclopentadiene. After graft polymerization with styrene, these polymers exhibit some remarkable properties compared with normal unsaturated polyesters: for example, they can be used to prepare coatings which do not stick and are absolutely dry after a short time without the addition of wax, and which can be wet-ground after a few hours. The hydroxy and color numbers and the reactivity of these unsaturated polyester resins depend on the esterification temperature and the time at which the dicyclopentadiene is added. It was shown by quantitative analysis of the products obtained by alkaline hydrolysis of the polyesters that the dicyclopentadiene reacts mainly as follows:

1) The cyclopentadiene formed by cleavage of the dicyclopentadiene during esterification adds onto the double of the maleic anhydride to give *endo*-methylenetetrahydrophthalic acid.

2) The mono-ester *(6)* formed in the first stage of the polycondensation from ethylene glycol and maleic anhydride adds on dicyclopentadiene at both the carboxyl and terminal hydroxyl functions.

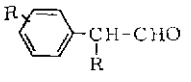


(6)

Whether the dicyclopentadiene is condensed into the polyester according to 1) or 2) depends on the temperature conditions during the reaction. Temperatures of 100–120 °C during the initial phase of the condensation and addition of the dicyclopentadiene to the preformed mono-ester *(6)* promotes condensation by Mechanism 2). At 180 °C, Reaction 1) is predominant. The reactivity and mechanical properties of the resins are optimum when the incorporation of dicyclopentadiene occurs mainly by Reaction 2).

H. Hopff and *E. K. Kleiner* (Zurich, Switzerland) reported on keto-enol tautomers as polymerization initiators. α-Phenylcarbonyl compounds having at least one hydrogen atom on the α-carbon or α-nitrogen, are effective initiators for the polymerization of vinyl compounds. They were extensively investigated in the polymerization of methacrylic esters and in the copolymerization of unsaturated esters with vinyl monomers. The activity of these initiators decreases in the sequence *(7)* > *(8)* > *(9)* > *(10)* > *(11)*.

The most effective compounds are: phenylformylacetonitrile, hydratropa-aldehyde, phenylacetaldehyde, methyl- and ethyl phenylformylacetate, phenylpyruvic acid and its esters, and benzylmethylglyoxal. The ketones *(9)*, *e. g.* deoxybenzoine,



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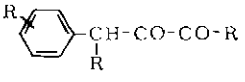

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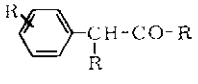

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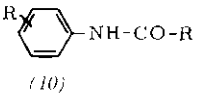

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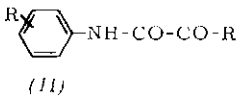
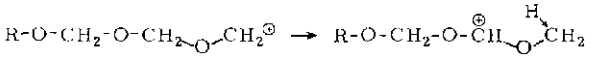
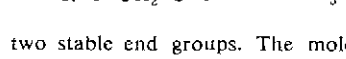


(11)

benzyl methyl ketone, and benzyl ethyl ketone, are much weaker. Among α-phenylcarbonyl compounds of which tautomers can be isolated, *trans*-enols show higher activity than *cis*-enols. Keto-isomers are much weaker initiators than *cis*- and *trans*-enols. The polymerizations were carried out, using 0.1 to 2% by weight of initiators at temperatures above 60 °C. Quinone, diphenylpicrylhydrazyl and nitro compounds are strong inhibitors, whereas hydroquinone has hardly any inhibiting effect. Traces of oxygen activate and so does ultraviolet irradiation. The hardening of polyester monomer solutions proceeds more equally with α-phenylcarbonyl initiators than with peroxides, and lower maximum temperatures are possible at similar gelling and hardening times. The polymers sometimes possess improved mechanical properties, *e. g.* impact hardness, but they need longer after-hardening for optimal hardness.

H. D. Hermann (Frankfurt/Main, Germany) reported on the influence of regulators for the trioxane polymerization. The stability to alkali of the end groups depends upon the nature of the regulators which was used for polymerization. Water, carboxylic acids and acid anhydrides yield alkali-labile end groups, whereas alcohols and carboxylic esters yield one stable and one labile end group. Acetals and ethers yield





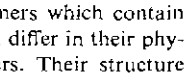
two stable end groups. The molecular weights are much smaller than theoretical. These observations and some experiments directed towards regulation of the trioxane polymerization by various chain transmitters led to the assumption that a hydride shift takes place as a side reaction: Boric esters and alkyl-substituted aromatic compounds were mentioned as new regulators.

H. G. J. Overmars and *G. M. van der Want* (Utrecht, Holland) reported on organolead compounds as catalysts in the formation of polyurethane foams. Polyether-urethane foams are usually prepared by reacting a polyether (mol. wt. 2000 to 3000) possessing hydroxyl end groups, with a diisocyanate, and using as foaming agent a volatile substance, such as Freon or carbon dioxide. The latter is formed by the reaction of water with an isocyanate group. As the addition of the isocyanate onto the polyol and onto water are slow reactions, both are accelerated by specific catalysts. The isocyanate-polyol reaction is usually accelerated by organotin compounds, among which compounds of the type R_2SnX_2 are particularly active and are used technically in foam processes. Among lead compounds only products of the type $RPbX_3$ possess catalytic activity. They catalyse both addition reactions to about the same degree. Organolead compounds are advantageous for the production of urethane foams, because there is no need for a tertiary amine as cocatalyst.

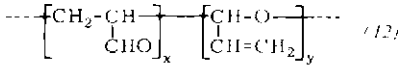
A. Krieger (Emmenbrücke, Switzerland) discussed the reactions of copper compounds in polyamide 6. The poor light- and heat-fastness of polycaprolactam or Nylon-6,6 fibres can be improved by the addition of stabilizing systems during the manufacture. The best-known group of stabilizers are copper compounds which may, however, cause precipitations in the polymer melt and discoloration of the polymer. As potential differences of up to 0.5 V can occur between different metals in technical plants and as the conductivity of the polyamide at 260 °C in the presence of electrolytes can reach 10^3 $ohm^{-1}cm^{-1}$, metallic copper can be deposited electrolytically under the conditions of polymerization. Secondary reactions of the copper sol lead to discoloration of the polymer. This can be prevented by complexing the copper before the start of the reaction, *e. g.* with salicylic or thioglycolic acids. Another way of improving the color fastness and the stability of the polymer consists in the addition of redox systems, *e. g.* potassium iodide, to the copper acetate.

K. Elbel (Wesseling, Germany) reported on the use of polymers as protection against ionizing radiation. The protecting effect can be improved by the addition of fillers. Heavy metals (lead, tungsten, and enriched uranium) or their compounds are suitable as fillers for polymers which are to absorb γ-rays. The absorption of γ-rays of different energies by lead-filled sheets of epoxide resin was discussed. Lithium-, boron-, cadmium-, and gadolinium compounds are suitable for the capture of thermal neutrons. Thus boron carbide and cadmium oxide are used as fillers for epoxide resins. Fast neutrons must be slowed down to thermal energy before they can be absorbed. Compounds of high hydrogen content (water, polyethylene) serve this purpose. Finally, possibilities for improving the stability of polymers to irradiation were discussed. Aromatic rings improve the stability, aliphatic ether groups and aliphatic double bonds have the opposite effect.

R. C. Schulz (Mainz, Germany) reported on the ionic polymerization of acrolein. As monomeric acrolein contains two groups capable of polymerization (vinyl and aldehyde group) which are conjugated, chemically and physically different polymers can be obtained, according to the nature of the catalysts and the reaction conditions. Radical catalysts cause only polymerization of the vinyl group, yielding polymers which possess very reactive aldehyde groups in the side chains



The use of ionic catalysts leads to polymers which contain both carbonyl and vinyl groups and which differ in their physical properties from the radical polymers. Their structure can be represented by formula *(12)*.



(12)

The ratio x:y can be varied widely by altering the catalyst and the conditions of polymerization. Solvents exert a considerable influence on the chemical structure of the polymers. The copolymerization of acrolein with vinyl compounds can be carried out with radical and with ionic catalysts. A new method was developed by which cross-linked polymers are obtained in two consecutive stages. The method is called two-stage copolymerization and is carried out as follows: a mixture of acroleine and styrene, for example, is converted into an unsaturated polymer of the type *(12)* by an ionic catalyst (*e.g.* sodium methoxide) acting selectively on acroleine; the styrene serves only as solvent. On addition of a radical catalyst, the styrene is copolymerized with the polyacroleine in a second step. The dimer of acroleine, 2-formyldihydropyrane, can be polymerized by ionic catalysts at the vinyl ether group and at the aldehyde group.

[VB 878/187 1E]
German version: Angew. Chem. 77, 221 (1965)

Symposium on Radiochemical Methods of Analysis

The "Symposium on Radiochemical Methods of Analysis" of the International Atomic Energy Agency (IAEA) was held in Salzburg (Austria) from October 19th to 23rd, 1964 and was attended by more than 300 participants from 25 countries in Europe and overseas. About sixty papers [*] covering the potentialities, importance, and fields of application of radiochemical methods of analysis were red.

H. Spenke, Vienna (Austria) reported on a method for the non-destructive determination of boron in steel from measurements of ^{59}Fe activation, which is inversely proportional to the boron content of the steel, owing to the high neutron capture cross-section of ^{10}B. A boron content of 0.1 % diminishes the activation of ^{59}Fe by 10 %. The limit of detection is 0.008 % B. The distribution of the boron can be determined by autoradiography.

The use of activation analysis in deciding the age of paintings by determining the trace elements in white lead pigments was described by *J. P. W. Houtman*, Delft (Holland). The nature of the impurities in white lead varies with the method used for purification of the lead. These methods were changed in the middle of the 19th century, so that the contents of Ag, Hg, Zn, and Cu can show whether a given sample of white lead was produced before or after 1850. Even if very small quantities are used, activation analysis can also give some indication of the Co, Cr, Ba, and Sb contents. Precipitation and extraction methods were used in the separation procedures required.

H. Stärk, Munich (Germany) dealt with the determination of Ta and W in niobium by activation analysis. Neutron activation leads to the short-lived isotope ^{94}Nb. After this has disappeared, the desired nuclides ^{182}Ta and ^{187}W can be readily determined without chemical separation by γ-spectroscopy, even in niobium of high purity.

The numerous difficulties encountered in the determination by activation analysis of traces of Cu, Zn, As, Sb, and Au in high-purity indium for semiconductor junctions were described by *J. V. Jakovlev* (USSR). Separation from the high-activity matrix is achieved quickly and readily by continuous extraction with isopropyl ether of a solution of the activated sample in 4.5 N HBr. The individual impurities were separated by distillation, extraction, or precipitation. After activation of a 100 mg sample for 12 h at a flux of 8.7×10^{12} neutrons/cm², the five trace elements could be determined to levels as low as 10^{-6}–10^{-8} %. Difficulties resulted mainly from the high activity and the marked self-shielding effect of the matrix.

Ch. Engelmann, Saclay (France) described the determination of oxygen, carbon, nitrogen, and other impurities in beryllium, calcium, sodium, and boron by means of γ-activation with a linear accelerator (28 MeV electrons). Extensive automation of the counting setup resulted in non-destructive analyses with sensitivity limits of 1–100 ppm. For the determination of very small amounts of oxygen, carbon, fluorine, and other light elements, particularly in materials of high purity (for semiconductors), use was made of (p,n), (p,α), and (p,pn) reactions in the cyclotron. Sensitivities were then increased to a lower detection limit of 0.001 ppm.

Sources of error in both quantitative and qualitative γ-spectroscopy were pointed out by *W. S. Lyon*, Oak Ridge (U.S.A.). Because of the number and complexity of effects which may distort the spectra, automatic analyses depending solely on γ-spectroscopy are highly liable to disturbances. Topics of discussion were: the dependence of the spectra on the geometrical arrangement of the detector and source, possible influences on spectra from Bremsstrahlung, reactions of high-energy γ-quanta with the shielding walls, and possibilities for the recognition and elimination of sources of error.

[*] The papers and verbatim reports of the discussions will be published by the IAEA.

The analytical scope of polydimensional γ-spectroscopy was investigated by *R. W. Perkins*, Richland (U.S.A.). The measuring device (impulse height analyser with 4096 channels) consisted of an anticoincidence screen and large detectors in order to maintain a low background radiation and to obtain maximum gain. The wide applicability of the method was illustrated by examples of the direct determination of radionuclides in mixtures: these included the direct determination of ^{22}Na, ^{60}Co, ^{88}Y, and ^{134}Cs in fall-out samples and the quantitative estimation of ^{64}Cu, ^{72}Ga, ^{76}As, ^{140}La, ^{140}Ba, ^{124}Sb, and ^{60}Co in reactor water.

S. Amiel, Yavne (Israel), showed how non-destructive determination of small quantities of a radionuclide in other high-activity material can be carried out if the nuclide in question emits high-energy γ-quanta. The method is based on the expulsion of photoneutrons from beryllium and deuterium by energies of 1.67 and 2.23 MeV, respectively. Since relatively few radionuclides have sufficiently high γ-energies, the method has a high inherent selectivity, even when only a determination of the half-life is used for the identification of an isotope. The measuring arrangement consists of a beryllium chamber or a D_2O container to hold the material under investigation, which is surrounded by a circular array of $^{10}BF_3$ neutron counting tubes. The error of the method is about ± 2 %; the detection limit is 1–100 μg.

New techniques of radiometric titration were reported by *E. Körös*, Budapest (Hungary). In radiocoulometric titration, the titrant is not added from a burette but is produced by electrolysis in solution. Here the analytical solution or the electrodes or both can be labelled. The course of radiometric titrations can be followed either by conventional procedures or by observations of β-absorption or reflective scattering. Both procedures have the advantage that it is possible to use an enclosed radiation source and thus to minimize sources of danger and to reduce licensing difficulties.

The technique of determining elements by addition of sub-stoichiometric quantities of reagent was described by *J. Ružicka*, Prague (ČSR) using iron as an example. The sample for analysis and an Fe standard are irradiated simultaneously and then the same quantity of iron carrier is added to both, followed by equal sub-stoichiometric quantities of cupferron to convert part of the iron into the Fe(III)-cupferron complex, which is extracted with chloroform; in this way it is unnecessary to determine the chemical yield. The iron content (Y) of the sample is calculated from the equation $Y = Y_S \cdot a/a_S$, where Y_S is the iron content of the standard and a and a_S are the activities of the chloroform extracts from the solutions of the sample and standard, respectively. For theoretical reasons, this method of analysis should have a much higher selectivity than the conventional method where excess reagent is added.

T. Florkowski, Cracow (Poland) described the determination of Fe, Zn, and Cu in ores by X-ray fluorescence analysis. He used Bremsstrahlung from a $^{3}H/Zr$ source and either a proportional counter with a Be window or a Geiger-Müller counter depending on whether measurements were to be made in the laboratory or at the mine. Sources of error such as the moisture content and the particle size and hardness of the sample were investigated, and the results of the method were compared with those of classical analytical techniques. The error in determinations of the Fe in iron ores with Fe contents of 0–40 % was from ± 0.2 to ± 0.5 %; the time required for completion of an analysis was 1–5 minutes. Important advantages of the method are rapidity and simplicity, and low investment and working costs for the measuring apparatus.

[VB 876/181 IE]

German version: Angew. Chem. 77, 220 (1965)

The Analytical Chemistry Division of the Gesellschaft Deutscher Chemiker together with the Chemistry Committees of the Gesellschaft Deutscher Metallhütten- und Bergleute, of the Steinkohlenbergbauverein, and of the Verein Deutscher Eisenhüttenleute, the Deutsche Arbeitskreis für Spectroskopie, and the Mass-Spectrometry Division of the Deutsche Physikalische Gesellschaft organized a lecture conference in Düsseldorf (Germany) from October 5th to 7th, 1964.

From the lectures:

The Detection and Analysis of Minute Amounts of Gas in Metals Using the Mass Filter

K. G. Günther, Nürnberg (Germany)

The accepted method for determining minute residual contents of gas in metals is that involving the hot extraction procedure. The sample of metal is heated in a graphite crucible *in vacuo* to expel any occluded gases. The most sensitive analytical instruments applying this principle can detect gas contents of down to about 0.1 ppm. Attempts to increase this sensitivity have so far failed because some of the gas is adsorbed in the apparatus or because the desorption of foreign gas layers is superimposed.

In order to lower the residual gas level and to avoid interfering adsorption phenomena, the entire analytical and extraction equipment was enclosed in an ultrahigh-vacuum container and put into operation only after a preliminary hot degassing cycle. The metal samples are heated by bombardment with electrons. A Bayard-Alpert vacuum gauge is used to measure the total pressure, and an electrical mass-filter is used to measure the partial pressure; the ion source required for the mass filter is placed in the immediate vicinity of the sample crucible. This instrument can be used to detect residual gas contents down to roughly 10^{-3} ppm at partial pressures in the range of 10^{-10} mm. A built-in chamber for holding samples permits the analysis of ten individual specimens in a single run. The gaseous fractions are estimated and analysed during their release from each sample. Changes in the individual partial pressures with time can be used to determine the composition of the gas and detect its supposed source (from regions in the vicinity of the surface, trapped gas-bubbles, or uniformly dissolved gases). By coupling the instrument with an oscillograph, short-lived eruptions of gas can also be detected and analysed. Examination of sample surfaces subjected to various different treatments showed that below 0.1 ppm the amount of gas adsorbed onto the surface can be much higher than that dissolved in the bulk of the material.

Detection of Non-Metals in Metals by Mass Spectroscopy

H. Hintenberger, Mainz (Germany)

There are two main techniques used in this procedure: hot extraction coupled with detection of the extracted substances by mass spectroscopy, and solid-sample mass spectroscopy using a spark-ion source.

Mass-spectroscopic analysis during hot extraction greatly increases the sensitivity of this method and enables the course of the degassing processes to be followed in detail. However, the isotope-dilution technique is even better for quantitative analysis of hot-extracted gases; this adaptation was tested particularly for the estimation by mass spectroscopy of oxygen in metals. The sensitivity of the detection of the inert gases is comparable to that of radioactive scaling methods.

Solid-sample mass-spectroscopy can be used to detect most elements in amounts between 10^{-3} and 1 ppm. In principle, it can be used to detect non-metals in metals as well as for the detection of metallic impurities. The detection limits for the various elements depend on the nature of the spectrum in the neighborhood of the lines to be examined. In general, with hydrogen, carbon, nitrogen, and oxygen, a decrease in the sensitivity of detection is to be expected owing to the background of fragmentation ions from impurities. Moreover, with these elements, interferences are caused relatively frequently by overlap of lines due to multicharged ions from the main elements in the samples. However, with elements of higher atomic weights, limits of detection in the region of 10^{-3} to 1 ppm can generally be achieved for non-metals as well, although errors of a factor of 2–3 are still unavoidable. At present, solid-sample mass spectroscopy using spark-ion sources can be regarded as a semi-quantitative analytical procedure of extremely high sensitivity which with a single measurement gives a good survey over all the impurities present in a metal.

The Estimation of Metallic Nickel and Nickel Oxide in Metallurgical Products

G. Kraft, Frankfurt/Main (Germany)

Halogen/methanol mixtures were found to be unsuitable, of metallic nickel and NiO were examined: the Cl_2/CH_3OH method, the Br_2/CH_3OH method, the chlorine-gas method, and the $Ag/CNS^{\ominus}$ method.

Halogen/methanol mixtures were found to be unsuitable, because they dissolve not only metallic Ni, but also some NiO; although both are dissolved at different rates, the amount of oxide dissolved was never below tolerable limits. The chlorine-gas procedure was also rejected because neither Ni nor NiO was converted into the chloride.

Completely satisfactory results were achieved with the $Ag/CNS^{\ominus}$ procedure; here a solution of AgCNS buffered at pH 5.0 with sodium acetate and containing excess NH_4CNS was used. However, the analytical sample must be pulverized to a grain size of less than 0.06 mm. Nickel is completely dissolved out of such powdered samples within 2 h at 36 °C; NiO is not attacked. After separation in this way, the components can be estimated by known procedures. The accuracy of the estimation is about ± 2% for both phases in 50 mg samples. Metallic iron, Fe_2O_3, and Fe_3O_4 do not interfere.

Advances in the Determination of Oxygen, Hydrogen, and Nitrogen in Metals

T. Kraus, Balzers (Liechtenstein)

In order to secure as rapid an analysis as possible of the carbon monoxide/nitrogen/hydrogen mixtures released on melting metallic samples in a graphite crucible *in vacuo*, a detector/recorder system is required which responds with practically no time lag and which delivers specific measurements directly from the gaseous phase without separation of the component gases. The most suitable solution to this problem incorporates measurement of the total pressure in a given volume in combination with heat conductivity and infrared absorption measurements [1].

The gas released in the vacuum melting furnace is pumped off very quickly under high vacuum (the final pressure being very low) and is collected in a pre-evacuated measuring cell; the total pressure is recorded continuously. When it is evident from the curve that the sample has been completely degassed, the analysis system is switched on and the analysis

[1] These three parameters are measured in the "Exhalograph" instrument manufactured by Balzers AG., Balzers (Liechtenstein).

proceeds automatically. To simplify interpretation of the results and to improve the sensitivity of the measurements, hydrogen is admitted into the measuring cell until a preselected total pressure has been attained. Since the previous measurements of the total pressure have already given the total amount of $H_2 + N_2 + CO$, heat conductance is now used to determine the partial amount of $N_2 + CO$ and the infrared absorbance to estimate the CO content; the amounts of hydrogen and nitrogen present are then calculated by difference. The accuracy of the hydrogen analysis can be increased even further by waiving an accurate nitrogen determination and using nitrogen instead of hydrogen to fill up the measuring cell. The heat conductance measurement then gives the amount of hydrogen alone.

Investigations by *A. Gerhardt* have shown that in the method described above, the error in the estimation of the three gases increases approximately linearly with the amount of gas released. The lower limits of detection are about 0.4 mm^3 (S.T.P.) for CO, about 1.3 mm^3 for N_2, and about 0.5 mm^3 for H_2. For 1 cm^3 of gas, the relative mean error for a single measurement is about $\pm$ 0.6 % for CO, about $\pm$ 0.2 % for N_2, and about $\pm$ 0.25 % for H_2. Hence this method provides a means of carrying out measurements not only very rapidly, but also with great accuracy.

Radioactive Nuclides for Investigating Physicochemical Processes in Graphite Electrodes during Excitation in an Electric Arc

H. Nickel, Jülich (Germany)

The combustion of graphite electrodes containing boron in a d. c. arc leads to the formation of boron carbide in the anode, independent of the working gas and of the nature of the boron compound in the graphite. The evaporation behavior, the losses resulting from fractionated evaporation and diffusion, and the distribution of material in the anode pellet after the electrodes were burned out were studied. For lack of a suitable radioactive boron isotope, ^{59}Fe was used as tracer. It could be shown that the boron is transported towards the burning surface of the anode, *i.e.* into the hot zone, during the electric discharge. Graphite electrodes doped with ^{59}Fe were used to study the influence of various parameters, *e.g.* the form of the counter-electrode or the dynamics of the working gas, on the evaporation properties of the iron. It was found that considerable amounts of the iron leaving the anode were deposited on the counter-electrode and that some of this material returned to the excitation zone via cathodic evaporation.

Estimation of the Oxygen in Uranium Carbides by Hot Extraction

H. Nickel and *J. Rottmann*, Jülich (Germany)

Nuclear fuels based on uranium carbide are of great interest for high-temperature reactors. The utility of these ceramic materials as nuclear fuels depends *inter alia* on their oxygen content, which influences their compatability with the coating of the fuel elements and their phase diagram. Comparative experiments on the estimation of oxygen in uranium carbides using the hot extraction method were carried out applying both the vacuum and carrier-gas techniques. It was found that the vacuum extraction is better than the carrier-gas method. Of the bath metals examined (iron, cobalt, nickel), cobalt used at 1900–2000 °C proved to be most suitable. The samples to be analysed were added in small pieces to the bath; powders were unsuitable because of the segregation of graphite in the baths.

Structures and Chemical Properties of Nitrides in Ternary Iron Alloys

K.-H. Sauer, Düsseldorf (Germany)

In order to estimate the nitrogen in metals after dissolution of the sample with acid, it is important to know which compounds of nitrogen occur in steels and how they react with non-oxidizing acids. For this reason, pure binary alloys of iron were produced and annealed in a stream of ammonia at 1000–1200 °C. The ammonia decomposes largely into its elements at this temperature and the nitrogen formed diffuses rapidly into the alloy. The nitrides formed in this process were separated from the nitrated layers by electrolytic isolation, and their structures and chemical properties were examined. Pure nitrides of chromium, aluminum, titanium, vanadium, zirconium, niobium, tantalum, and boron – silicon nitrides form exceptions – are dissolved by acid or by sulfuric acid plus bisulfate, and the nitrogen transformed quantitatively into the ammonium salt. The bromine-ester procedure makes it possible to distinguish between the nitrogen dissolved in the metal lattice, that originating from iron nitride, and that originating from alloying elements.

Determination of Traces of Impurities in Highly Purified Germanium(IV) Chloride and Germanium(IV) Oxide

E. Wunderlich and *E. Göring*, Goslar (Germany)

In analyses of the impurities in germanium, to date it has been common practice to remove the germanium from its compounds by volatilizing it off as $GeCl_4$ by evaporating a sample with hydrochloric acid in the presence of nitric acid, and then to determine the impurities in the residue, taking a separate portion for every trace element. The concentrations of the impurities generally lie below 0.5 ppm. The most important elements are As, Fe, Cu, and Ni. They can be determined in one sample (with extensive recovery of the Ge contained in the sample) in the following manner: A 50 ml sample of $GeCl_4$ is shaken with 10 ml of 6 N HCl containing bromine. The As, Fe, Cu, and Ni are taken up quantitatively into the hydrochloric acid phase. Alternatively, 50 g of GeO_2 are decomposed with pure hydrochloric acid in the presence of nitric acid in a closed apparatus. The $GeCl_4$ is distilled off and the residual germanium-free solution evaporated to dryness. Separations: The As is extracted from the brominated hydrochloric acid solution (d = 1.19) with benzene; the iron is extracted from 6–7 N HCl solution with isobutyl methyl ketone; the copper is extracted from 0.5 N HCl solution with dithizone in CCl_4; the nickel remains in the aqueous phase. About 0.05–0.1 ppm of these impurities can be determined. About 98 % of the germanium can be recovered from the $GeCl_4$, and about 90 % from the GeO_2.

[VB 867/170 IE]

German version: Angew. Chem. 77, 267 (1965)

Symposium on Magnetic Nuclear and Electron Resonance

This symposium was held at Freiburg/Brsg. (Germany) from October 22nd to 23rd, 1964. It was arranged by the Chemische Institut der Universität Tübingen and by the Institut für Elektrowerkstoffe der Universität Freiburg, with the support of the Wirtschaftsministerium of Baden-Württemberg.

A. Mannschreck, Heidelberg (Germany), spoke on the determination of the structure of organic compounds in solution using proton resonance spectroscopy. Caused by fine-structure effects, extreme chemical shifts can occur, *e.g.* in the methyl protons of 15,16-dimethyl-15,16-dihydropyrene (τ = 14.2 ppm), in the methylene protons of 1,6-methanocyclodecapentaene (τ = 10.5 ppm), in the β-proton of dimethyl *trans,trans*-muconate (τ = 1.8 ppm) or in the methyl proton of diphenylmethyl hexafluoroantimonate (τ = 0.3

ppm). Splitting by spin coupling was illustrated for the spin systems AB (AX), AB_2 (AX_2), A_2B_2 (A_2X_2) and A_2X_3.

The structure determination by proton resonance was discussed on selected examples: *e.g. N*-methylisoindole is protonated and deuterated in 2-position by sulfuric acid. The *cis-trans* equilibrium of *N*-methyl-*N*-benzylmesitylcarboxamide in CCl_4 was derived from the PMR spectrum. Finally, structure determinations of isothiazoles and the deuteration of thiamine were discussed.

According to *H. Kessler*, Tübingen (Germany), proton resonance allows the investigation of reversible intramolecular isomerizations. The rate constants and the energies of activation were determined in proton exchange reactions. Isomerizations by internal rotation were discussed on the example of acid amides possessing partial double bond character; polar solvents increase the participation of polar structures and thereby the energy of activation of the inversion. For acid amides the energies of activation are 10 kcal/mole and for their *O*-protonated modifications 13 kcal/mole. Examples were given of *cis-trans*-isomeric rotamers in the classes of nitrosamines, nitrites and methyl diazotate. Ring inversions were demonstrated on cycloheptatriene (energy of activation 6.3 to 9.2 kcal/mole, depending on the substituent). Valence-bond tautomerizations were described for benzonorcaradiene and homocycloheptatriene.

N. C. Franklin, Tübingen (Germany), dealt with the conformations of substituted cyclohexanes. Caused by the difference of energy between chair and boat forms of cyclohexane, separate PMR signals appear at low temperatures for the equatorial (e) and axial (a) protons of the chair form. Splitting of the signals by spin coupling depends upon the conformation ($J_{a,a} \approx 11.5$ cps; $J_{a,e} \approx 4$ cps; $J_{e,e} \approx 3$ cps). Conformational equilibria can be determined from the band widths (ω):

$$K = \frac{\omega_a - \omega}{\omega - \omega_e}; \quad \omega_a = 2(J_{a,a} + J_{a,e}); \quad \omega_e = 2(J_{e,a} + J_{e,e})$$

Nitrocyclohexane, 2-methylcyclohexylamine and di-t-butylcyclohexanoles were investigated.

B. Dischler, Freiburg (Germany), discussed the principles and methods of analysis of NMR spectra. Spectra of the types AB (AX, A_2), AB_2 (ABX, AX_2, A_3) and A_2B_2 which can be evaluated without any or with very simple calculations were treated systematically (equations for their evaluation were given). The analysis of spectra from more complicated spin systems (A_2BX, ABC, A_2B_2C) was then discussed. The analysis of the A_2B_2X spectrum of *p*-fluoronitrobenzene was achieved by dividing it into two A_2B_2 spectra. In the case of the ABC spectrum of 1,2,4-trichlorobenzene and of the AB_2C_2 spectrum of pyridine, the measured and calculated spectra were compared. The method of iteration was explained for the calculation of A_2B_2C systems. The sign of the coupling constant of α,β-dibromopropionic acid (ABC type) was determined by experiments using double resonance and from the doubly-quantized spectrum.

H. Dreeskamp, Stuttgart (Germany), spoke on the magnitude and sign of indirect nuclear spin interaction and its dependence on angles and substituents. The coupling constant J was defined and the normalized coupling constant J' was introduced.

The coupling constants of the hydrides of Group IV elements, XH_4, were measured. Here, all coupling constants J'_{X-H} are positive. The relation between J_{CH} and $E_X \cdot R_{CX}$ (E_X = electronegativity of X; R_{CX} = distance CX) in compounds CH_3X with different substituents X gives: $J_{C-H} > 0$. The silanes $^{29}SiH_x(CH_3)$ from x = 4, y = 0 to x = 0, y = 4 and the stannanes $^{117/119}SnH_x(CH_3)_y$ were investigated. It was found that $J_{Si-C-H} < 0$ and $J_{Sn-C-H} < 0$. When $K = J_{X-C-H}/J_{X-H}$ is introduced, a correlation between K and J_{C-H} can be found from which the sign of the coupling constant can be derived.

A. Saupe, Freiburg (Germany), discussed NMR spectra of orientated molecules. Molecules can be orientated in an electrical field, in clathrates and on expanding surfaces, and particularly in crystalline liquids (*e.g.* nematic *p*-azoxyanisol) at higher temperatures. The following spectra were measured: 1,2,3,5-tetrachlorobenzene in di-*p*-heptoxyazoxybenzene at 82 °C, 1,3,5-trichlorobenzene in di-*p*-hexoxyazoxybenzene at 80 °C and 170 °C, [*carboxyl*-D]-*p*-chlorobenzoic acid in [*carboxyl*-D]-*p*-butoxybenzoic acid at 144 °C, and 1-methoxy-2,3,4,6-tetrachlorobenzene in di-*p*-heptoxyazoxybenzene at 92 °C. The PMR spectrum of benzene in di-*p*-hexoxyazoxybenzene was particularly impressive. Here, due to direct dipole-dipole interactions, 50 lines of the benzene spectrum (which theoretically has 78 lines) can be observed. With growing number of protons the spectra of orientated molecules soon become very complicated even if the protons are structurally equivalent.

Compared with the ^1H–NMR spectra, the NMR spectra of heavier nuclei are often simple (*e.g.* due to the large chemical shifts; $\tau_F \approx 700$ ppm), as *E. Fluck*, Heidelberg (Germany), pointed out. However, complications can arise with quadrupolar nuclei. NMR spectroscopy of the ^{11}B, ^{19}F, and ^{31}P nuclei is of particular importance in inorganic compounds.

Examples of ^{19}F resonance: The AB_2 spectrum of ClF_3 at 10 Mc at different temperatures proves an exchange of F atoms. In the case of the cyclic compound $(SONF)_3$, two stereoisomers are possible. The ^{19}F spectra of JF_5, SF_4, and R_3PF_2 at 30 Mc were discussed. The application of ^{19}F resonance to problems of bonding was shown: differences in electronegativity are related to chemical shifts. The ionic character of the Xe–F bonds in xenon fluorides was discussed.

Examples of ^{31}P resonance: The state of oxidation and the coordination number of phosphorus can often be determined from the chemical shift of the ^{31}P resonance (*e.g.* identification of $PCl_6^{\ominus}$ in solution). The chemical shifts in spectra of phosphorus compounds can be calculated from increments, provided that no fluorine is bound to phosphorus. The products formed in the reaction of $(C_6H_5)PCl_2$ with S_4N_4 were identified with the help of the ^{31}P spectrum. The spectrum of $(C_6H_5)_4P_4K_2$ was discussed and the reaction of $[(C_6H_5)_2P]_3N$ with $(C_6H_5)_2PCl$ was described. The $^{203(205)}Tl$ resonance spectrum of thallium ethoxide proves the molecule to be tetrameric.

Nuclear quadrupole resonance spectroscopy allows the determination of polarity, ionic character and double bond character of a bond from the nuclear quadrupole resonance coupling constant eQq [*W. Zeil*, Kiel (Germany)]:

$$(eQq)_{mole} = (1 - s + d - I - \pi/2) - (eQq)_{atom}$$

(s = % s-character; d = % d-character; π = % double bond character; I = % ionic character of the bond; Q = nuclear quadrupole moment; q = field gradient.)

The ^{35}Cl resonance spectrum of crystalline CCl_4 at about −180 °C shows 15 lines, because all Cl atoms in the crystal (Z = 4) are different. The eQq values of several alkyl halides were reported and the ionic character of the bonds was compared with values for the splitting of the hyperfine structure in microwave spectra in gases. The ionic character increased in the series R–I < R–Br < R–Cl (*e.g.* $CHCl_3$: eQq = 68.4 cps, 26.6 % ionic character. C_2H_5Cl: eQq = 66.0 cps, 28.2 % ionic character). Only the electron which is available for a covalent bond determines the quadrupole coupling constant, *e.g.* Cl_2: eQq = 108.95 cps, Cl: eQq = 109.74 cps, Cl^-: eQq = 0. It was shown that the CCl-, CBr- and CI-bonds in the acetylenes $(CH_3)_3X-C\equiv C-Cl$ (X = C, Si, Ge, Sn) and $H_3C\equiv C-Y$ (Y = Cl, Br, I) have strong double bond character (more than 50 %). In alkyltellurium halides and tellurium halides the Te-valence bipyramid has different electronegativities at the top and at the base.

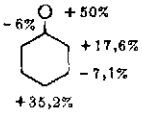
F. Gerson, Zurich (Switzerland), discussed simple ESR spectra of radical anions of benzene, naphthalene and

pyrazole, and the influence of molecular symmetry on the spectra of the radical anions of naphthalene and quinoline. The spin densities ρ_μ at the carbon atoms (μ) of aromatic radical anions are derived from the coupling constants a_μ for the proton attached to the C_μ atom, according to: $a_\mu = Q \cdot \rho_\mu$ ($Q \approx 23$ Gauss). Hückel's theory, *i.e.* the equation

$$\Psi^2 = \sum_\mu c_\mu^2 \Phi_\mu^2$$

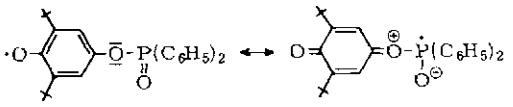
yields reliable results for the real spin densities, as shown for some radical anions of benzene and the acenes (relation between a_μ and $\rho_\mu = c_\mu^2$). The following ESR spectra were described: radical anion and radical cation of 1,3,6,8-tetraazapyrene, several dimethylnaphthalene anions, radical anions of 1,6-methanocyclodecapentaene and pyrrolo [2,1,5-*cd*]-indolizine, radical anion and radical cation of 15,16-dimethyl-15,16-dihydropyrene. The spectra allow the calculation of the electron densities in the molecules and thereby the direct measurement of the wave functions (*e.g.* position of orbitals in bridged perimeters). If the binding and anti-binding orbitals are symmetrical to the non-binding state, then the ESR spectra of radical cations and radical anions are equal (*e.g.* in phenanthrene).

According to ESR investigations on aroxyls by *A. Rieker*, Tübingen (Germany), splitting of the hyperfine structure (coupling with the nuclear momentum of the protons) allows one to decide whether or not the radical electron is located at the oxygen. The ESR spectra of pentachlorophenoxyl, 2,3,4,6-tetrachlorophenoxyl, 2,4,6-trichlorophenoxyl, 2,4,6-tris(diphenylmethyl)phenoxyl *(1)* and [1-^{13}C]-2,6-di-t-bu-



(1), $-CH(C_6H_5)_2$ at positions 2, 4, and 6

tyl-4-butoxyphenoxyl are characteristic. In the first example, the carbon atoms 1, 3 and 5 show negative spin densities; the spin density on the O atom is +50 %. Spin densities in positions 3 and 5 were determined for 2,6-di-t-butylaroxyls with 23 different substituents in position 4. Interestingly there is a linear correlation between the coupling constants a_H [cps] and the absorption maximum $\tilde{\nu}$ [cm^{-1}] of longest wavelength. Examples were given of comparative measurements on deuterated *p*-phenylphenoxyls, with the aim of clarifying more complicated spectra. Hetero-atoms between aromatic rings in aroxyls influence the ESR spectra, *i.e.* they carry finite spin densities [*e.g. (2)*].



(2)

Irradiation of organic single crystals (amino acids) often gives rise to long-lived radicals (years!) which, according to *G. Schoffa*, Karlsruhe (Germany), can be investigated by ESR spectroscopy. The anisotropy of the g-factor can be determined (*e.g.* in hematin). An irradiated monocrystal of betaine $[(CH_3)_3\overset{\oplus}{N}-CH_2-CO_2^{\ominus}]$ yields a 30-line spectrum, corresponding to the location of the unpaired electron in the trimethylammonium group (no further splitting by the methylene group). Analogously the fine structure of the ESR spectrum of *N*-acetylvaline showed the electron to be located in the isobutylidene group. Difficulties in these investigations often arise from the fact that several radicals are formed simultaneously in the irradiation of crystals.

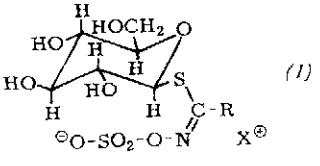
J. Schneider, Freiburg (Germany), reviewed the importance of electron spin resonance for investigations of the solid state. ESR of free conducting electrons in metals and semiconductors, of color centers in crystals, of donators and acceptors in semiconductors, of ions with 3d- and 4f-shells and of centers of luminescence was described. The F-centers, V_F-centers, V_K-centers and M-centers of alkali halides were discussed. The M-centers can be paramagnetic in the excited state. In silicon which possesses P, As, or Sb as donator, the donator level lies about 0.05 eV below the conductivity level, and at sufficiently low temperatures the interaction of the electron with the donator can be derived from the ESR spectra. Cr^{3+} in Al_2O_3, Nd^{3+} in CaF_2, Eu^{2+} in NaCl were mentioned as examples for the application of ESR spectroscopy to 3d- and 4f-ions. The spectra are influenced by the symmetry of the neighborhood of the ions. Centers of luminescence (acceptors in ZnS, CdS, or ZnO) are paramagnetic in the excited state and can, therefore, be examined by ESR spectroscopy, in particular when a high concentration of excited states can be achieved by excitation with a laser. [VB 877/183 1E]

German version: Angew. Chem. 77, 269 (1965)

Symposium on Isothiocyanates

The Chemical Society and the Biological Institutes of the Czechoslovakian Academy of Sciences, in conjunction with the Faculty of Chemistry of the Slovakian Technical University, Bratislava, organized a symposium on isothiocyanates from October 15th to 17th, 1964 in Smolenice Castle (ČSR). Over thirty lectures were given on syntheses, reactions, physicochemical properties, biological effects, and medical applications of isothiocyanates and of mustard oil glucosides (as the precursors of native isothiocyanates).

Mustard oil glucosides, *e.g. (1)*, form an interesting class of organic natural products; their structures were long the



(1)

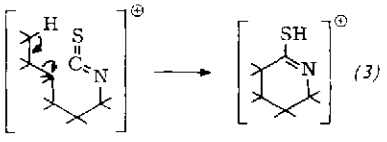
subject of much controversy, but they are now known with certainty to be substituted imino thioesters.

The formation of isothiocyanates from the glucosides is explained by an intramolecular rearrangement following enzymatic hydrolysis of the glucosidic linkage. Up to the present, about fifty glucosides with the same basic structure *(1)* but with different R groups are known; R can he a saturated or unsaturated aliphatic group, an unbranched chain with a hydroxyl or carbonyl funtion in the β- or γ-position and with methylmercapto, methylsulfoxy, or methylsulfonyl groups, and it can be aromatic, cycloaliphatic, or heterocyclic groups.

A. Kjaer, Copenhagen (Denmark) reported on the elucidation of the structures of isothiocyanates R'NCS of natural origin. Because of the extremely minute amount of material available combination of gas chromatography and mass spectrometry proved particularly useful. Isothiocyanates with unbranched R' chains had lines of mass number 72, which can be ascribed

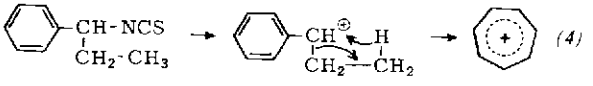
(2)

to the mesomerically stabilized ion *(2)*. All R′ groups with six or more carbon atoms can be recognized by lines originating from an ion *(3)* of mass number 115 formed by β-fragmentation and subsequent cyclization.



(3)

Araikyl isothiocyanates, *e.g. (4a)*, have a maximum at mass number 91, which is characteristic of the tropylium cation *(4)*. If the aromatic nucleus is substituted, then the fragment

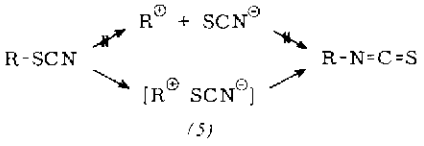


(4a) (4)

obtained is a benzylium cation. The ion $CH_3-S-CH_2^{\oplus}$ of mass number 61 is formed from all ω-methylthioalkyl isothiocyanates.

One particularly interesting mustard oil glucoside, which presumably occurs in all species of *Brassica* and *Raphanus*, is glucobrassicin investigated by *N. Kutáček* et al., Prague (ČSR); it is *(1)* with R = 3-indolylmethyl. It is thought to be the factor in cabbage species which gives rise to strumitis, for on enzymatic hydrolysis at pH 7, this glucoside yields to 3-indolylmethyl isothiocyanate, which immediately decomposes and releases the strumigenic thiocyanate ion. The 3-indolylmethylene cation formed at the same time is transformed by ascorbic acid in the cabbage into ascorbigen. The biosynthesis of glucobrassicin proceeds via tryptophan; the tryptophan content of plants – particularly barley – was found to be augmented by the presence of Zn^{2+} but reduced by irradiation. When young cauliflower plants were grown in an atmosphere containing $^{35}SO_2$ (1.7 mC/l) while being irradiated with a 500 watt lamp, labelled glucobrassicin was later detected by paper chromatography, and $^{35}SCN^{\ominus}$ was found after enzymatic hydrolysis with myrosinase. These results deserve particular consideration in view of the high SO_2 concentrations in the atmosphere around industrial areas.

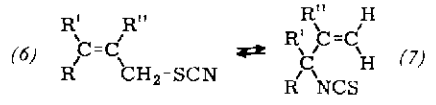
The mechanism of the isomerization of thiocyanates to isothiocyanates was discussed by *A. Fava*, Perugia (Italy). From the results of labelling experiments, it appears that the rearrangement of saturated aliphatic thiocyanates cannot be regarded as being due to a dissociation; instead, it proceeds via an internal ion pair *(5)*.



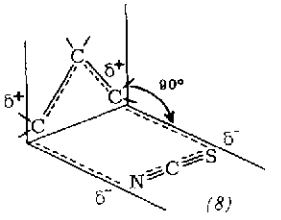
(5)

The effects of substituents and solvents on the kinetically controlled isomerization of allyl thiocyanates *(6)* are so slight that an intramolecular non-ionic transition state *(8)* seems to be involved.

If the carbon skeleton formed by the isomerization is less stable than that of the original thiocyanate, then the reaction yields only an equilibrium concentration of the isothiocyanate. This situation occurs for example in the transformation of γ-methylallyl thiocyanate [*(6)* with R = CH_3 and R′ = R″ = H] into α-methylallyl isothiocyanate [*(7)* with R = CH_3 and R′ = R″ = H], where a loss of hyperconjugative energy occurs when the methyl group becomes isolated from the double bond. Isomerization via

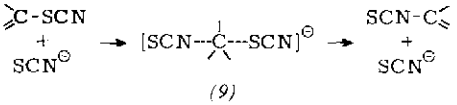


(6) (7)



(8)

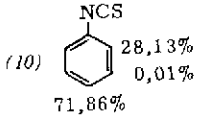
the ambident thiocyanate ion *(9)* by direct nucleophilic exchange occurs with primary thiocyanates (*e.g.* benzyl and benzhydryl isothiocyanates) which exhibit no tendency to ionize.



(9)

K. Antoš, Bratislava (ČSR) found that the reaction of thiophosgene with amines to give isothiocyanates does not occur when the amino group, like that in 9-aminoacridine, can participate in amino-imino tautomerism. Amino groups that are strongly hydrogen-bonded are also unable to react with thiophosgene. Thus, 2-aminoazobenzene reacts with thiophosgene only when an additional methyl group is introduced at position 3 in order to force the molecule into a conformation which is unfavorable for the participation of the amino group in hydrogen bonding.

A number of reports dealt with the structure and reactivity of the isothiocyanate group. Because of the values found for the dipole moments of *m*- and *p*-substituted phenyl isothiocyanates, especially the value for *p*-phenylene diisothiocyanate, which is very close to zero (0.009 D), *K. Antoš*, *A. Martvoň*, and *P. Kristián*, Bratislava (ČSR) assumed an approximately linear arrangement of the aromatic residue with the NCS group. An angle of 162°44′ was calculated for *p*-chlorophenyl isothiocyanate. The theoretical yields for the nitration of phenyl isothiocyanate *(10)* were calculated from the dipole moments of phenyl isothiocyanate (2.9 D) and of t-butyl isothiocyanate (3.73 D). Electrophilic substitution of aromatic isothiocyanates has not yet been achieved. It can bee seen from *(10)* that the isothiocyanate group exerts a −I effect comparable with that of halogeno substituents.



(10)

A. M. Kardos, Prague (ČSR) investigated the polarographic reduction of *m*-substituted phenyl isothiocyanates and found a linear correlation of the half-wave potentials and the σ_m constants of polar substituents with a slope of $\rho = 0.22$. Polarographic measurement of the kinetics of the addition of hydroxyl anion onto isothiocyanates in a water/methanol/dioxane system also gave a linear Hammett relationship between the logarithms of the rate constants and the σ_m constants with a slope of $\rho = 1.57$. *Š. Kováč*, Bratislava (ČSR) reported on the infrared spectra of a series of *m*- and *p*-substituted phenyl isothiocyanates in solvents of differing polarity. The vibrational frequencies of the NCS group and the integrated intensities of the absorption bands at 2100 cm^{-1}

gave a linear correlation with the Hammett σ constants. Accordingly, isothiocyanates containing electron-attracting substituents are supposed to have preferably the mesomeric structure *(11)* while those with electron-donating groups are given the structure *(12)*. The NCS group hardly participates in the mesomerism of the aromatic ring.

(11) *(12)*

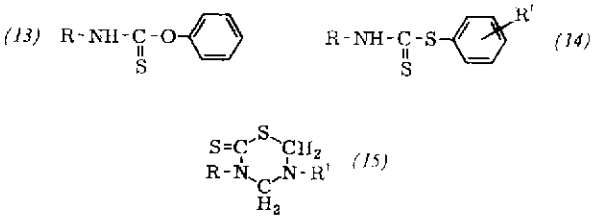
The Raman spectra of *p*-substituted phenyl isothiocyanates were discussed by *M. Pisárčik*, Bratislava (ČSR). All the spectra contain a broad absorption band at about 2100 cm^{-1}, a strong absorption at 1250 cm^{-1}, and a weak absorption at 927 cm^{-1}; the appearance of the first band is influenced by the nature of the substituents. The position of the maximum near 2100 cm^{-1} exhibits a linear dependence upon the Hammett σ_p constants with a negative tangential gradient. The value for the NCS group was found by extrapolation to be $\sigma_{p_{NCS}} = 0.34 \pm 0.09$.

Contributions to the relationships between the structure and the biological activity of isothiocyanates and to the mode of action of isothiocyanates upon cellular metabolism were made by *P. Kristián, Ľ. Drobnica*, and *P. Nemec*, Bratislava (ČSR). A linear correlation was observed between the biological activity (log ED_{50}; log ID_{50}) [*] of *m*- and *p*-substituted phenyl isothiocyanates and the values which characterize the reactivity of the NCS group (log k; σ) or a physical property of the complete molecule (logarithm of the molar solubility or of the partition coefficient). For example the bacteriostatic activity of isothiocyanates is determined by their reactivity. This can be described by a modified Hammett equation (a) in which τ_i and τ_r are measures of the biological activity of substituted isothiocyanates and of phenyl isothiocyanate, respectively, α is the tangential gradient, and β expresses the physical properties of the substituent [1]. The rate constants for the reaction of the isothiocyanates with glycine are taken as a measure of β.

$$\log (\tau_i/\tau_r) = \alpha \beta \qquad (a)$$

A case, in which the solubility determines the activity of the isothiocyanates, is the inhibition of the growth of yeasts. This can be explained by the difference in the structure of bacterial and yeast cells: in bacteria, the isothiocyanates react with the proteins and enzymes located in the cell walls, hence their antimicrobial activity is determined by their chemical reactivity. Their effect on the growth of yeast cells, on the other hand, requires that they first penetrate into the interior of the cell, so that their biological activity depends primarily upon their lipid solubility. *Ľ. Drobnica*, Bratislava (ČSR) and *T. Zsolnai*, Debrecen (Hungary) consider the antimicrobial activity of isothiocyanates to be due to their interference in protein and ribonucleic acid metabolism and their blockage of enzymes containing mercapto groups. It is assumed that the essential groups are blocked by isothiocyanates in the series $SH > NH_2 > OH$.

The occasionally high toxicity and pungency of isothiocyanates allow only limited medical application, *e.g.* as anthelminthics or for expelling trichophytosis. In this connection, the proposition of *A. Rieche* and *D. Martin*, Berlin (Germany) to synthesize simple compounds which liberate isothiocyanates under physiological conditions deserves consideration. Thus, synthetic isothiocyanate precursors modelled on the mustard oil glucosides were prepared; these have a broader range of application because they can be obtained in greater purity and can be dosed with precision; in addition, unlike the plant extracts containing mustard oil glucosides, these preparations contain no ballast materials. Suitable compounds for this purpose include *N*-monosubstituted thiocarbamidic esters *(13)*, dithiocarbamidic esters *(14)*, and 2-thionotetrahydro-1,3,5-thiadiazines *(15)*.



(13) *(14)*

(15)

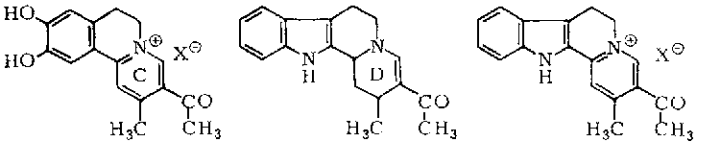
Compounds such as *(13)*, *(14)*, and *(15)* are practically non-toxic (LD_{50} = 2000 mg/kg in mice) and exhibit bacteriostatic, fungistatic, and virostatic activity in concentrations as low as 0.5–1.0 γ/ml. Optimum activity is obtained with *(13)* when R = phenethyl, with *(14)* when R = benzyl and R′ = *p*-chloro, and with *(15)* when R = benzyl and R′ = carboxymethyl. Compounds of type *(15)* have an aureomycin-like growth-promoting effect on young animals, according to investigations by *H. Haenel*, Berlin (Germany) and have a broad spectrum of application for fungal infections. According to *R. Narasimha*, Bangelore (India), the toxicity of isothiocyanates is strongly reduced in their bisulfite adducts without deterioration of their antimicrobial efficiency.

[VB 873/182 IE]
German version: Angew. Chem. *77*, 271 (1965)

Synthesis of Heterocyclic Compounds and Model Reactions of Alkaloid Biogenesis

H.-J. Teuber, Frankfurt/Main (Germany)

Dihydroxyphenylalanine hydrochloride reacts in water with acetoacetaldehyde dimethylacetal or 1-methoxy-1-buten-3-one to give the quaternary ammonium salt *(1)*; analogously, tryptamine hydrochloride yields a mixture of *(2)* and *(3)* [1].



(1) *(2)* *(3)*

X = Cl

These reactions proceed at almost neutral pH and are therefore in accordance with the hypothesis that acetic acid residues are used instead of aromatic amino acids of the phenylalanine type in the biosynthesis of indole alkaloids of the α-series [2]. Since ring D in *(2)* [or *(3)*] is built up

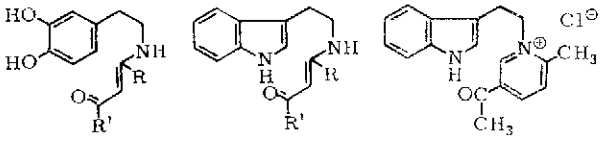
[*] ED_{50} = concentration (moles/l) which inhibits growth of microorganisms by 50 %; ID_{50} = concentration (moles/l) which inhibits metabolic processes by 50 %.

[1] See also *R. Zahradník* and *M. Chvapil*, Experientia *16*, 511 (1960).

[1] *H.-J. Teuber* and *U. Hochmuth*, Tetrahedron Letters *1964*, 325; *H.-J. Teuber* and *D. Laudien*, Angew. Chem. *76*, 534 (1964); Angew. Chem. internat. Edit. *3*, 507 (1964); *H.-J. Teuber*, *O. Glosauer*, and *U. Hochmuth*, Chem. Ber. *97*, 557 (1964).

[2] Review: *R. Robinson*, Pure appl. Chem. *6*, 601 (1963).

from acetate residues exclusively, it may be considered that the C_1 unit (formaldehyde equivalent) in indole alkaloids of the α-type is located in ring E and not in ring D [corresponding to a bridge between the CH_3-groups of *(2)* or *(3)*]. Preliminary tracer experiments seem not to preclude this possibility [3].



(4) *(5)* *(6)*

During attempts to convert acylalkenylamines of type *(4)* and *(5)* [R = H or alkyl, R′ = alkyl or aryl] into their hydrochlorides, they cyclized in a Pictet-Spengler-type reaction to yield derivatives of tetrahydroisoquinoline or tetrahydro-3-carboline with one or two substituents in the 1-position. These compounds can in turn be converted into heterocycles of the type *(1)–(3)* [*D. Laudien, Th. Raabe*]. Dihydroresorcinol condenses with tryptamine hydrochloride to give an acylalkenylamine analogous to *(5)*. Tryptaminobutenone *(5)*, R = H, R′ = CH_3, reacts with acids to form the pyridinium salt *(6)*.

[GDCh-Ortsverband Mühlheim/Ruhr (Germany), November 11th, 1964]

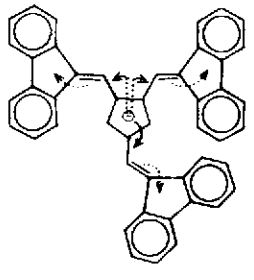
[VB 886/195 IE]

German version: Angew. Chem. 77, 224 (1965)

New Results in the Chemistry of Quasi-Aromatic Compounds

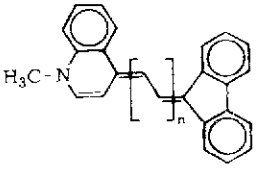
Ch. Jutz, München (Germany)

3,4-Bis-(9′-fluorenylidenemethyl)-6-(9′-fluorenyl)fulvene was prepared as red needles, m.p. 234.5 °C, *via* its anion *(1)*, λ_{max} = 588 mμ, log ε = 4.87, from 3,4-bis-(9′-fluorenylideneprethyl)-6-dimethylaminofulvene and fluorenyl-lithium. It moved to be the most acidic hydrocarbon known to date. In the anion *(1)*, the negative charge can be distributed over four cyclic π-sextets.



(1)

Related to the 9-aminofulvenes are the deep-colored heterologues of sesquifulvapolyene. Vinylogous 1-methyl-4(2)-fluorenylidene-1,4(1,2)-dihydroquinolines, *e.g. (2)*, were made by treating the corresponding polymethine salts with fluorene and sodium methoxide. Protonation of the 9-position of the fluorenyl residue with mineral acids gives rise to quinolinium salts.



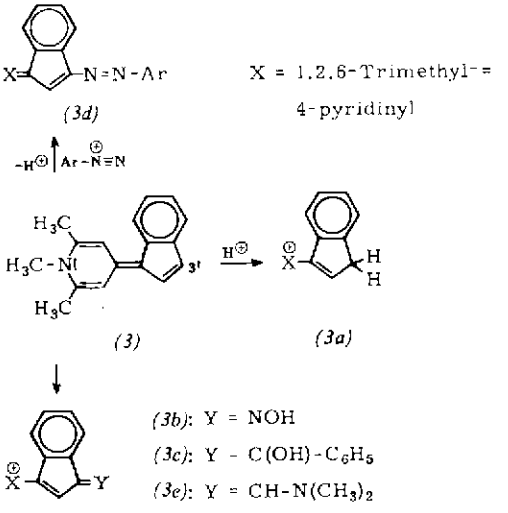
(2)

n = 0, 1, 2, 3

[3] Cf. the contradictory results obtained by *E. Leete* and *S. Ghosal*, Tetrahedron Letters *1962*, 1179, and by *A. R. Battersby, R. Binks, W. Lawrie, G. V. Parry*, and *B. R. Webster*, Proc. chem. Soc. (London) *1963*, 369.

A vinylogue of 1-methyl-4-cyclopentadienylidene-1,4-dihydropyridine with n = 3 was obtained similarly. It is a strongly basic, labile, blue compound.

1,2,6-Trimethyl-4-cyclopentadienylidene-(or-4-indenylidene-)1,4-dihydropyridine is a particularly good model for studying electrophilic substitutions in quasi-aromatic systems. The indenylidene compound *(3)* undergoes reactions at the 3′-position: protonation gives *(3a)*, nitrosation yields *(3b)*, benzoylation leads to *(3c)*, coupling with aromatic diazonium salts gives *(3d)*, and on substitution with dimethylformamide/phosphorus oxychloride one obtains *(3e)*; substitution with azastreptocyanin cations also occurs at the 3′-position.



(3d) X = 1,2,6-Trimethyl-4-pyridinyl

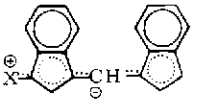
(3) *(3a)*

(3b): Y = NOH

(3c): Y = C(OH)-C_6H_5

(3e): Y = CH-$N(CH_3)_2$

Cyclopentadienylsodium or indenylsodium displace the secondary amino group in salts of type *(3e)* to form intensely colored merocyanins with a latent carbanionomethine structure *(4)*.



(4)

[GDCh-Ortsverband Düsseldorf (Germany), December 7th, 1964]

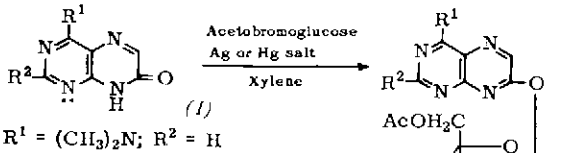
[VB 887/196 IE]

German version: Angew. Chem. 77, 224 (1965)

Syntheses of Heterocyclic O- and N-Glycosides

W. Pfleiderer, Stuttgart (Germany)

2-Amino-4-alkoxy-7-oxodihydropteridines are converted, on direct glycosidation under the conditions described by *Fischer* and *Helferich*, into 2-amino-4-alkoxy-7-glycosyloxypteridines [1]. Pteridine *N*(8)-glycosides were not obtained, even after varying the substituent on the pyrimidine moiety of the 7-hydroxypteridine skeleton. 4-Dimethylamino- *(1a)* [2], 2-amino- *(1b)*, and 2-dimethylamino-7-oxodihydropteridine *(1c)* in the form of their heavy-metal salts react uniformly with α-acetobromoglucose to yield the *O*-glycosides *(2a)–(2c)*.



(1)

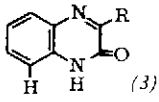
(a): R^1 = $(CH_3)_2N$; R^2 = H

(b): R^1 = H; R^2 = NH_2

(c): R^1 = H; R^2 = $(CH_3)_2N$

(2)

Similarly, 2-oxodihydroquinoxalines *(3)*, R = H, CH_3, C_6H_5, or $CO_2C_2H_5$, yield 2-glycosyloxyquinoxalines exclusively and in excellent yields on glycosidation by the silver- or mercury salt method.

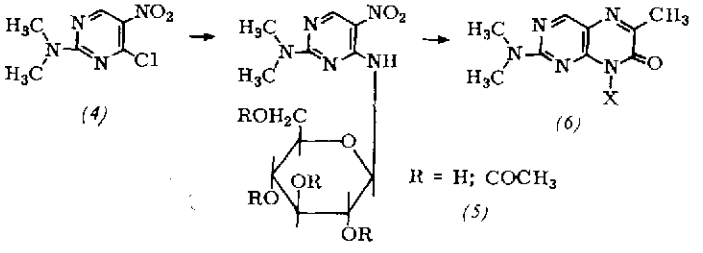


(3)

The selective *O*-glycosidation is explained by a steric inhibition of the *N*-glycosidation by the hydrogen atom on C-8 in *(3)*, and by the lone electron pair in *(1)*. This interpretation is supported by the facts that *O*-glycosides are not rearranged to *N*-glycosides by $HgBr_2$ [3] and that *O*- and *N*-trimethylsilyl derivatives of 2-oxoquinoxalines fail to react with halogeno sugars [4].

Pteridine *N*(8)-glycosides *(6)* may be obtained from 4-aminopyrimidine derivatives [2], or more advantageously by way of a novel route [5] from 4-chloro-5-nitropyrimidines and 1-amino sugars. In 4-chloro-5-nitro-2-dimethylaminopyrimidine *(4)*, the chlorine is readily substituted nucleophilically by 1-amino-β-D-glucose or its 2,3,4,6-tetraacetyl derivative in aprotic solvents.

Catalytic reduction of the 5-nitro group of *(5)* yields 5-amino derivatives, which are key compounds for condensations to pteridine *N*(8)-glycosides *(6)* (using C_2-units), to purine



(4) *(6)*

R = H; $COCH_3$

(5)

(7) *(8)*

N(9)-glycosides *(7)* (using C_1-units), and to triazolo[4,5-*d*]-pyrimidine *N*(3)-glycosides *(8)* (using nitrous acid).

Starting from 1,3-dimethyl-4-chloro-5-nitrouracil, we succeeded in synthesizing, by an analogous route, the first theophylline *N*(9)-glycoside [6]. In this case, steric factors again exert a decisive influence on the course of the reaction.

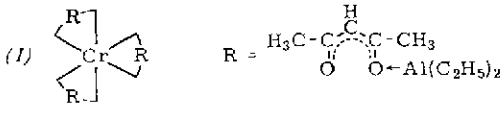
[GDCh-Ortsverband Tübingen (Germany),
December 11th, 1964] [VB 893/198 IE]
German version: Angew. Chem. *77*, 273 (1965)

[1] *W. Pfleiderer* and *R. Lohrmann*, Chem. Ber. *95*, 738 (1962).
[2] *W. Pfleiderer* and *D. Söll*, J. heterocyclic Chem. *1*, 23 (1964).
[3] *G. Wagner* and *H. Pischel*, Arch. Pharmaz. *295*, 373 (1962); *T. L. V. Ulbricht*, Proc. chem. Soc. (London) *1962*, 298.
[4] *L. Birkofer*, *A. Ritter*, and *H. P. Kühltau*, Chem. Ber. *97*, 934 (1964).
[5] *E. Bühler* and *W. Pfleiderer*, Tetrahedron Letters *1964*, 3007.
[6] *E. Bühler* and *W. Pfleiderer*, Angew. Chem. *76*, 713 (1964); Angew. Chem. internat. Edit. *3*, 638 (1964).

SELECTED ABSTRACTS

Monomeric FCN was obtained in over 50 % yield by *F. S. Fawcett* and *R. D. Lipscomb* by pyrolysis of $(FCN)_3$ at 1300 °C/50 mm. The trimer is passed through an electric arc, the reaction products are immediately quenched and trapped at the temperature of liquid nitrogen. Apart from FCN (m.p. −82 °C, b.p. −46.2 °C), F_3CCN, CF_4, C_2F_4, and other products are also formed. Liquid FCN polymerizes rapidly at room temperature to give $(FCN)_3$ and a high-melting substance that decomposes in water. In the gaseous phase at 1 atm and room temperature, some FCN is still present after a few weeks. FCN can be caused to explode. / J. Amer. chem. Soc. *86*, 2576 (1964) / −Kr. [Rd 124/311 IE]

Mainly 1,2-polybutadiene is formed from butadiene using the soluble complex catalyst *(1)* prepared from chromium acetylacetonate and triethylaluminum according to *C. E. H. Bawn*, *A. M. North*, and *J. S. Walker*. By varying the ratio of the



(1)

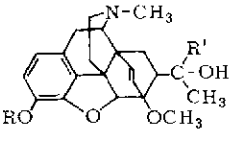
components and the ageing time of the catalyst, either syndiotactic or isotactic 1,2-polybutadiene or a mixture of both can be obtained. For example, with a molar ratio of triethylaluminum to chromium acetylacetonate of 11.6:1, a polymer was obtained at 30 °C, whose analysis by infrared spectroscopy indiciated it to contain 12 % *cis*-1,4- (15.8 μ), 18 % *trans*-1,4- (10.3 μ), and 70 % 1,2-linkages (11.0 μ). Freshly prepared catalyst yields exclusively syndiotactic 1,2-polybutadiene. The growth process is of the first order based on monomer. The number of active sites remains constant throughout the polymerization. / Polymer *5*, 419 (1964) / −Hl. [Rd 184/393 IE]

A simple method for the synthesis of chromium oxide trichloride, $CrOCl_3$, was discovered by *R. B. Johannesen* and *H.-L. Krauss*. It is formed by the reaction

$$6\,CrO_2Cl_2 + 4\,BCl_3 \rightarrow 6\,CrOCl_3 + 3\,Cl_2 + 2\,B_2O_3$$

in refluxing boron trichloride (−13 °C), nitrogen being passed through to carry off the chlorine produced. Excess BCl_3 and unreacted CrO_2Cl_2 are removed from the reaction mixture by vacuum distillation, and the remaining $CrOCl_3$ is then sublimed onto a cold finger at −30 °C. This is the first time that a homopolar Cr(V) compound has been obtained in good yield (50 %). / Chem. Ber. *97*, 2094 (1964) / −Gn. [Rd 165/352 IE]

Alcoholic derivatives of tetrahydro-6,14-endoethenothebaine have a high analgetic effect, according *R. E. Lister*. Although the parent opium alkaloid thebaine has no therapeutic action, some of its tetrahydro-6.14-endoetheno derivatives have activities which are far beyond that of morphium; compounds of type *(1)* have the best analgetic effects.

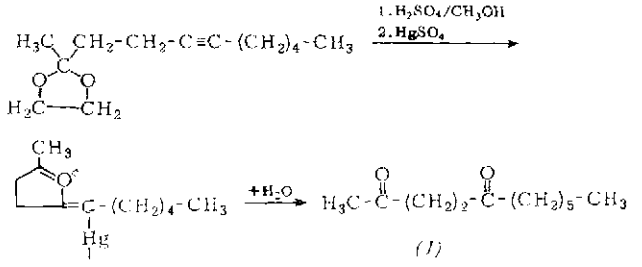


(1a), R = H, R′ = n-propyl
(1b), R = $COCH_3$, R′ = n-propyl
(1c), R = H, R′ = $(CH_2)_2$–$CH(CH_3)_2$

Their relative activities (morphium = 1) are 2060 for *(1a)*, 5330 for *(1b)*, and 7800 for *(1c)*, while their relative toxicities in rats are increased only by factors of 10.8, 16.7, and 27.5, respectively. These compounds therefore possess significantly better therapeutic indices than morphium. / J. Pharmacy Pharmacol. *16*, 364 (1964) / −De. [Rd 68/355 IE]

Complete separation of nucleoside monophosphates has been achieved by *K. Randerath* using two-dimensional thin-layer chromatography on cellulose impregnated with poly(ethyleneimine) which acts as an ion exchanger. Development with 1 N HCOOH in one direction and with 60 % ammonium sulfate in the other not only permits differentiation of AMP, GMP, CMP, UMP (TMP), and their deoxy derivatives, but also effects separation of isomeric purine 2'- and 3'-nucleotides. The separations require only 2 h. / Experientia (Basel) *20*, 406 (1964) / –Re. [Rd 132/319 IE]

1,4- and 1,5-diketones can be prepared from unsymmetrically substituted acetylenes containing a carbonyl group in the γ- or δ-position, according to *G. Stork* and *R. Borch*. The hydration of the triple bond catalysed by H_2SO_4 is directed by a neighboring group effect of the carbonyl group so that 1,4- or 1,5-diketones are produced. Undecane-2,5-dione *(1)*



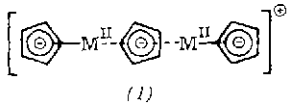
(1)

was obtained in an overall yield of 40 %. The hydration of undec-6-yn-2-one proceeds via a quasi-six-membered ring and yields exclusively undecane-2,6-dione. The formation of 1,5-diones proceeds much slower than that of 1,4-diketones. / J. Amer. chem. Soc. *86*, 935 (1964) / –Re. [Rd 90/360 IE]

Triple decker sandwich complexes derived from ferrocene and nickelocene were found by *E. Schumacher* and *R. Taubenest* during mass-spectrometric investigations of these compounds. The new complexes are presumably formed by ion-molecule association:

$$MCp^{\oplus} + MCp_2 \rightarrow [M_2Cp_3]^{\oplus} \quad (1),$$

where M = Fe or Ni, and Cp = C_5H_5, in the ion source of the mass spectrometer. Peaks with mass numbers which can be



(1)

assigned to mixed triple deckers, $[FeNiCp_3]^{\oplus}$, were also found. / Helv. chim. Acta *47*, 1525 (1964) / –Hz. [Rd 169/378 IE]

N,N-Dialkylhydroxylamines are formed by Michael addition of hydroxylamines onto activated C=C double bonds. *A. A. R. Sayigh, H. Ulrich*, and *M. Green* thus used Reactions (a) and (b) to improve the hitherto unsatisfactory methods of preparing *N,N*-dialkylhydroxylamines. The hydroxylamine hydrochlorides are dissolved in water or methanol with sodium carbonate and the solution of the vinyl component is added dropwise at room temperature over 30 min.

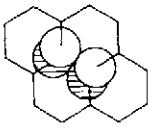
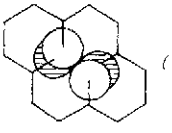
$$RCH{=}CH_2 + H_3CNOH \rightarrow RCH_2{-}CH_2{-}N(CH_3)OH \qquad (a)$$

$$2\,RCH{=}CH_2 + NH_2OH \rightarrow (RCH_2{-}CH_2)_2NOH \qquad (b)$$

Examples: Reaction (a): R = 2-pyridyl, 79 % yield; R = $SO_2C_2H_5$, 49 % yield; Reaction (b): R = 2-pyridyl, 61.5 % yield; R = $SO_2C_2H_5$, 88.5 % yield. With divinyl sulfone, Reaction (a) gives bis-2-(*N*-methylhydroxylamino)ethyl sulfone, m.p. 166–167 °C (74 % yield), and Reaction (b) gives 4-hydroxytetrahydro-1,4-thiazine-1,1-dioxide, m.p. 192–193 °C (85.5 % yield). / J. org. Chemistry *29*, 2042 (1964) / –Jg. [Rd 116/303 IE]

Emission-spectrometric analysis using intermittent beams from a laser for excitation of the samples was described by *E. F. Runge, R. W. Minck*, and *F. R. Bryan*. Here the laser beam is used instead of the conventional discharge or flame to evaporate and photoexcite the material for analysis. Each flash from the laser supplies an energy of 50–75 MJoules in 15–20 nanosec. The photocurrent intensity in the neighborhood of an optical image lies above 10^{13} Watts/cm². This technique brings the significant advantage that even non-conductors can be analysed; furthermore, the analytical sample can be enclosed in a vacuum or under an inert atmosphere. The reproducibility attained so far for quantitative analysis is about 95 %. / Spectrochim. Acta *20*, 733 (1964) / – Hz. [Rd 58/364 IE]

[14]-Annulene occurs as two conformers *(1a)* and *(1b)*; this is the conclusion drawn by *Y. Gaonis* and *F. Sondheimer* from its two sharp NMR signals at τ = 4.42 p.p.m. *(1a)* and τ = 3.92 p.p.m. *(1b)*. The conformers can even be separated by

(1a)   *(1b)*

thin-layer chromatography on silica gel impregnated with $AgNO_3$ and give ultraviolet absorption spectra with slightly different intensities (maxima and shoulders at 317 and 378–380 mμ, respectively). The equilibrium *(1a)* ⇌ *(1b)* depends on the temperature: 5.6:1 at 30 °C, 4.6:1 at 80 °C. X-ray analysis of the crystals at 20 °C indicates only a single molecular form, probably the centrosymmetrical conformer *(1a)*. The attainment of the equilibrium can be followed in freshly prepared solutions, *e.g.* by ultraviolet spectroscopy. / Proc. chem. Soc. (London) *1964*, 299 / –Jg. [Rd 161/348 IE]

Free-radical intermediates of Grignard reactions have been detected by *K. Maruyama*. When nitrobenzene or *p*-nitrosotoluene was mixed in a 1:1 to 1:5 proportion with phenyl- or *p*-toluylmagnesium bromide at –78 °C, the reaction solution

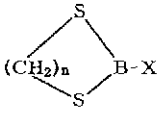
$$C_6H_5NO + C_6H_5MgBr \rightarrow C_6H_5{-}\underset{\displaystyle O^{\bullet}}{N}{-}C_6H_5 \quad (1)$$

$$C_6H_5NO + p\text{-}CH_3{-}C_6H_4MgBr \rightarrow p\text{-}CH_3{-}C_6H_4{-}\underset{\displaystyle O^{\bullet}}{N}{-}C_6H_5 \quad (2)$$

$$p\text{-}CH_3{-}C_6H_4NO + C_6H_5{-}MgBr \rightarrow p\text{-}CH_3{-}C_6H_4{-}\underset{\displaystyle O^{\bullet}}{N}{-}C_6H_5 \quad (2)$$

suddenly turned brown, and strong electron-spin resonance signals due to the free radicals *(1)* and *(2)* could be observed. / Bull. chem. Soc. Japan *37*, 1013 (1964) / –Kr. [Rd 123/310 IE]

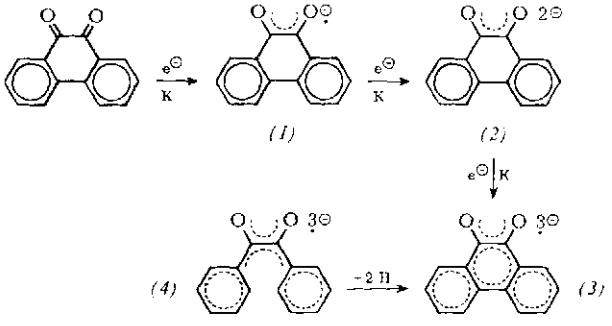
The production and properties of boron heterocycles containing sulfur are described by *A. Finch* and *J. Pearn*. Compounds of type *(1)* were prepared by adding suitable dithiols to BCl_3 or phenylboron dichloride in CH_2Cl_2 at –80 °C and allowing the mixture to warm up to room temperature. The heterocyclic products *(1)* are readily hydrolysed, and though sensitive to oxygen are stable at room temperature and resist heating at



(1) X = Cl, C_6H_5

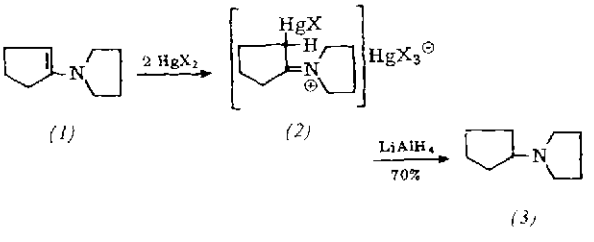
100 °C for several hours. Examples of *(1)* are 2-chloro-1,3,2-dithiaborolane (n = 2), b.p. 24–25 °C/0.1 mm (obtained in 88 % yield), 2-chloro-1,3,2-dithiaborinane (n = 3), b.p. 56–58 °C/0.2 mm (80 % yield), 2-phenyl-1,3,2-dithiaborolane (n = 2), b.p. 97–98 °C/0.1 mm (92 % yield), and 2-phenyl-1,3,2-dithiaborinane (n = 3), b.p. 109–110 °C (90 % yield). / Tetrahedron *20*, 173 (1964) / –Ma. [Rd 128/315 IE]

A novel radical trianion was obtained by *N. L. Bauld* on treatment of phenanthroquinone with potassium metal. The free-radical monoanion *(1)* formed first is transformed into the dianion *(2)* and finally into the free-radical trianion *(3)* by progressive addition of electrons. The product *(3)* is purple with λ_{max} = 555 and 410 mμ and behaves like a triacidic base on titration with acid. Its ESR spectrum shows a signal for the unpaired electron. The third electron is released very readily to reducible materials, with reconversion of *(3)* to the dianion *(2)*, which can be trapped in 70 % yield with benzoyl chloride in the form of 9,10-di-(benzoyloxy)phenanthrene. The trianion *(3)* is also obtained from the radical trianion *(4)* of benzil, which loses two of its *ortho*-hydrogens spontaneously from a *cis*-configuration.



Molecular-orbital calculations suggest that the two extra electrons in *(2)* are located in a non-bonding orbital of its 1,2-dioxo grouping. On the other hand, the third electron in *(3)* is supposed to be distributed in an orbital spread out over the aromatic rings with high spin density in the four positions *ortho* and *para* to the keto groups. The resolution of the ESR signals into 5 lines confirmed this hypothesis. / J. Amer. chem. Soc. *86*, 3894 (1964) / –Eb. [Rd 194/403 IE]

***C*-Mercuration of an alkenylamine** has been observed for the first time by *K. Broderson, G. Opitz*, and *D. Breitinger*. The tertiary alkenylamine pyrrolidinocyclopentene *(1)* was known from earlier studies by these authors to be highly reactive. When treated with HgX_2 in ether, it gives an amorpbous precipitate $C_9H_{15}N \cdot nHgX_2$, where n = 1.9 (X = Cl) or 2.0 (X = Br). The



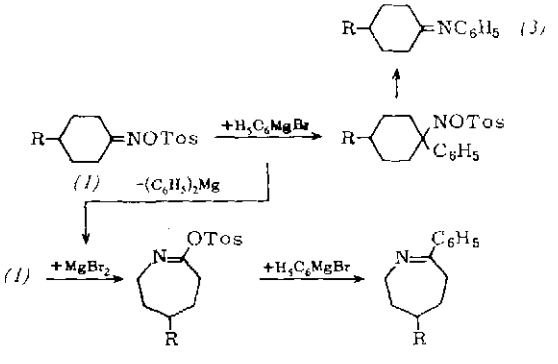
hypsochromic shift of the double-bond absorption from 1630 cm^{-1} in the alkenylamine to 1657 cm^{-1} in the adducts supports their formulation as *(2)*; confirmatory evidence is obtained from the reduction of the adducts, which affords *(3)*. Moreover, cyclopentanone should have been obtained by degradation of the product if it had been an *N*-mercurated compound, but no cyclopentanone could be detected. / Chem. Ber. *97*, 2046 (1964) / –Gn. [Rd 163/350 IE]

A synthesis of nitriles from α-chloro ethers and NaCN is reported by *P. A. Argabright* and *D. W. Hall*. Although α-chloro ethers do not react with NaCN or KCN in hydrocarbons or ethers, they react vigorously in other non-protonated solvents such as dimethylformamide or dimethylsulfoxide. Thus, for example, methoxyacetonitrile, b.p. 111 °C/624 mm, was obtained in 62 % yield from H_3COCH_2Cl and biscyanomethyl ether, m.p. 38–39 °C, in 30 % yield from bischloromethyl ether (crude yield 90 %) in this way. / Chem. and Ind. *1964*, 1365 / –Ma. [Rd 126/313 IE]

The mechanism of the end-product inhibition of aspartate transcarbamylase (ACTase) is described by *J. C. Gerhart* and *A. B. Pardee*. The enzyme from *Escherichia coli* is tetrameric (molecular weight = 250000) and consists of subunits with a molecular weight of 65000. The feedback inhibitor cytidine triphosphate (CTP) acts by strengthening the bonding between the subunits, thus decreasing the affinity of the enzyme for its substrate aspartic acid. The enzyme can be broken down into its subunits without loss of activity; the subunits cannot be inactivated with CTP. Adenosine triphosphate is a competitive antagonist of CTP. This mechanism is an example of the allosteric inhibition described by *Monod* [1], whereby the inhibitor becomes attached to a site on the enzyme which is remote from the site of attachment of the substrate. The inhibitor alters the conformation of the enzyme and thus decreases the affinity for the substrate. / Federat. Proc. *23*, 727 (1964) / –Hö. [Rd 190/399 IE]

An unusually high H/D isotope effect of 24.2 was discovered by *L. Funderburk* and *E. S. Lewis* for the proton transfer from 2-deuterio-2-nitropropane to 2,4,6-collidine as acceptor during iodination of the compound. This is a sterically hindered and therefore slow acid-base reaction which can be followed conveniently at room temperature by measuring (by spectrophotometry in butanol/water at 24.88 °C) the decrease in the concentration of the iodine, which is used up in a rapid reaction following the rate-determining anionization. This isotope effect lies above the highest observed to date (k_H/k_D = 16) and above the maximum permissible by the classical theory of absolute reaction rates ($k/_Hk_D$ = 17); the authors consider that it can be explained only by quantum mechanical tunnelling. It is known that compressional energies are strongly dependent upon alterations in the interatomic distances. Since the reaction investigated has a transition state which is essentially characterized by compressional energies, the energy profile must be narrow and very high. This is the ideal prerequisite for the occurrence of a tunnel effect. / J. Amer. chem. Soc. *86*, 2531 (1964) / –Eb. [Rd 191/400 IE]

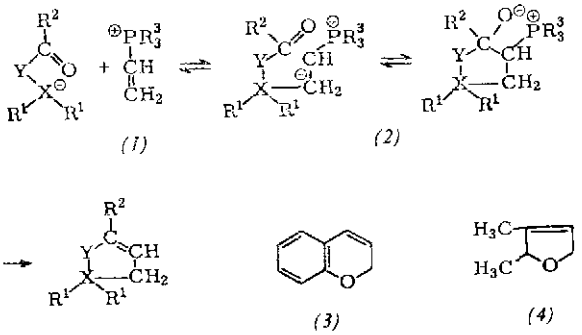
The reaction of oxime tosylates with phenylmagnesium bromide was investigated by *R. E. Lyle* and *St. S. Palosi*. Since the tosyl group – in contrast to the *O*-hydrogen on oxime groups – is stable towards the Grignard reagent, side reactions are avoided. Rearrangement occurs and the Schiff bases are formed in yields of about 80 %. – The formation of 60 % 5-t-butyl-2-phenyl-1-azacycloheptene *(2)* and 20 % 4-t-butylcyclohexanone anil *(3)* from 4-t-butylcyclohexanone oxime *O*-tosylate *(1)* and phenylmagnesium bromide can be explained as follows:



It was shown that the Lewis base $MgBr_2$ catalyses the rearrangement of the oxime by rearranging pure benzophenone oxime *O*-tosylates with $MgBr_2$ in ether. / Chem. Engng. News *42*, No. 16, p. 45 (1964) / –Re. [Rd 91/361 IE]

[1] *J. Monod, J.-P. Changeux*, and *F. Jakob*, J. molecular Biol. *6*, 306 (1963).

A novel general synthesis of heterocyclic and carbocyclic compounds is described by *E. E. Schweizer*. Anions formed from ROH, R_2NH, RSH, R_3CH, or R_2PH add onto triphenylvinylphosphonium bromide *(1)* to form phosphorylides *(2)* which in turn attack functional groups. For example, *(1)* reacts with the sodium salt of salicylaldehyde at 110 °C to give 3,4-chromene *(3)*, b.p. 91–93 °C/13 mm, in 62 % yield together with triphenylphosphine oxide; in acetonitrile the yield rises to 71 %. Acetoin and NaH react in ether with *(1)* when dimethylformamide is subsequently added to give 2,5-dihydro-2,3-dimethylfuran *(4)*, b.p. 104 °C, in 39 % yield within 48 h at room temperature, together with 49 % triphenylphosphine oxide.



(1) *(2)* *(3)* *(4)*

Y is any bivalent aliphatic or aromatic group, X may be O, N, or C; R^1 is an aliphatic, aromatic, or electron-attracting group, or can be omitted (*e.g.* when X = O); R^2 is an aliphatic or aromatic group or hydrogen, and R^3 is C_6H_5. / J. Amer. chem. Soc. *86*, 2744 (1964) / –Ma. [Rd 131/318 IE]

BOOK REVIEWS

Thermodynamik der irreversiblen Prozesse (Thermodynamics of Irreversible Processes). By *R. Haase*. Fortschritte der Physikalischen Chemie (Advances in Physical Chemistry) Vol. 8. Edited by *W. Jost*. Dr. Dietrich Steinkopff Verlag, Darmstadt 1963. 1st Edit., XII + 552 pp., 40 figs., 23 tables, hard covers DM 90.– (about $ 22.50), linen DM 95.– (about $ 24.00).

The discussion in this book is limited to the macroscopic-phenomenological theory of the thermodynamics of irreversible processes; the problems concerned with statistical or kinetic confirmation of the postulates used are left untouched.

In the first chapter, a summary is given of thermodynamic fundamentals, equilibrium criteria, and stability conditions, and the entropy balance for homogeneous systems is derived; next the linear equations for the connections between generalized currents and forces are introduced, and the Onsager-Casimir reciprocity relationships are postulated. A final section on the transformation of currents and forces completes the principles of the theory, which is then developed further in the next chapters.

The second chapter deals with processes in homogeneous systems (chemical reactions, relaxation phenomena, the speed of sound in liquid phases), while the third chapter is devoted to processes occurring in discontinuous heterogeneous systems (electrokinetic effects, membrane processes, and thermomechanical effects).

In the fourth chapter, processes in continuous systems are discussed. During the development of the formulae for the entropy balance in Part A, the reduced thermal current is used throughout, and thus the local production of entropy and the total entropy current remain independent of the reference speed in many practically important cases. Part B deals with isothermal and Part C with non-isothermal processes, separate sections (*e. g.* on thermodiffusion, concentration cells, centrifugal cells, thermo-cells, electrolytic thermoelements, *etc.)* being devoted to electrolyte solutions. Part D gives a discussion on processes with internal friction, in magnetic fields, and in anisotropic media. – The fifth chapter gives a discourse on stationary states and closes with an outlook towards biological systems.

The book is characterized by the ease with which it can be read, owing to the combination of scientific exactness with a broad presentation of topics and to the effort to give each symbol a characteristic individual meaning by purposeful use of sub- and superscripts. The frequent comparisons of theory with experimental results should arouse considerable interest, for this conveys some impression of the order of magnitude or importance of the coefficients which crop up.

The unfortunately high price of the volume evokes the question whether scientific monographs should not be regarded as being worthy of subvention. *M. Becker* [NB 330/188 IE]

Die chemische Bindung. Drei Vorlesungen für Chemiker (The Chemical Bond – Three Lectures for Chemists). By *H. Hartmann*. Springer-Verlag, Berlin-Göttingen-Heidelberg 1964. 2nd Revised edit., vi + 109 pp., 61 figs., linen DM 9.80 (about $ 2.50).

In his three lectures *H. Hartmann* develops the theory of the chemical bond on the basis of the field theory of matter. The book has been developed from lecture manuscripts and is intended primarily for the use of chemistry students.

In the first lecture, the fundamentals of the field theory of the "cathode substance" (*i.e.* the electron), the electronic theory of the atom, and the periodic system of the elements are discussed. The second lecture deals with problems relating to the chemical bond. Examples are used to illustrate the hydrogen-molecule ion, directed valences, hybridization of the carbon atom, and simple and multiple bonds. The third lecture is confined to the discussion of a few special problems of bonding. The basic principles of the ligand field theory are derived, starting from a consideration of ion lattices and ion complexes. The bond order in complicated molecules, the theory of π-electron systems, and finally the energy bands in metal lattices form the subjects for discussion. The lecture closes with a brief interpretation of the transition states of chemical reactions.

The book does not demand a knowledge of mathematics, but still does not make easy reading, for not only does it convey information about the chemical bond, but strives to impart a complete understanding of the phenomenon. Hence it can definitely be recommended to every student of chemistry who is seeking a firmer foundation for his knowledge. In addition, on account of its original approach and unusual presentation of ideas, the book will certainly be of interest to all associated with didactic problems in chemical education.

H. Zimmermann [NB 269/126 IE]

Lehrbuch der anorganischen Chemie (Textbook of Inorganic Chemistry). By *A. F. Holleman* and *E. Wiberg*. Verlag Walter de Gruyter & Co., Berlin 1964. 57th–70th Edits., xxi + 766 pp., 177 figs., one table, linen DM 32.– (about $ 8.00).

The popularity of "Holleman-Wiberg" has been maintained for decades by its readers and is shown in the rapid sequence of new editions. This is due principally to the success with which the authors have constantly revised and modernized their textbook. Here only the most important of the numerous additions and improvements included in this printing (which corresponds to a total of 14 editions) can be recorded.

The chapter on the chemical bond has been significantly extended and modernized. The wave-mechanical concepts of s-,

p-, and d-orbitals, the explanation of the formation of σ- and π-bonds according to the valence bond theory, and the stereochemical consequences of hybridization are discussed in a new eleven-page section illustrated with numerous figures. Brief reference is also made to the ligand field theory and its more quantitative aspects. Considerable extensions have been made to the chapters on metal carbonyls and aromatic complexes, molecular spectroscopy (including nuclear magnetic resonance), and the lattice structures of elements and compounds – a field that was hitherto only incompletely considered. One valuable didactic improvement in the textbook is the enclosure of "three-dimensional" illustrations, which when viewed through red/blue spectacles reproduce the stereoscopic images of the most important molecular and lattice structures; this innovation will be especially welcomed by younger students who are not yet accustomed to picturing such structures in three dimensions. The atomic weights of the elements are all referred to the new basis $^{12}C = 12.000$. The historical and biographical appendices have been augmented, and both author index and subject index are included. Another welcome feature is the inclusion for the first time of numerous references to review articles and monographs in order to facilitate further reading by those interested in specialized topics of inorganic chemistry.

This new presentation of "Holleman-Wiberg" fulfills all the requirements of a modern textbook on inorganic chemistry, and its clarity and topicality leaves nothing to be desired.

R. Nast [NB 262/120 IE]

Fortschritte der Chemie organischer Naturstoffe (Advances in the Chemistry of Organic Natural Products). Vol. XXI. Edited by *L. Zechmeister*. Springer-Verlag, Vienna 1963. 1st Edit., VII + 362 pp., 14 figs., linen DM 76.– (about $19.50).

The high quality of previous contributions to this series has been maintained in the present volume. *W. Oroshnik* and *A. D. Mebane* discuss the chemistry of "Polyene Antifungal Antibiotics". Since all of these compounds are macrolides and cannot be distinguished from other macrolides biogenetically, it would be better to designate them as polyene macrolides and thus avoid confusing them with acetylene antibiotics such as mycomycin. The elucidation of the structures and the chemical properties of tetracyclines are described by *H. Muxfeldt* and *R. Bangert* in a detailed review. Attempts at their synthesis are mentioned only briefly here as they are to be discussed in detail in a later contribution. Derivatives of 7,8,9,10-tetrahydro-5,12-tetracenoquinone are termed anthracyclinones by *H. Brockmann* who gives the first comprehensive survey of this antibiotic natural pigment. *L. Crombie* reviews recent developments in the field of rotenoids, particularly the clarification of the absolute configurations of these compounds. The chapters by *J. Bonner* on the biosynthesis of rubber and by *L. Jaenicke* and *C. Kurtzbach* on folic acid and folate enzymes go beyond the conventional limits of this series, for here it is mainly enzymatic reactions that are discussed. Although the interest of natural-product chemists in biochemistry is increasing constantly, the reviewer doubts that extension of the coverage of the series in this direction in future volumes would be advantageous.

A study of Vol. 21 will also be most profitable even to those whose interests are only remotely connected to the chemistry of natural products. It would be good if the publishers decided to designate the formulae with Arabic numerals.

H. Grisebach [NB 246/104 IE]

Allgemeine Biochemie. By *J. Kostir*. VEB Gustav Fischer Verlag, Jena 1963. 1st Edit., xiv + 509 pp., 24 figs., 3 tables, linen DM 64.70 (about $16.50).

Textbooks on biochemistry tend to emphasize either the biological aspects or the chemical aspects of the subject. In his "General Biochemistry" *J. Kostir* attempts to present both points of view in a manner advantageous to the student. The chemical portion is placed in the foreground; its content is more than sufficient to satisfy the needs of the medical student. On the other hand, the presentation of the functional topics is less gratifying. Even though some new results have been considered, the outlay and description of functional processes are not in keeping with a modern short presentation of the field of biochemistry. This already becomes apparent from the arrangement of the material, where, for example, the concept of "biocatalysis" is prominently displayed; although this may have been a valuable approach at one time, it is didactically erroneous nowadays. The book is valuable as a supplementary textbook, since it attempts to reproduce a condensed but comprehensive coverage of the whole field. However, it is not to be recommended as sole textbook for an introduction to biochemistry. *M. Klingenberg* [NB 247/105 IE]

The Chemistry of Nucleosides and Nucleotides. By *A. M. Michelson*. Academic Press, Inc., London-New York 1963. 1st Edit., ix + 622 pp., several figs. and tables, linen £6.6.0 (about $17.50).

Following a short historical introduction, the first two chapters describe the isolation, structure, chemical properties, and chemical syntheses of nucleosides and nucleotides, their intramolecular anhydrides, and cyclonucleosides and cyclic nucleotides. In Chapter 4 mixed anhydrides of nucleoside phosphates with other acids are discussed, according to the same pattern. This group includes nucleoside diphosphates and triphosphates and their compounds with sugars and peptides, diphosphopyridine nucleotide and triphosphopyridine nucleotide, nicotinamide adenine dinucleotide, and mixed anhydrides with sulfuric acid, carbonic acid, and organic acids. After the section on the chemical syntheses of these compounds, the next chapter deals with their biosynthesis. Chapters 6–9 are devoted to high molecular-weight nucleic acids. The organic chemistry of nucleic acids is dealt with first, emphasis being on the purification, isolation, and identification of these substances and on their chemical and enzymatic reactions. In the next chapter, the various possibilities for synthesizing oligonucleotides are described. This is followed by discussion of the physical chemistry of nucleic acids: this section includes, for example, the investigations on their hypochroism and other optical properties, their hydrogen-bond formation, the formation of double helices, the determination of their charge, their viscosities, their flow birefringence, and the processes occurring during their denaturation and renaturation. In the concluding chapter a short survey is given of the biological functions of nucleic acids, including a discussion of transformation and transduction and of their importance for protein synthesis. As already indicated by the title of the book, it is the chemistry of the nucleic acids that is emphasised, in accordance with the field of research of the author who is himself a prominent nucleic-acid chemist. The individual sections have been worked out with great care and criticism and are amply illustrated by numerous formulae. The volume contains over 2000 references divided into groups at the end of each chapter.

Factual information in this field is increasing so rapidly that it is hardly longer surveyable without the aid of this excellent book. Despite its shortness, the immensity of its content makes it more a work of reference than a textbook.

The reviewer himself has often consulted the book as regards his own work for some time now, and can therefore say from his own experience that it will be needed by everyone wanting to work in the field of nucleic acids.

G. Schramm [NB 281/139 IE]

Methods in Carbohydrate Chemistry. Edited by *R. L. Whistler, R. J. Smith, J. N. BeMiller*, and *M. L. Wolfrom*. Vol. IV: Starch. Academic Press, New York-London 1964. 1st Edit., xvi + 335 pp., numerous illustrations and tables, linen $13.50.

The chemistry of starch is complicated by differences in its composition depending on its source, by its formation from

two different polysaccharides, and by the numerous products which contaminate it. It is therefore to be welcomed that a volume on starch has been published in the series on "Methods in Carbohydrate Chemistry". Sixty-one authors combine to discuss the entire field in six chapters: 1. Production of starch and its fractions; 2. Chemical analysis; 3. Physical analysis; 4. Microscopy; 5. Degradation reactions; and 6. Derivatives and modifications (oxidation products).

A great advantage of the book is that the individual sections have been written by acknowledged experts and that the practical procedures given can be repeated without reference to further literature. However, the divison into very short contributions has also some disadvantages which cannot be overlooked. For example, there is unavoidably a lack of objectivity, since understandably, every contributor places his method in the forefront. One result of this is that, as in the volume on cellulose, German publications are hardly mentioned, although this would in fact be highly justified. The uniformity also suffers as a result of the book having so many authors; thus, sometimes only starch is discussed, and at other times only amylose and amylopectin are considered, without any recognizable organizing principle. This finds its expression in the highly differentiated and frequently inadequate characterizations given; data on the degree of degradation effected by the individual reactions or on the characterization by viscosity measurements throughout would greatly simplify use of the volume.

The treatment of the physical methods does not appear to be very fortunate; the basic priniples of diffusion, light scattering, and ultracentrifugation are described, topics which can be read up in many monographs, but practically no examples are given. It would be more important for the reader if tables of substances that have been investigated by these methods were compiled.

The book is suitable as a guidebook for introductory preparative work in the field of starch. For more intensive work on the subject, other monographs or original publications must be consulted.

E. Husemann [NB 282/140 IE]

Complexation in Analytical Chemistry. A Guide to the Critical Selection of Analytical Methods Based on Complex Formation Reactions. By *A. Ringbom*. Chemical Analysis: A Series of Monographs on Analytical Chemistry and its Applications, Vol. XVI. Edited by *P. J. Elving* and *I. M. Kolthoff*. Interscience Publishers, a Division of John Wiley & Sons, New York - London 1963. 1st Edit., x + 395 pp., numerous illustrations and tables, linen $15.00.

This excellent book by the well-known Finnish analyst deals with complex formation in aqueous solution using a theoretical approximation which permits simple prediction of important quantitative data with sufficient accuracy to satisfy the practitioner, *e.g.* on the most favorable experimental conditions, on the effect of interfering side-reactions in conventional analytical procedures, or on suitable methods for solving a particular analytical problem. Here the concept of "complex" is used in a rather broad sense and encompasses *inter alia* acids and bases as well. Complex formation is discussed with regard to masking, complexometric titrations, acid-base titrations, ion exchange, extraction, and electrochemical and photometric analysis. In these sections the theoretical basis of each method is discussed without giving comprehensive literature surveys or special working procedures. The application of the approximation method is illustrated by numerical examples. An appendix comprising eighty pages contains stability constants *etc.*

For the analyst who has a good knowledge of the theory of aqueous electrolyte solutions, this very valuable book will help him to avoid much experimental groundwork in appraising any specific analytical procedure. For those who are less familiar with the field, especially students, it will serve as an easily intelligible introduction to the subject, since the text is lucid and readily comprehensible.

Werner Fischer [NB 243/101 IE]

Interfacial Phenomena. By *J.T. Davies* and *E. K. Rideal*. Academic Press, New York-London 1963. 2nd Edit., viii + 480 pp., numerous illustrations and tables, linen $15.00.

This book deals with the phenomena associated with the interfaces between non-miscible liquids, between liquids and gases, and between solids. The treatment is intelligible even to those who are not experts in this field, and the text is supplemented by abundant references; it is directed mainly at chemists and biologists. The principal theme is about the fundamental problems of interfacial phenomena; the more technical aspects of the subject fade somewhat into the background. Theory and experimental methods are discussed in detail. Separate chapters are devoted to electrostatic and electrokinetic phenomena, adsorption at interfaces, the properties of monomolecular layers (including the damping of waves), reactions at interfaces, and diffusion through interfaces. The final chapter deals with the most important properties of disperse systems and with adhesion insofar as they are related to the fundamentals disclosed earlier in the book. This chapter includes a discussion of aerosols, emulsions and suspensions, and phenomena such as foaming and lubrication, and also wetting problems are analysed.

A. Saupe [NB 272/129 IE]

Interpretation of Mass Spectra of Organic Compounds. By *H. Budzikiewicz, C. Djerassi*, and *D. H. Williams*. Holden-Day, Inc., San Francisco 1964. 1st Edit., xiii + 271 pp., numerous illustrations, linen $8.75.

The impetus for the publication of this book came from the papers (over fifty in number) which appeared over somewhat less than three years. In these papers *Djerassi* and *Budzikiewicz* have discussed their work on mass spectrometric investigations of organic compounds. The book is directed exclusively towards the organic chemists, and typical mass spectrometric fragmentations, *e.g.* of alcohols, ethers, thiols, carbonyl compounds, amines, amides, halides, and nitriles, are described in detail with recourse to the complete literature. The sections on heterocyclic and aromatic compounds are particularly good.

The only departure from the general approach adopted in the book is the too detailed discussion of a few highly specialized classes of compounds (cyclic ketones and amides). The sections on tobacco alkaloids and steroids are superfluous, since the same authors have announced their intention to publish separate books on these subjects. However, it might have been expected that the pioneer work by *Stenhagen* and *Ryhage* would have been discussed more thoroughly.

In order to give as uniform a presentation of fragmentation reactions as possible, the concept is adopted at the outset that in compounds containing a hetero-atom, the electron which is split off during ionization is removed only from the hetero-atom. Although this is usually true for simple molecules, the validity of this assumption cannot be generalized, particularly for larger molecules. The attempt to explain all fragmentations using this scheme leads to reaction mechanisms such as that given on page 5 where an electron pair and a single electron inexplicably migrate in the same direction, or to the postulation of degradation reactions (p. 90, decomposition of compound LI) for which simpler explanations are at hand (cf. *H. Audier, M. Fetizon*, and *W. Vetter*, Bull. Soc. chim. France *1963*, 1971).

The arguments presented in the text are supplemented by a wide selection of mass spectra. A short subject index provides an aid to rapid reference.

G. Spiteller [NB 252/110 IE]

Chemical Kinetics of Gas Reactions. By *V. N. Kondrat'ev*, translated from the Russian by *J. M. Crabtree* and *S. N. Carruthers*, edited by *N. B. Slater*. Pergamon Press, Oxford-London-New York-Paris 1964. 1st Edit., xi + 812 pp., 200 figs., 62 tables, linen £5.5.0 (about $15.00).

The kinetics of chemical reactions in the gas phase has made tremendous theoretical advances and has been applied to various new fields within recent years. Theoretical treatment

by numerous authors of elementary chemical processes has met with a large measure of success. Such processes include the use of transition-state methods or quantum-mechanical methods, of unimolecular reactions by *Slater*, and of the transfer of translatory, vibrational, and rotational energy. From the experimental standpoint, the classic thermal reactions have been supplemented by many new ones, *e.g.* reactions occurring in the upper terrestial atmosphere, reactions occurring in electrical discharges, radiochemical reactions, and novel flame reactions.

In his book which appeared in Russian in 1958, *Kondrat'ev* gave an excellent survey of these developments; the same can be said of the present English translation edited by *Slater*, which also provides extensive coverage of work meanwhile reported. The topics dealt with include the general laws of chemical reactions and their mechanisms, the theory of elementary processes, unimolecular, bimolecular, and termolecular reactions, energy conversions during molecular collisions, photochemical reactions causing fluorescence or quenching of fluorescence, reactions initiated by electrical discharges, bombardments with fast ions and atoms, the effects of penetrating radiation, chain reactions, and combustion reactions.

An enormous number of theoretical and experimental results have been evaluated with great care; *Kondrat'ev* has classified these and called attention to many imperfections and disparities requiring further theoretical and experimental investigations.

The book should prove to be of value to all chemists; it can even be considered indispensible to all working on reaction kinetics in the widest sense. It can be recommended to students on account of its lucid and simple presentation of the theoretical side of the subject.

W. Groth [NB 259/117 IE]

Tables of Experimental Dipole Moments. By *A. L. McClellan*. W. H. Freeman and Co., San Francisco-London 1963. 1st Edit., 713 pp., linen £5.0.0 (about $ 16.00).

Every chemist who sometimes wants to know the dipole moment of a certain compound is familiar with the difficulties involved in finding the desired value because only older incomplete tables are available so that he must look for the dipole moment in general abstract journals or in the original literature. For this reason the author of this book has undertaken the commendable task of collecting all the dipole-moment values published up to the end of 1961 and arranging them into three tables. Table I contains the dipole-moments for about 250 compounds containing no carbon atoms, Table II summarizes those for about 4500 compounds containing one or more carbon atoms, and Table III lists the values for about 100 compounds whose formulae are not exactly known. The method of tabulation corresponds to that of the formula indexes of Chemical Abstracts, so that all the compounds listed can be found rapidly. Each entry in the tables gives the molecular formula, the dipole moment (with limits of error), and reference to the source of the measurement, together with the name of the appropriate compound, its state of aggregation or solvent used, the temperature, measuring procedure, and the atomic polarization used for evaluation. The only worthwhile data missing are particulars of the methods used to calculate the values from the dielectric constants.

The quality of the tables can be appreciated from their completeness, the correctness of the data, and the orderliness of arrangement. Numerous references selected at random proved that 90–95 % of the entries taken from the literature are correctly listed. The layout of the tables is very orderly. A few small errors are naturally unavoidable within the confines of such an extensive work; *e.g.* all the dipole-moments given that were allegedly determined by the "fluorescence" method were actually found from the dependence of the dielectric constants of solutions on the concentration, and the dipole moment of *p*-dimethylamino-ω-nitrostyrene is given on page 495 under the formula and name of the corresponding stilbene.

The book can be recommended to every chemical library, and it will soon be a familiar work of reference for every chemist who has to search frequently for dipole moments. It is only to be hoped that supplements will appear at short intervals.

W. Liptay [NB 263/121 IE]

Advances in Chemical Physics. Edited by *I. Prigogine*. Vol. VI. Interscience Publishers, a Division of John Wiley & Sons, London-New York-Sidney 1964. 1st Edit., ix + 506 pp., several illustrs. and tables, linen £6.0.0 (about $ 17.00).

Most of the contributions in this volume attempt at as stringent a discussion of the theory of the respective topic as possible: thus, for example, in the first article "Towards an analytic theory of chemical reactions", *H. Aroeste* states prefatorily: "The main purpose of an analytic approach to the theory of chemical reactions is to furnish a detailed understanding of the elements involved rather than to provide a quick comparison with experimentally determined macroscopic rates".

Similar remarks apply to the contribution of *A. Bellemans* and *M. de Leener* on the "Electron gas in a lattice of positive charges". *M. Fixman*'s treatment of „The critical region", although fundamentally theoretical, lies closer to experimentation. This chapter can be recommended to all interested in this field, which is still far from stagnating. The same can be said of the following chapter by *H. L. Frisch* on "The equation of state of the classical hard-sphere fluid". This is a strongly idealized model of a liquid, but it can be carried through up to comparison with experiment. The next chapter too, "Studies in the kinematics of isothermal diffusion. A macrodynamical theory of multicomponent fluid diffusion" by *O. Lamm*, concerns the experimentor. The next contribution, on the "Many-electron theory of atoms, molecules, and their interaction", by *O. Sinanoglu* conveys an impressive view of the high level of theoretical chemical research in the U.S.A., but is only accessible to the theorist. The same might hold for the article by *J. Stecki* on "Ionic solvation". Another theoretical article by *J. Chr. Erikson* attempts to improve the unsatisfactory situation in the thermodynamics of surface systems. The final chapter by *A. R. J. P. Ubbelohde* on the "Melting mechanisms of crystals" is again of a more experimental orientation.

The volume is of high quality throughout and ought to provide a good work of reference for all specialists in these fields, but is probably much too specialized for the average pure chemist.

W. Jost [NB 267/138 IE]

Analytical Chemistry of the Actinide Elements. By *A. J. Moses*. Vol. 9 of the International Series of Monographs on Analytical Chemistry edited by *R. Belcher* and *L. Gordon*. Pergamon Press, Oxford-London-New York-Paris 1963. 1st Edit., 137 pp., numerous illustrations and tables, linen £2.5.0 (about $6.25).

In view of the increasing scientific and technical importance of the actinides, the appearance of this monograph is to be welcomed. The scope of the book is limited in so far as the analytical chemistry of the transamericium elements is still relatively unknown, although some known procedures might be applicable to them. The presentation of the material is terse and clear, especially due to numerous tables. Appropriate space has been devoted to the description of the nuclear properties and the analytical applications of the radioactivity of the nuclides; several pictures of radiation detection and irradiation facilities covering full pages are however more of an illustrative nature than of utility. The importance of chromatographic separation procedures should have been accounted for to a greater extent. The numerous methods of detection and determination described will be especially appreciated. Although detailed analytical procedures are given only occasionally, the book provides useful hints and suggestions for the analyst in helping him to solve even special problems of actinide analysis.

K. Schwochau [NB 274/131 IE]

The Theory of the Electronic Spectra of Organic Molecules. By *J. N. Murrell*. Methuen & Co., Ltd. London; John Wiley & Sons, Inc., New York 1963. 1st Edit., xiv + 328 pp., numerous illustrations and a few tables, linen £2.15.0 (about $8.00).

J. N. Murrell, University of Sheffield (England), presents the subject here so that it will appeal to those interested in either the practical or theoretical aspects of electronic spectra. In the first three chapters, the quantum-mechanical fundamentals and theories of electronic spectra are discussed, particular attention being paid to the valence bond theory and the molecular orbital theory, the latter with emphasis on the treatment of the free electron and the LCAO approximation. The author describes this introduction as being intended merely as a resumé and as a recapitulation for readers who already have some knowledge of quantum mechanics. Chapters 4–6 are devoted to the absorption spectra of ethylene, acetylene, conjugated open-chain unsaturated hydrocarbons, and benzenoid hydrocarbons. Here the experimental findings are taken as the starting point for a discussion of the theoretical aspects of the spectra, their mathematical evaluation, and of the resulting information about the structures of the molecules concerned. Somewhat surprisingly, but perhaps justifiably on account of its non-stereotypical spectrum, benzene itself is discussed after the other benzenoids. The remaining eight chapters deal with more specific problems: chromophores with weak interactions, transitions of non-bonding electrons, inductive, mesomeric, and steric effects, radicals and ions, molecular complexes, and fluorescence and phosphorescence. Some mathematical theorems and calculation procedures are discussed in an appendix separated from the main body of the text. Every chapter is embellished with references (as footnotes) including sources of more detailed information for further study. The book closes with a rather inadequate subject index, but its lay-out and print are excellent. The reviewer considers the book unsuitable for occasional cursory reference, but whoever takes the trouble to work through it methodically will be amply rewarded and will find it an excellent guidebook.

W. Brügel [NB 279/136 IE]

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The Chemistry of Diimine

BY PROF. DR. S. HÜNIG [1], DR. H. R. MÜLLER, AND DR. W. THIER

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The presence of diimine in solution can be shown conclusively by the stereospecific cis-hydrogenation of symmetrical multiple bonds. Apart from reactions which have hitherto been attributed to hydrazine, this review deals primarily with the various sources and secondary reactions of diimine.

I. Early History of Diimine

In spite of the highly developed state of azo-chemistry, the question of the existence of the parent compound, "azohydrogen", *i.e.* diimine [2], remained unanswered until a few years ago, although the first attempts to detect it date back to the last century.

The smooth decarboxylation of the potassium salt of azodicarboxylic acid *(1)* on hydrolysis at room temperature led *Thiele* [3] (1892) to believe that he had evidence for the existence of diimine. However, the hydrolysis products consist of equivalent quantities of nitrogen and hydrazine [Reaction (a)], and *Thiele*, therefore, interpreted this reaction as the disproportionation (b) of diimine. By subsequent investigations on the kinetics of

$$\underset{(1)}{HO_2C\text{-}N{=}N\text{-}CO_2H} \xrightarrow[\sim 20^\circ C]{H_2O} {}^1/_2\,N_2 + {}^1/_2\,N_2H_4 + 2\,CO_2 \quad (a)$$

$$2\,N_2H_2 \rightarrow N_2 + N_2H_4 \quad (b)$$

the decarboxylation of *(1)*, the reaction was shown to be vigorously catalysed by protons, but there was no further evidence for the participation of diimine itself [4].

According to *Raschig* [5a, 5b], diimine occurs as an intermediate in the cleavage of the benzenesulfonyl hydrazide *(2)* with hot alkali. *Raschig* found equivalent quantities of nitrogen and hydrogen, which he assumed to result from the decomposition (d) of the intermediate diimine. According to *Raschig* [5a, 5b], *Thiele*'s results

$$\underset{(2)}{C_6H_5\text{-}SO_2\text{-}NH\text{-}NH_2} + OH^\ominus \xrightarrow{100^\circ C} C_6H_5\text{-}SO_2^\ominus + N_2 + H_2 + H_2O \quad (c)$$

$$N_2H_2 \rightarrow N_2 + H_2 \quad (d)$$

were due to attack of the decomposing diimine on azodicarboxylic acid. Thus it appeared to him that the disproportionation of diimine was simply simulated according to Reaction (e); a similar interpretation of this finding was given by *H. Wieland* [6].

$$^\ominus O_2C\text{-}N{=}N\text{-}CO_2^\ominus + N_2H_2 \rightarrow N_2 + {}^\ominus O_2C\text{-}\underset{H}{N}\text{-}\underset{H}{N}\text{-}CO_2^\ominus \quad (e)$$

$$2\,CO_2 + 2\,OH^\ominus + N_2H_4 \xleftarrow{+2\,H_2O}$$

Although these contradictory results are consistent with the occurrence of diimine as an intermediate, they do not prove its existence. Moreover, the secondary reaction still remains unexplained: does the diimine disppor-

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[2] The nomenclature here is just as confused as in the case of the species NH. Diimine appears less ambiguous than diimide and maintains association with the older literature. The systematic name "diazene", suggested by *W. R. McBride* and *E. M. Bens* [J. Amer. chem. Soc. *81*, 5546 (1959); c.f. *H. Bock* and *G. Rudolph*, Chem. Ber. *94*, 1457 (1961)] would be appropriate if NH was analogously named "azene".

[3] *J. Thiele*, Liebigs Ann. Chem. *271*, 127 (1892).

[4] *C. V. King*, J. Amer. chem. Soc. *62*, 379 (1940).

[5a] *F. Raschig*, Angew. Chem. *23*, 972 (1910).

[5b] *F. Raschig*: Schwefel- und Stickstoffstudien. Verlag Chemie, Leipzig-Berlin 1924.

[6] *H. Wieland*: Die Hydrazine. F. Enke-Verlag, Stuttgart 1913, p. 4.

tionate, does it decompose into its elements, or does the reaction follow both paths, depending on the temperature, solvent, and basicity of the medium? These questions have been answered in the last few years.

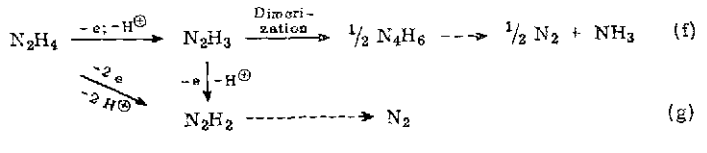
II. Properties of Diimine

A. Diimine in the Gas Phase

Diimine was first detected by mass spectrometry [7] during the decomposition of hydrazoic acid or hydrazine in an electric discharge under reduced pressure. The decomposition products, which can be isolated as a yellow coating at −180 °C, still contain particles having the required mass number of 30. Anthracene-9,10-bisimine *(5)* loses diimine at about 100 °C in the mass spectrometer, showing that diimine has a relatively high thermal stability [8]. On the other hand, diimine cannot be detected mass-spectrometrically during the thermal decomposition of hydrazine in argon at 1470 to 2770 °C [9].

B. Diimine in Solution

The somewhat contradictory results obtained on oxidation of hydrazine [10a–10f] were traced back to the competition between two reactions by *Higginson* [10d]. According to this author, the formation of ammonia is always associated with a one-electron oxidation [10d], which is brought about especially by Ce(IV) and Fe(III) in acidic solution [Equation (f)]. On the other hand, two-electron acceptors [10c, 10d], such as Tl(III), Cr(VI),



(f)

(g)

and V(V) in acidic solution, and the one-electron oxidant $Fe(CN)_6^{3\ominus}$ in alkaline solution, give only nitrogen [Equation(g)]. In agreement with this view, labelling with isotopes [10e, 10f] shows that nitrogen obtained according to Equation (f) is formed from two molecules of hydrazine, while that obtained according to Equation (g) is formed from one molecule of hydrazine. Thus, diimine, N_2H_2, is probably an intermediate in Equation (g). The polarographic two-electron oxidation of alkaline hydrazine solutions also requires the occurrence of diimine as an intermediate [11].

The existence of diimine has now been confirmed chemically: In the Wolff-Kishner reduction of long-chain ketocarboxylic acids having a double bond in the ω-position, a more or less marked hydrogenation of the double bond is observed as soon as the hydrazone is formed. This side reaction can be completely suppressed by exclusion of atmospheric oxygen, showing that hydrogenation of the double bond is not caused by hydrazine itself, but by a dehydrogenation product of hydrazine [12]. The stoichiometry of this redox reaction, the stereochemistry of the hydrogenation, and the discovery that the olefinic double bond is also hydrogenated by decomposing benzenesulfonyl hydrazide or azodicarboxylate, lead to the conclusion that the hydrogenating agent is diimine [13–15].

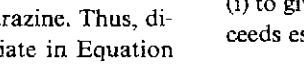
The same conclusion was reached almost simultaneously by *Corey* [16], *van Tamelen* [17], and *Aylward* [18], evidently as a result of similar observations. Since then, as the following survey shows, the chemistry of diimine has become well-known.

It should be stressed here that the only evidence for the existence of diimine in solution is the hydrogenation of multiple bonds. Attempts to isolate diimine by a Diels-Alder reaction have so far been unsuccessful [13, 14, 16].

III. Sources of Diimine

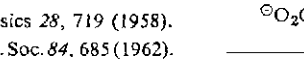
The numerous sources of diimine mentioned below were discovered through the uncatalysed hydrogenation of olefins.

1. Hydrazine yields diimine in accordance with Equation (h) in the presence of oxidizing agents such as atmospheric oxygen [15, 16, 18], peroxides (especially with traces of Cu^{2+}) [16], mercuric oxide [15], *N,N*-dichlorotoluenesulfonamide [14], and particularly Chloramine T [14] and hexacyanoferrate(III) [15].



(h)

2. Azodicarboxylate [15–17] decomposes in agreement with *Thiele*'s view [3], and in accordance with Reaction (i) to give diimine and carbon dioxide; this reaction proceeds especially readily in the presence of acid [4, 17].



(i)

[7] *S. Foner* and *R. L. Hudson*, J. chem. Physics *28*, 719 (1958).

[8] *E. J. Corey* and *W. L. Mock*, J. Amer. chem. Soc. *84*, 685 (1962).

[9] *R. W. Diesen*, J. chem. Physics *39*, 2115 (1963).

[10a] Review: *L. F. Audrieth* and *B. A. Ogg*: The Chemistry of Hydrazine. Wiley, New York 1951; *W. Higginson*, J. chem. Soc. (London), Special Publ. *10*, 95 (1957).

[10b] *E. J. Cuy* and *W. C. Bray*, J. Amer. chem. Soc. *46*, 1786 (1924).

[10c] *R. E. Kirk* and *A. W. Browne*, J. Amer. chem. Soc. *50*, 337 (1928).

[10d] *W. Higginson*, *D. Sutton*, and *P. Wright*, J. chem. Soc. (London) *1953*, 1380.

[10e] *W. Higginson* and *D. Sutton*, J. chem. Soc. (London) *1953*, 1402.

[10f] *J. Cahn* and *R. Powell*, J. Amer. chem. Soc. *76*, 2568 (1954).

[11] *S. Karp* and *L. Meites*, J. Amer. chem. Soc. *84*, 906 (1962).

[12] *W. Eckardt*, Diploma Thesis, Universität Marburg, 1959; Ph. D. Thesis, Universität Marburg, 1960; *S. Hünig* and *W. Eckardt*, Chem. Ber. *95*, 2498 (1962).

[13] *H. R. Müller*, Diploma Thesis, Universität Marburg, 1961.

[14] *H. R. Müller*, Ph. D. Thesis, Universität Würzburg, 1962.

[15] *S. Hünig*, *H. R. Müller*, and *W. Thier*, Tetrahedron Letters *1961*, 353.

[16] *E. J. Corey*, *W. L. Mock*, and *D. J. Pasto*, Tetrahedron Letters *1961*, 347.

[17] *E. E. van Tamelen*, *R. S. Dewey*, and *R. J. Timmons*, J. Amer. chem. Soc. *83*, 3725 (1961).

[18] *F. Aylward* and *M. Sawistowska*, Chem. and Ind. *1962*, 484.

3. Arenesulfonyl hydrazides [15,19–21] undergo thermal cleavage, primarily in accordance with Equation (j). This is similar to *Raschig*'s scheme (c) [5a, 5b], but the

$$ArSO_2\text{-}NH\text{-}NH_2 \xrightarrow{100\text{-}150^\circ C} ArSO_2H + HN{=}NH \qquad (j)$$

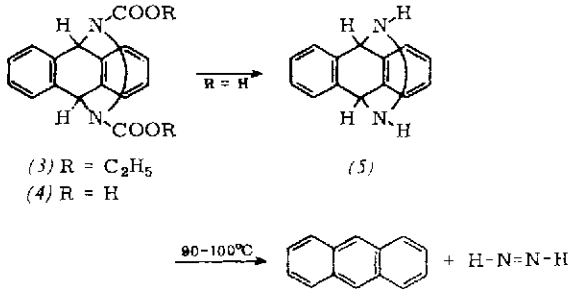
yield of hydrogenated olefin is reduced by strong alkali [20,21]. Diimine can be obtained from *m*-, *p*-, and *o*-nitrobenzenesulfonyl hydrazide, at a rate suitable for preparative use, at about 75, 50, and 25 °C, respectively [21].

4. The hydrochloride of chloroacetyl hydrazide decomposes in alkaline medium even at 0 °C according to Equation (k).

$$ClCH_2\text{-}CO\text{-}NH\text{-}NH_2\cdot HCl + 2\,NaOH \longrightarrow 2\,NaCl + 2\,H_2O + H_2C{=}C{=}O + HN{=}NH \qquad (k)$$

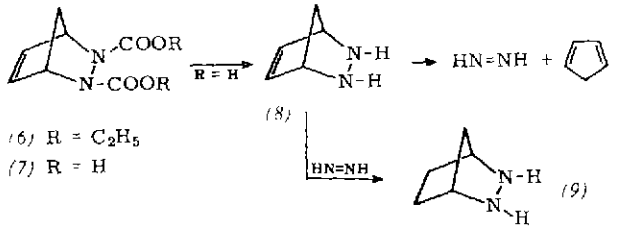
Ketene is formed as a second energy-rich intermediate which adds on water or acylates hydrazine resulting from disproportionation of diimine [21a].

5. Mild hydrolysis of the diene adduct *(3)* [22] yields the dicarboxylic acid *(4)*, controlled decarboxylation of which leads to the formation of anthracene-9,10-bisimine *(5)* [8]. This undergoes thermal decomposition to yield anthracene and diimine.



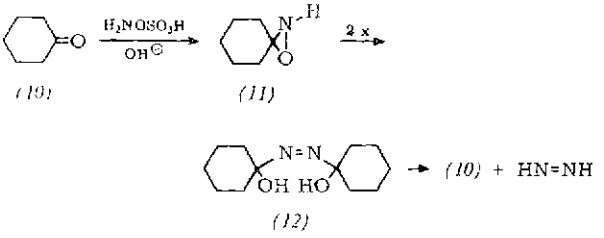
(3) R = C_2H_5
(4) R = H
(5)

6. When the diene adduct *(6)* [23] undergoes the series of reactions mentioned in Paragraph 5, the free carboxylic acid *(7)* cannot be isolated. The expected decarboxylation product *(8)* spontaneously undergoes a retrodiene reaction. The resulting diimine is consumed in a hydrogenation reaction, *e.g.* with formation of *(9)* [24].



(6) R = C_2H_5
(7) R = H
(8)
(9)

7. Cyclohexanone *(10)* and hydroxylamine-*O*-sulfonic acid react at 10 °C, *via (11)*, to form the crystalline 1,1′-dihydroxyazocyclohexane *(12)* which liberates diimine even at room temperature [25,26].



(10)
(11)
(12)

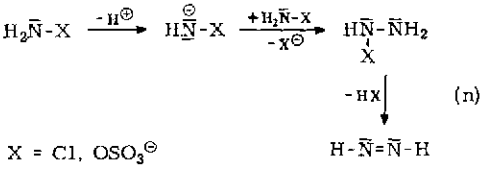
8. Diimine is also formed on decomposition [see Equation (1)] of hydroxylamine-*O*-sulfonic acid [27,28].

$$2\,H_2N\text{-}O\text{-}SO_3^\ominus \xrightarrow{-2\,H^\oplus} HN{=}NH + 2\,SO_4^{2\ominus} \qquad (l)$$

9. The alkaline cleavage of chloramine [28] follows a course similar to that described in Paragraph 7 [27,28].

$$2\,H_2NCl \xrightarrow{-2\,H^\oplus} HN{=}NH + 2\,Cl^\ominus \qquad (m)$$

In cases 8 and 9, the mechanism is probably as shown in Equation (n) [26].



Raschig [5b] had already pointed out that the overall Reaction (o) must proceed in several steps, but the intermediate formation of diimine only became obvious when olefin was present.

$$3\,NH_2Cl + 3\,NaOH \rightarrow N_2 + NH_3 + 3\,NaCl + 3\,H_2O \qquad (o)$$

IV. Detection of Diimine

A. Stoichiometry of the Hydrogenation of Olefins by Oxidation of Hydrazine

If the hydrogenation of olefins in the presence of hydrazine is due to the oxidation stage of diimine, this must be apparent in the stoichiometry of the redox reaction. This can be tested using hexacyanoferrate(III) as

[19] *E. E. van Tamelen* and *R. S. Dewey*, J. Amer. chem. Soc. *83* 3729 (1961).

[20] *S. Hünig, H. R. Müller*, and *W. Thier*, Angew. Chem. *75*, 298 (1963); Angew. Chem. internat. Edit. *2*, 214 (1963).

[21] *W. Thier*, Ph. D. Thesis, Universität Würzburg, 1964.

[21a] *R. Buyle, A. van Overstraeten*, and *F. Eloy*, Chem. and Ind. *1964*, 839.

[22] *O. Diels, S. Schmidt*, and *W. Witte*, Ber. dtsch. chem. Ges. *71*, 1186 (1938).

[23] *J. C. Mackenzie, A. Rodgman*, and *G. F. Wright*, J. org. Chemistry *17*, 1666 (1952).

[24] *S. G. Cohen, R. Zand*, and *C. Steel*, J. Amer. chem. Soc. *83*, 2895 (1961); see also *J. K. Stille* and *T. Anyos*, J. org. Chemistry *27*, 3352 (1962).

[25] *E. Schmitz, R. Ohme*, and *S. Schramm*, Angew. Chem. *75*, 208 (1963); Angew. Chem. internat. Edit. *2*, 157 (1963).

[26] *E. Schmitz*, Angew. Chem. *76*, 197 (1964); Angew. Chem. internat. Edit. *3*, 333 (1964); for a discussion, see [72] p. 714ff.; *R. A. Abramovitch* and *B. A. Davies*, Chem. Reviews *64*, 149 (1964).

[27] *R. Appel* and *W. Büchner*, Angew. Chem. *73*, 807 (1961); Liebigs Ann. Chem. *654*, 1 (1962).

[28] *E. Schmitz* and *R. Ohme*, Angew. Chem. *73*, 807 (1961).

the oxidizing agent for hydrazine in the presence of an olefin, since the oxidation of hydrazine by path (p) requires exactly four oxidation equivalents [29, 30], whereas that by path (q) should require only two equivalents.

$$4\ [Fe(CN)_6]^{3\ominus} + N_2H_4 \longrightarrow N_2 + 4\ H^{\oplus} + 4\ [Fe(CN)_6]^{4\ominus} \quad (p)$$

$$2\ [Fe(CN)_6]^{3\ominus} + N_2H_4 + >C{=}C< \longrightarrow N_2 + 2\ H^{\oplus} + 2\ [Fe(CN)_6]^{4\ominus} + >\underset{H}{C}\text{-}\underset{H}{C}< \quad (q)$$

The stoichiometry of Reaction (q) can be observed together with the oxidation which always proceeds by path (p), if the oxidizing agent consumed and the volume of nitrogen formed are determined simultaneously. If the sum of the oxidation equivalents consumed by paths (p) and (q) is denoted by $Ox = Ox_p + Ox_q$ and the number of moles of nitrogen liberated by $B = N_{2p} + N_{2q}$, the number of moles of hydrogenated olefin (C) at any time during the reaction (slow addition of the $[Fe(CN)_6]^{3\ominus}$ solution to the alkaline solution of olefin and hydrazine) can be easily determined [13, 15] from

$$C = Ox_p/2 = 2\ B - Ox/2.$$

The values calculated in this way agree to within ± 4 % with those obtained by bromometric titration of the unreacted olefin.

A plot of the yield of hydrogenated olefin against the number of oxidation equivalents per mole of olefin initially present gives the curves of Figure 1. Exclusive hydrogenation of the olefin according to Equation (q) would be expected to give the straight line.

In fact, however, oxidation of the hydrazine to nitrogen according to Equation (p) competes with Reaction (q). The extent of competition depends on the ease of hydrogenation of the olefins (see Section IV.C) [14, 15].

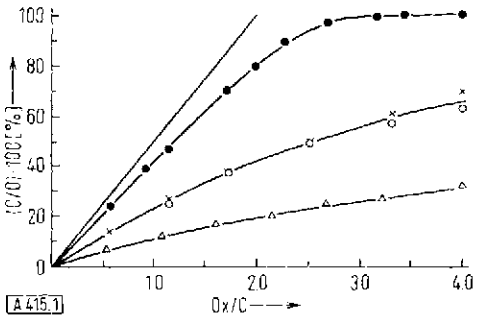


Fig. 1. Hydrogenation curves for fumaric acid (●), *trans*-cinnamic acid (x and o), and *cis*-cinnamic acid (Δ) [6 mmoles of acid, 36 mmoles of hydrazine hydrate, and 100 mmoles of ethanolamine were made up to 100 ml with water; 40 ml of 0.6 N $K_3[Fe(CN)_6]$ solution were added over about 60 min; pH 10–11; 25.0 °C].

Abscissa: Ox/C = oxidation equivalents consumed per mole of olefin initially present.

Ordinate: (C/O)·100 = percentage of hydrogenated olefin.

Since the stoichiometry of the hydrogenation is always found to follow Equation (q) [31], it is certain that the hydrogenating agent has an oxidation stage corresponding to that of diimine, although the structure of the hydrogenating agent is not thereby established.

B. Stereochemistry of the Hydrogenation

As Table 1 shows, it has been determined by infrared analysis [13–15, 32] and by gas chromatography [13, 14] that hydrogenation of the carbon-carbon multiple bonds proceeds at least 97–98 % stereospecifically *via cis*-addition [32]. Deuterium is likewise introduced by N_2D_2 unambiguously *via cis*-addition onto the olefin, whereas catalytic deuteration involves subsequent exchange reactions on the catalyst.

Table 1. Stereochemistry of the hydrogenation of olefins with diimine.

Source of diimine	Substrate	Product	Ref.
$N_2H_4/[Fe(CN)_6]^{3\ominus}$	phenylpropiolic acid [*]	*cis*-cionamic acid	[13, 15]
$H_2N{-}OSO_3^{\ominus}/OH^{\ominus}$	phenylpropiolic acid [*]	*cis*-cinnamic acid	[27]
N_2H_4/H_2O_2	diphenylacetylene [*]	*cis*-stilbene	[32]
$C_6H_5{-}SO_2{-}NH{-}NH_2$	diphenylacetylene [*]	*cis*-stilbene	[21]
N_2H_4/H_2O_2	dimethylmaleic acid	*meso*-2,3-dimethyl-succinic acid	[32]
N_2D_4/oxidizing agent	maleic acid	*meso*-[2,3-D_2]-succinic acid	[32]
or	fumaric acid	(±)-[2,3-D_2]-succinic acid	[32]
$KO_2C{-}N{=}N{-}CO_2K/D_2O$	*cis*-2-butene-1,4-diol	*meso*-[2,3-D_2]-butane-1,4-diol	[32]
	trans-2-butene-1,4-diol	(±)-[2,3-D_2]-butane-1,4-diol	[32]
	cis-stilbene	*meso*-[1,2-D_2]-1,2-diphenylethane	[32]
	trans-stilbene	(±)-[1,2-D_2]-1,2-diphenylethane	[32]

[*] Perhydrogenation of acetylene derivatives also occurs, even when the system is deficient in diimine.

Since the stereospecificity is the same for various olefins as well as for various "sources of hydrogen",

1. the hydrogenation must be effected by the same reagent in every case, and

2. the two hydrogen atoms must be transferred simultaneously.

[29] *P. R. Ray* and *H. K. Sen*, Z. anorg. allg. Chem. *76*, 380 (1912).

[30] *C. J. Dernbach* and *J. P. Mehlig*, Ind. Engng. Chem., analyt. Edit. *14*, 58 (1942).

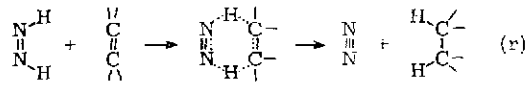
[31] The stoichiometry suggested by *F. Aylward* and *M. Sawistowska*, Chem. and Ind. *1961*, 433, and J. chem. Soc. (London) *1964*, 1435:

$$2\ N_2H_4 + 3/2\ O_2 + >C{=}C< \rightarrow >CH{-}HC< + 2\ N_2 + 3\ H_2O$$

is certainly incorrect. Difficulties were probably encountered in the evaluation, owing to the gaseous oxidizing agent.

[32] *E. J. Corey*, *W. L. Mock*, and *D. J. Pasto*, J. Amer. chem. Soc. *83*, 2957 (1961).

This, together with the stoichiometry, is accepted as proving the existence of diimine. The hydrogenation may be formulated as a concerted reaction (r) [13–15, 32].



(13)

Stepwise hydrogen-transfer, *e.g. via* $H-\ddot{N}-\ddot{N}:^{\ominus}$ can be ruled out. On the other hand, *cis*-hydrogen transfer by the unsymmetrical isomer of diimine, $H_2\overset{\oplus}{N}=\ddot{N}:^{\ominus}$, is not impossible. However, the fact that various sources of diimine have the same effect favors the symmetrical uncharged diimine, and the cyclic transition state requires the *cis*-form of diimine. While the infrared spectrum of solid diimine seems to indicate the exclusive occurrence of the *cis*-form, the configuration of gaseous diimine could so far not be determined unequivocally [32a].

If, as in the case of difluorodiimine, the energy of the *cis*-form is about 27 kcal/mole greater than that of the *trans*-form [33], *cis*-diimine must be formed from its precursors in a kinetically controlled reaction [14]. If the energy difference is less, it must be assumed that an equilibrium is rapidly reached between the isomers.

C. Substrate-Specificity of the Hydrogenation

In agreement with the symmetrical transition state *(13)*, the hydrogenation with diimine has a high substrate specificity. Unsymmetrical multiple bonds such as

$$C\equiv N,\ -NO_2,\ -N=C\langle,\ \rangle S=O$$

are not attacked [13, 14, 34], and no hydrogenolysis of the bonds

Ar–I, Ar–Br, R–Br, R–SH, R–S–S–R, R–S–C–S–R

can be observed [13, 14, 34]. Instead, hydrogen is generally transferred to symmetrical multiple bonds of the type

$$C=C,\ \rangle C=C\langle,\ N=N-,\ O-O$$ [34].

This pronounced difference permits selective hydrogenations. Since even the labile disulfide bond remains intact, diallyl sulfide can be smoothly hydrogenated to give dipropyl sulfide in 93 to 100% yield. This reaction cannot be accomplished by any other route [34].

The N=N double bond of azobenzene takes up hydrogen smoothly from various sources of diimine [8, 14, 16, 17, 25, 26]. Azodicarboxamide is a very active hydrogen acceptor. This compound, which is almost insoluble in water, not only reacts in suspension with diimine, but is even hydrogenated by hydrazine itself [14]. This shows that *Thiele*'s experiment [Equations (a) and (b)] gives no information about the disproportionation of diimine, and that *Raschig*'s interpretation [5a, 5b] is probably correct (see Section 1). The nature of the olefin has a strong influence on the relative rates of hydrogenation, as can be seen from Figure 1. The deviation of the hydrogenation curves from the theoretical straight line results from competition between the hydrogenation of the olefin and the secondary reactions of the diimine. Since only the olefin is varied under the standardized conditions, it is possible to calculate the relative rates of hydrogenation [14, 35]. Table 2 shows the values obtained for a number of olefinic carboxylic acids, based on a value of 100 for fumaric acid [14]. The table also shows the degree of hydrogenation after the liberation of one equivalent of diimine. The differences in the relative rates of hydrogenation exhibit the following regularities which also confirm the cyclic transition state *(13)*:

Table 2. Yield (C/O) on hydrogenation of olefinic carboxylic acids, and relative rates of hydrogenation v_r (cf. Fig. 1).

	Olefinic carboxylic acid	C/O·100 [%]	v_r
1	fumaric acid	80	100
2	acrylic acid [36]	ca. 74	ca. 52
3	undecenoic acid	69	40
4	maleic acid	41	10
5	maleamic acid [36]	38	8
6	crotonic acid [36]	22	5
7	methylfumaric acid	18	3
8	methylmaleic acid	4	0.7
9	ethylenetetracarboxylic acid [36]	2.9	0.3
10	β,β-dimethylacrylic acid	2.6	0.3
11	dimethylfumaric acid	≈0	0.0
12	dimethylmaleic acid	≈0	0.0
13	*trans*-cinnamic acid	41	10
14	*p*-dimethylaminocinnamic acid	32	8
15	*p*-methoxycinnamic acid	37	8
16	*p*-chlorocinnamic acid	37–39	8–9
17	*p*-nitrocinnamic acid	35–44	7–11
18	*o*-chlorocinnamic acid	44	11
19	*cis*-cinnamic acid	20	3
20	α-methylcinnamic acid	5	1.4
21	β-methylcinnamic acid	5	1.4

1. *trans*-olefins are hydrogenated 3–10 times faster than *cis*-olefins (cf. compounds nos. 1 and 4; 7 and 8; 13 and 19 in Table 2);

2. the rate of hydrogenation decreases rapidly with increasing number of substituents on the double bond (one substituent: nos. 2, 3; two substituents: nos. 1, 4, 5, 6, 13, 19; three substituents: nos. 7, 8, 10, 20, 21; four substituents: nos. 9, 11, 12 in Table 2).

The relative ease of hydrogenation by diimine of all positional and stereoisomeric n-undecanes confirms these results [37].

Points 1 and 2 are to be expected in general for cyclic transition states in additions to double bonds [38], as was shown by systematic investigations of the 1,3-dipolar addition [38] and the diene addition [39]. Since, in the transition state, the bond angles of the olefin are compressed from 120° to about

[32a] *E. J. Blau* and *B. F. Hochheimer*, J. chem. Physics *41*, 1147 (1964).

[33] *C. G. Hoffman* and *R. G. Neville*, Chem. Reviews *62*, 1 (1962).

[34] *E. E. van Tamelen, R. S. Dewey, M. F. Lease*, and *W. H. Pirkle*, J. Amer. chem. Soc. *83*, 4302 (1961).

[35] *S. Hünig* and *H. R. Müller*, Angew. Chem. *74*, 215 (1962); Angew. Chem. internat. Edit. *1*, 213 (1962).

[36] Unpublished work together with *H. R. Müller*.

[37] *F. Asinger, B. Fell, G. Hadik*, and *G. Steffan*, Chem. Ber. *97*, 1568 (1964). According to *F. Aylward* and *M. Sawistowska* [18], *cis*-olefins react somewhat more rapidly than *trans*-olefins; this result should, however, be checked.

[38] *R. Huisgen, H. J. Sturm*, and *H. Wagenhofer*, Z. Naturforsch. *17b*, 202 (1962); *R. Huisgen*, Angew. Chem. *75*, 742 (1963); Angew. Chem. internat. Edit. *2*, 633 (1963).

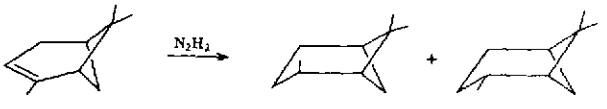
[39] *J. Sauer, H. Wiest*, and *A. Mielert*, Z. Naturforsch. *17b*, 203 (1962); *J. Sauer, D. Lang*, and *H. Wiest*, ibid. *17b*, 206 (1962). Chem. Ber. *97*, 3208 (1964).

109°, substituents on the double bond increase the activation energy. *Cis*-substituents are more strongly affected by this change in bond angle than *trans*-substituents, so that *cis*-olefins react more slowly than their *trans*-isomers. Moreover, there are specific substituent effects, since deactivation increases in the order $-CO_2^{\ominus} < -C_6H_5 < -CH_3$, *i.e.* the bulk of the substituents is not the only determining factor. It is not yet known whether this is due mainly to a difference in the electron density of the double bond or to specific solvation (aqueous medium) [40]. A strong effect due to the π-electron density is inconsistent with point 3, which is compatible with a cyclic intermediate.

3. *p*-Substituents in the phenyl nucleus have almost no effect on the hydrogenation rate. Their effect is even less than in the case of 1,3-dipolar additions [38]. Since 70 kcal/mole are liberated during hydrogenation [7, 16], the position of the equilibrium, according to the Hammond principle [41], must be assumed to lie well on the side of the substrate. The slight electronic substituent effect fits into this picture.

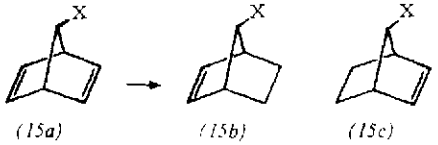
It is remarkable that dimethylmaleic acid is hydrogenated with hydrazine/H_2O_2 in methanol [32], while neither this compound nor the more reactive dimethylfumaric acid are appreciably hydrogenated under our conditions, even when nine equivalents of diimine are used [14]. This agrees with the fact that Δ^9-octalin is not attacked by decomposing benzenesulfonyl hydrazide in boiling glycol monomethyl ether [21].

As a result of the high stereoselectivity and the steric relationships in the transition state *(13)*, diimine always attacks the olefin from the least hindered side, even if this gives rise to the thermodynamically labile hydrogenation product [42]. This stereokinetic control is shown especially in the case of α-pinene *(14)* which reacts with diimine to give a 99% yield of *cis*-pinane *(15)* (having the methyl group in the less favorable position) [42].



(14) *(15)*, 99% 1%

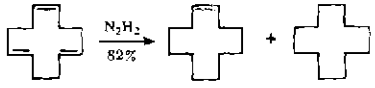
Norbornadienes *(15a)* substituted at the 7-position are hydrogenated at the *syn*-double bond and yield *(15b)* instead of *(15c)* as expected. Deuterium atoms are introduced in *exo*-positions, using N_2D_2 as reagent [42a].



(15a) *(15b)* *(15c)*

X = OH, $OCO\text{-}CH_3$, $OC(CH_3)_3$

The rigidity of the ring of *cis*, *trans*, *trans*-1,5,9-cyclododecatriene *(15d)* produces large differences in the conformations of the possible transition states for the diimine reaction, so that specific hydrogenation of the *trans*-double bonds is possible. Such a marked selectivity is not observed with acyclic olefins.



(15d) 95 : 5

V. Hydrogenations with "Hydrazine"

The discovery that double bonds are not hydrogenated by hydrazine itself, but by diimine formed by oxidation, provides the key to many hydrogenations which were formerly attributed to hydrazine [43].

As early as 1914, *Falciola* and *Mannino* isolated the hydrazide of stearic acid from a mixture of oleic esters and hydrazine hydrate which had been allowed to stand at room temperature [44]. This surprisingly mild, and at the same time unexpected, hydrogenation of an isolated olefinic double bond has since then been repeatedly observed, both with the esters [44–46] and with the unsaturated fatty acids themselves [47, 48]. This reaction is even recommended in one patent for the hardening and refining of oils [49].

If, in the last step of the synthesis of dioleyl cephalins, the phthaloyl residue is eliminated as usual [50] using hydrazine, hydrogenation occurs [51].

Systematic investigations of the hydrogenation of unsaturated fatty acids by "hydrazine" suffer from poor reproducibility [52–57]. Nevertheless, it has been possible to show that the double bond does not migrate during the hydrogenation [53, 55, 58], nor does it isomerize to the *trans*-form [58]. Thus, the positions of the double bond in the chain can be unambiguously marked by N_2D_4, whereas catalytic deuteration may be accompa-

[40] The polarizability of the substituents may play some part; cf. [38].

[41] *G. S. Hammond*, J. Amer. chem. Soc. *77*, 334 (1955).

[42] *E. E. van Tamelen* and *R. J. Timmons*, J. Amer. chem. Soc. *84*, 1067 (1962).

[42a] *W. C. Baird jr.*, *B. Franzus*, and *J. H. Surridge*, Abstr. 148th Meeting ACS, Chicago, Div. org. Chemistry. p. 915 (1964).

[43] The well-known reductions with hydrazine and a catalyst (palladium, Raney nickel, *etc.*) do not relate to the present problem [cf. *A. Furst* and *R. E. Moore*, J. Amer. chem. Soc. *79*, 5492 (1957); *Houben-Weyl*: Methoden der organischen Chemie. Thieme-Verlag, Stuttgart 1957, Vol. 11, p. 454].

[44] *P. Falciola* and *A. Mannino*, Ann. Chim. applicata *2*, 351 (1914).

[45] *P. Falciola*, Gazz. chim. ital. *50* I, 162 (1920); Chem. Zbl. *1920* III, 276.

[46] *J. van Alphen*, Recueil Trav. chim. Pays-Bas *44*, 1064 (1925).

[47] *J. Hanuš* and *J. Vořišek*, Collect. Trav. chim. Tchécoslov. *1*, 223 (1929); Chem. Zbl. *1929*, II, 551.

[48] *J. Vořišek*, Chem. Listy *26*, 285 (1932).

[49] Brit. Pat. 621037 (1945), inventor: *E. L. D'Astecky-Callery*.

[50] *H. R. Ing* and *R. H. Manske*, J. chem. Soc. (London) *1926*, 2348.

[51] *T. Malkin*, Chem. and Ind. *1961*, 605.

[52] *M. K. Pajari*, Fette u. Seifen *51*, 347 (1944).

[53] *F. Aylward* and *C. V. Narayana Rao*, J. appl. Chem. *6*, 248, 559 (1956); *7*, 134, 137 (1957).

[54] *C. V. Narayana Rao*, J. sci. ind. Res. (New Dehli), Sect. B *17*, 204 (1958); *18*, 131 (1959); Chem. Abstr. *53*, 1125 (1959); *53*, 21631 (1959).

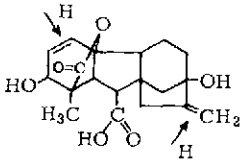
[55] *K. Schilling*, Fette u. Seifen *63*, 421 (1961); *65*, 395 (1963).

[56] *C. R. Scholfield*, *E. P. Jones*, *J. Nowakowska*, *E. Selke*, and *H. J. Dutton*, J. Amer. Oil Chemists' Soc. *38*, 208 (1961).

[57] *N. Dinh-Nguyen*, *R. Ryhage*, and *S. Ställberg-Stenhagen*, Ark. Kemi *15*, 433 (1960).

[58] *B. N. Tyutyunnikov* and *I. J. Novitzkaya*, Masloboino-Zhirovaya Prom. *24*, 12 (1958).

nied by migration of the double bond [57]. Competitive experiments show that terminal double bonds are more rapidly hydrogenated than non-terminal ones, and are conjugated more rapidly than isolated double bonds [55]. However, the differences are too small to be of preparative use (cf. Table 2) [13,14]. Hydrogenation with "hydrazine" has scarcely found any application outside fatty-acid chemistry, with the exception of *Hans Fischer*'s hydrogenation of vinyl groups in porphyrins [59] and, more recently, *Cross*' hydrogenation of gibberellic acid *(16)* [60] which has also been reduced with diimine [16].



(16)

In all these reactions the significance of atmospheric oxygen remained hidden, and was ultimately recognized by *Hünig* [13-15], *Corey* [16], and *Aylward* [18,61]. The hydrogenation of aromatic azocompounds by hydrazine [62,63] also requires air [14,36].

VI. Secondary Reactions of Diimine

Let us now consider how diimine reacts when there is no foreign acceptor for the labile hydrogen, *i.e.* whether the diimine is disproportionated into hydrogen and hydrazine, as suggested by *Thiele* [3], or whether it decomposes into its elements, in agreement with *Raschig*'s hypothesis [5a, 5b] [cf. Section I].

A. Competition between Disproportionation and Decomposition

The answer was first found with benzenesulfonyl hydrazide as the source of diimine, since in this case nitrogen and hydrogen can be quantitatively determined without interference by the oxidizing agent or the source of diimine [21,64].

As is shown in Figure 2, the decomposition of benzenesulfonyl hydrazide follows *Raschig*'s scheme [5a, 5b] [Equation (c); Section I] quantitatively only in strongly alkaline solution. As the concentration of alkali decreases, the volume of gas also decreases, although all the sulfonyl hydrazide is consumed. Gas analysis shows that the hydrogen component decreases twice as rapidly

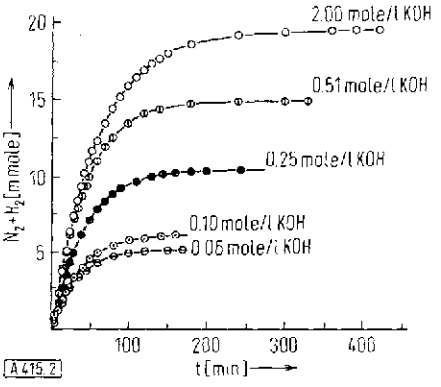


Fig. 2. Gas yield ($N_2 + H_2$) during the decomposition of 10.0 mmoles of benzenesulfonyl hydrazide in 165 ml of glycol monomethyl ether at 99 °C, as a function of the KOH concentration and of time.

in volume as the nitrogen component, until finally, in a weakly alkaline medium, the gas liberated consists only of nitrogen (Table 3). It can be seen from Table 3 that the quantity of gas ($N_2 + 2\ H_2$) required to make up the amount expected from *Raschig*'s scheme [Equation (c)] appears quantitatively as hydrazine, since it is found that, within the limit of error,

$$[N_2 + H_2] + 3\ [N_2H_4] = 200\,\%.$$

Table 3. Total quantity of gas and quantities of hydrazine, hydrogen, and nitrogen obtained on cleavage of 10 mmoles of benzenesulfonyl hydrazide in 165 ml of glycol monomethyl ether at 99 °C.

KOH [moles/l] [a]	$N_2 + H_2$ [%] [b]	N_2 [%] [c]	H_2 [%] [c]	N_2H_4 [%] [c]	Diimine	
					Disproportionation [%]	Decomposition [%]
2.00	196	99	97	1	3	97
0.51	150	83	67	17	33	67
0.25	104	67	37	32	63	37
0.10	62	54	8	46	92	8
0.06	52	51	1	49	99	1

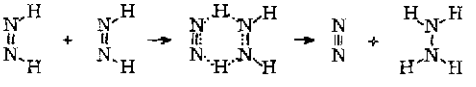
[a] Initial KOH concentration.

[b] 2 moles per mole of benzenesulfonyl hydrazide ≡ 200 %.

[c] 1 mole per mole of benzenesulfonyl hydrazide ≡ 100 %.

The decomposition of diimine gives rise to products of composition ($2\ N_2 + 2\ H_2$), while the disproportionation gives products of composition ($N_2 + N_2H_4$). The disproportionation products therefore lack gas of composition ($N_2 + 2\ H_2$) as compared to the decomposition products. *Thus the disproportionation and decomposition of diimine are competitive reactions.*

The disproportionation can be formulated as the hydrogenation of a second molecule of diimine, in which, by



(17)

analogy with the hydrogenation of olefins [cf. *(13)*], a cyclic transition state *(17)* is likely. The liberated energy of 75 kcal/mole [7,16] corresponds to that of the hydrogenation of olefins. The decomposition of diimine is base-catalysed, and so presumably proceeds according to Equation (s) *via* the anion of diimine, from which a hy-

[59] *H. Fischer* and *H. Gibian*, Liebigs Ann. Chem. *548*, 183 (1941).

[60] *E. Cross*, J. chem. Soc. (London) *1960*, 3028.

[61] *F. Aylward* and *M. Sawistowska*, Chem. and Ind. *1961*, 404, 433.

[62] *W. C. J. Ross* and *G. P. Warwick*, Nature (London) *176*, 298 (1955); J. chem. Soc. (London) *1956*, 1724.

[63] *W. H. Stafford*, *M. Los*, and *N. Thomson*, Chem. and Ind. *1956*, 1277.

[64] *S. Hünig*, *H. R. Müller*, and *W. Thier*, Angew. Chem. *75*, 298 (1963); Angew. Chem. internat. Edit. *2*, 214 (1963).

dride ion, and hence ultimately hydrogen, is liberated [Equation (t)]. The possibility that the decomposition

$$HN{=}N{-}H + :B^{\ominus} \rightleftarrows HN{=}N{:}^{\ominus} + HB \qquad (s)$$

$$HN{=}N{:}^{\ominus} \rightarrow N_2 + H^{\ominus} \qquad (t)$$

$$H^{\ominus} + HB \rightarrow :B^{\ominus} + H_2$$

proposed by *Raschig* does not proceed from the diimine stage, but directly from the sulfonyl hydrazide anion

$$R{-}SO_2{-}\overset{\ominus}{\underset{(18)}{N}}{-}NH_2 \rightarrow RSO_2^{\ominus} + N_2 + H_2$$

(18), can be ruled out, owing to the similar behavior of other sources of diimine.

If *N,N'*-bis(methoxycarbonyl)anthracene-9,10-bisimine *(3)* is hydrolysed in boiling glycol monomethyl ether at *e.g.* 125 °C, *i.e.* under conditions in which the expected bisimine *(5)* immediately loses diimine, the quantity of gas liberated again increases with increasing KOH concentration. The decomposition of the diimine liberated in this way therefore shows the same dependence on the concentration of the base (see Fig. 3) [36].

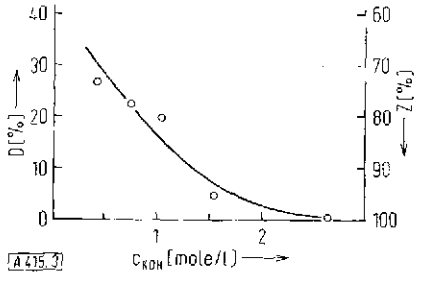


Fig. 3. Disproportionation (D [%]) and decomposition (Z [%]) of the diimine liberated from 1.4 mmole of *N,N'*-bis(methoxycarbonyl)-anthracene-9,10-bisimine *(3)* in 25 ml of boiling glycol monomethyl ether, as a function of the KOH concentration (c_{KOH}).

B. Competition between Decomposition and Hydrogenation of Olefins

Since the hydrogenation of olefins proceeds *via* neutral diimine, the deprotonation and subsequent decomposition of the latter in strongly alkaline solution greatly reduces the yield of hydrogenation product. Thus, tolane is no longer attacked by decomposing benzenesulfonyl hydrazide in 2.5 N KOH/glycol monomethyl ether; the more reactive styrene, on the other hand, is hydrogenated to 77% under the same conditions [21]. It can, therefore, be concluded that either the deprotonation rate of diimine is similar to the hydrogenation rate of the olefin, or, as shown in Equation (s), deprotonation leads to rapid establishment of an equilibrium, and the decomposition rate of the anion is of the same order of magnitude as the hydrogenation rate of the olefin. The second interpretation would explain a rapid *cis-trans* isomerization of the diimine.

Competition by Raschig decomposition of the diimine is also responsible for reducing the yield of hydrogenation product as the alkali concentration in the system hydrazine/hexacyanoferrate(III)/undecenoic acid [13,14] is increased.

Where sulfonyl hydrazides are used as sources of diimine, it has been possible in every case investigated to eliminate this undesirable side-reaction completely by using ethanolamine as the base. The diimine formed exclusively undergoes disproportionation [see Reaction (u)]. These are also the best conditions for hydrogenating

$$R{-}SO_2{-}NH{-}NH_2 \xrightarrow[-\,BH^{\oplus}]{+:B} RSO_2^{\ominus} + N_2H_2 \rightarrow \underbrace{{}^1/_2\,N_2 + {}^1/_2\,N_2H_4} \qquad (u)$$

olefins; no by-products containing sulfur are formed [21]. (Cf. thermal cleavage of sulfonyl hydrazides, Section VIII).

C. Competition between Disproportionation and Hydrogenation of Olefins

Since the disproportionation of diimine can be regarded as an autohydrogenation, it competes with the hydrogenation of olefins, as indicated in Scheme (v).

$$HN{=}NH \begin{cases} \xrightarrow{HN=NH} N_2 + H_2N{-}NH_2 \\ \xrightarrow{>C{=}C<} N_2 + >\underset{H}{C}{-}\underset{H}{C}< \end{cases} \qquad (v)$$

Thus, at a given diimine concentration, the disproportionation is suppressed by a higher olefin concentration, as can be seen from Figure 4 [21]. The ratio of the rates of the two

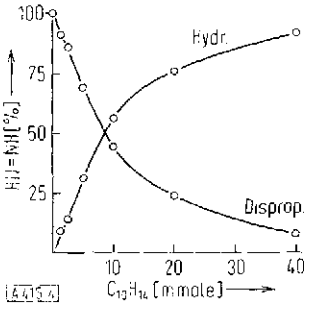


Fig. 4. Disproportionation and hydrogenation of olefins during the reaction of 10 mmoles of benzenesulfonyl hydrazide with dihydrodicyclopentadiene ($C_{10}H_{14}$) in 150 ml of glycol monomethyl ether/ethanolamine at 78.8 °C.

reactions naturally also depends on the ease of hydrogenation of the olefin (see Section IV, B and C). Moreover, the temperature coefficients of the two competing reactions are very different. Thus, if diimine is liberated from various substituted benzenesulfonyl hydrazides at temperatures of equal decomposition rates, the same stationary diimine concentration leads to widely different yields of hydrogenation product (Table 4) [21]. Owing to the higher activation energy

Table 4. Reaction of sulfonyl hydrazides (5m moles) with dihydrodicyclopentadiene (5 mmoles) in glycol monomethyl ether/ethanolamine (60 ml).

Hydrazide	Temp. [°C]	Disprop. of N_2H_2	N_2H_2 effecting hydrogenation
$C_6H_5{-}SO_2N_2H_3$	104.9	55 ± 2	45 ± 2
m-NO_2-$C_6H_4{-}SO_2N_2H_3$	78.8	69	31
o-$NO_2{-}C_6H_4{-}SO_2N_2H_3$	39.1	97	3

for the hydrogenation of olefins as compared to their disproportionation, high yields of hydrogenation product are to be expected at high temperatures.

Consideration of Table 4, together with the data for *p*-nitrobenzenesulfonyl hydrazide [21], shows that the rate of cleavage increases in the following order:

$$H \ll p\text{-}NO_2 < m\text{-}NO_2 \ll o\text{-}NO_2 \text{ [65]}$$

In fact, the only secondary reaction of diimine in weakly basic media is hydrogen transfer to a symmetrical double bond, even in the presence of hexacyanoferrate(III). Thus, if a solution of hydrazine is added to the undecenoic acid/hexacyanoferrate(III) solution, the olefin will be extensively hydrogenated, in spite of the permanent excess of oxidizing agent. This result of reversing the reaction procedure was completely unexpected and provides strong evidence that the further oxidation of diimine is of no importance in the hydrogenation of olefins.

The stoichiometric conversion (w) [10, 29]

$$N_2H_4 + 4\ [Fe(CN)_6]^{3\ominus} + 4\ OH^{\ominus} \rightarrow N_2 + 4\ [Fe(CN)_6]^{4\ominus} + 4\ H_2O \quad (w)$$

therefore corresponds only to the diimine stage of a direct oxidation (x).

$$N_2H_4 + 2\ [Fe(CN)_6]^{3\ominus} + 2\ OH^{\ominus} \rightarrow N_2H_2 + 2\ [Fe(CN)_6]^{4\ominus} + 2\ H_2O \quad (x)$$

The subsequent disproportionation (y)

$$2\ N_2H_2 \longrightarrow N_2 + N_2H_4 \quad (y)$$

yields hydrazine, which is again oxidized to the diimine. The anodic oxidation of hydrazine can be similarly interpreted [11].

As regards the rates of the two competing reactions, only that of the disproportionation increases with the square of the intermediate diimine concentration (the rate of the hydrogenation of olefins increases with the first power of the diimine concentration). The yield of hydrogenation product is therefore reduced, *e.g.* in the system $N_2H_4/[Fe(CN)_6^{3\ominus}]$/undecenoic acid, under all conditions leading to an increase in the diimine concentration [13, 14, 36]:

a) increased rate of addition of the $[Fe(CN)_6]^{3\ominus}$ solution to N_2H_4/undecenoic acid,

b) increased rate of addition of N_2H_4 to $[Fe(CN)_6]^{3\ominus}$/undecenoic acid,

c) increased N_2H_4 concentration in the N_2H_4/undecenoic acid mixture, and

d) increased $[Fe(CN)_6]^{3\ominus}$ concentration in the $[Fe(CN)_6]^{3\ominus}$/undecenoic acid mixture.

[65] *A. Th. Dunn* and *W. Davies*, J. chem. Soc. (London) *1929*, 1050; *W. Davies, F. R. Storrie*, and *St. H. Tucker*, ibid. *1931*, 624.

VII. Reduction of Nitrobenzenesulfonyl Chlorides with Hydrazine

If nitrobenzenesulfonyl chlorides in benzene are added dropwise to excess hydrazine in alcohol at 30 to 60 °C, a high yield of sulfinic acid is formed, together with the calculated quantity of nitrogen, corresponding to Equation (z) [65]. The reaction can be used both for the preparation of sulfinic acids and (by variation of the temperature) for the separation of isomeric nitrobenzenesulfonyl chlorides [65]. According to the results available

$$2\ ArSO_2Cl + 2\ N_2H_4 \rightarrow 2\ ArSO_2H + N_2 + N_2H_4 \cdot 2\ HCl \quad (z)$$

at present, the initially formed sulfonyl hydrazide (cf. Table 4) undergoes cleavage according to Equation (α).

$$2\ ArSO_2\text{–}NH\text{–}NH_2 \rightarrow 2\ ArSO_2H + 2\ N_2H_2 \rightarrow N_2 + N_2H_4 \quad (\alpha)$$

The sulfonyl chloride is therefore not directly reduced either by hydrazine or by diimine [21].

VIII. Thermal Cleavage of Benzenesulfonyl Hydrazide

The cleavage of benzenesulfonyl hydrazide described in Section VII is apparently in contradiction to the technically used thermal decomposition [66] which corresponds to the overall Equation (β). The products are *S*-phenyl

$$4\ C_6H_5\text{-}SO_2\text{-}NH\text{-}NH_2 \xrightarrow{100\text{–}140^{\circ}C} C_6H_5\text{-}SO_2\text{-}S\text{-}C_6H_5 + C_6H_5\text{-}S\text{-}S\text{-}C_6H_5 + 4\ N_2 + 6\ H_2O \quad (\beta)$$

(19)

benzenethiosulfonate *(19)* [67] and diphenyl disulfide [68], while all the nitrogen is liberated as gas [68]. Reaction (β) proceeds in stages, as is shown by the rate of evolution of nitrogen in solution (Fig. 5) [21].

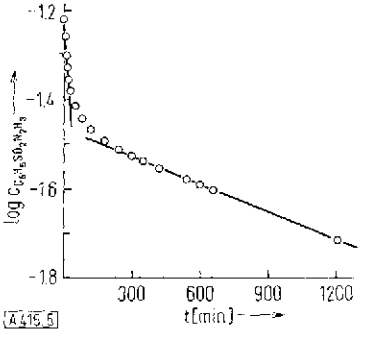


Fig. 5. Course of the thermal cleavage of benzenesulfonyl hydrazide (10 mmoles) in glycol monomethyl ether (165 ml) at 119.2 °C

Only the initial reaction corresponds to the cleavage of the sulfonyl hydrazide in accordance with Equation (γ).

[66] *F. Lober*, Angew. Chem. *64*, 71 (1952); *F. Muth* in *Houben-Weyl*: Methoden der organischen Chemie. 2nd Edit., Thieme-Verlag, Stuttgart 1955, Vol. 9, p. 650.

[67] *J. Cymerman* and *J. B. Willis*, J. chem. Soc. (London) *1951*, 1332.

[68] *Th. Curtius* and *F. Lorenzen*, J. prakt. Chem. *58*, 160 (1898).

This is shown by the preparative hydrogenation of olefins [15, 19–21]. If the disproportionation is suppressed

$$Ar\text{-}SO_2\text{-}NH\text{-}NH_2 \xrightarrow{k_1} ArSO_2H + N_2H_2 \quad (\gamma)$$

$$N_2H_2 \xrightarrow{fast} {}^1/_2\,N_2 + {}^1/_2\,N_2H_4$$

by an excess of styrene, the yield of gas is doubled, while the cleavage proceeds at almost the same rate ($k_1 = 8.2 \times 10^{-2}$ min^{-1}).

As a result of the initial cleavage, sulfinic acid and hydrazine are formed in the ratio 2:1. The reaction stops at this stage if the sulfinic acid is neutralized by a base (see Section VI, B and Figure 2). If the corresponding quantity of hydrazinium dibenzenesulfinate $[(C_6H_5SO_2H)_2 N_2H_4]$ [68] is decomposed under the conditions of Figure 5, nitrogen is liberated at the rate ($k_2 = 1.5 \times 10^{-3}$ min^{-1}) which characterizes the second stage of the cleavage. Again, diimine is formed initially, as can be shown by the hydrogenation of allylbenzene. Thus, it must be assumed that benzenesulfonyl hydrazide is regenerated

$$2\ ArSO_2H \xrightarrow{fast} Ar\text{-}SO_2\text{-}SO\text{-}Ar + H_2O$$

$$Ar\text{-}SO_2\text{-}SO\text{-}Ar \xrightarrow{slow} (Ar\text{-}SO_2\text{-}O\text{-}S\text{-}Ar) \quad (\delta)$$

in the second stage, although it is still unknown whether this is preceded by the reaction sequence (δ) [69] which could be followed by formation of the hydrazide as follows:

$$(ArSO_2\text{--}O\text{--}S\text{-}Ar) + H_2N\text{-}NH_2 \rightarrow ArSO_2\text{-}NH\text{--}NH_2 + (ArSOH). \quad (20)$$

The expected sulfenic acid *(20)* is known to disproportionate in accordance with Scheme (ε) to form the products observed in the cleavage of benzenesulfonyl hydrazide [70].

$$4\ (C_6H_5\text{-}SOH) \rightarrow 2\ (C_6H_5\text{--}SO\text{--}S\text{--}C_6H_5) + 2\ H_2O \quad (\varepsilon)$$

(20)

$$2\ (C_6H_5\text{-}SO\text{-}S\text{-}C_6H_5) \rightarrow C_6H_5\text{-}S\text{-}S\text{-}C_6H_5 + C_6H_5\text{--}SO_2\text{-}S\text{-}C_6H_5$$

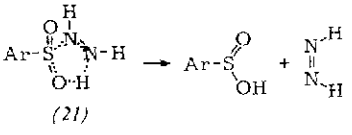
This Scheme (ε), which has yet to be confirmed in detail, satisfies the stoichiometry of the overall reaction. Thus the quantitative liberation of nitrogen in the thermolysis of benzenesulfonyl hydrazide requires formation of free sulfinic acid. It should also be mentioned that the initial thermal cleavage of benzenesulfonyl hydrazide requires a much higher ordering in the transition state than does the cleavage in the presence of ethanolamine (Table 5) [21].

Table 5. Thermal cleavage of benzenesulfonyl hydrazide (10 mmoles) in glycol monomethyl ether (165 ml).

Base	Temp. [°K]	$k_1 \times 10^2$ [min^{-1}] [a]	E_A [kcal/mol] [b]	$\Delta H^{\neq}$ [kcal/mol] [b]	$\Delta G^{\neq}$	$\Delta S^{\neq}$ [cal/deg./mole] [c]
0.91 M ethanolamine	352.0	0.71	23.5	22.8	27.0	−12.0
	372.3	4.4			27.3	−12.2
none	372.3	1.94	20.9	20.1	27.9	−21.0
	392.4	8.26			28.3	−20.9

[a] Mean relative error: ± 2 %.
[b] Mean relative error: ± 3 %.
[c] Margin of error: ± 6 %.

For the same free energy of activation, $\Delta G^{\neq}$, of 27 to 28 kcal/mole, the entropy loss associated with the transition state in the thermal cleavage of benzenesulfonyl hydrazide is almost twice as large as when a proton acceptor is present; therefore, a transition state *(21)* is likely.



(21)

IX. Outlook

During the last decade, the use of unstable neutral organic substances has led to many novel reactions. An excellent example of this is carbene chemistry [71]. Similarly, the field of organic syntheses should profit from the use of labile neutral inorganic substances [19]. Here the chemistry of the imenes [72] and of diimine are the first results.

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[69] *J. L. Kice* and *N. E. Pawlowski*, J. org. Chemistry *28*, 1162 (1963).

[70] *H. J. Backer* and *H. Kloosterziel*, Recueil Trav. chim. Pays-Bas *73*, 129 (1954).

[71] Recent reviews: *Ph. Miginic*, Bull. Soc. chim. France *1962*, 2000; *E. Chinoporos*, Chem. Reviews *63*, 235 (1963).

[72] *Cf. L. Horner* and *A. Christmann*, Angew. Chem. *75*, 707 (1963); Angew. Chem. internat. Edit. *2*, 599 (1963).

Exchange Rates of Ligands in Complex Ions

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It is possible to study the very rapid exchange rates between molecules or ions, L, coordinated to paramagnetic ions and the free molecules or ions, L, in the body of the solution by measuring the line width of the NMR signal of L*.*

$$ML_n + L^* \rightleftharpoons ML_n^* + L$$

Lifetimes of coordinated ligands that can be measured fall into the range of milliseconds to microseconds. The lifetime, or an upper limit to the lifetime, can be measured directly.

1. Introduction

The effect of rapid chemical exchange in an equilibrium situation on nuclear magnetic resonance spectra has given us the rates of many types of exchange that have not been accessible by other methods. As examples, these types of reactions have included: exchange of hydroxylic protons in alcohols, alcohol-water mixtures, hydrogen peroxide solutions, and of amine protons in aqueous amine solutions; rates of rotation about chemical bonds as in ring inversion in cyclohexane derivatives and rates of rotation about the OC–N bond in amides; rates of ligand exchange in transition metal complexes [1].

The determination of rates of exchange in paramagnetic complexes depends upon the fact that the coordinated species has a much shorter nuclear spin lifetime (larger line width of the NMR signal) than the uncoordinated species in the bulk solution.

The nuclear spin lifetime is short in a paramagnetic environment because the nucleus is subjected to strong, fluctuating magnetic fields from the unpaired electrons which are responsible for the paramagnetism. These magnetic fields act on the small magnetic dipole of the nucleus and cause it to "flip over", or change its direction. Thus, the lifetime of a given spin state (*i.e.* the orientation of the magnetic dipole) is shortened.

2. Mathematical Principles

The shape of NMR signals in the absence of chemical exchange can be predicted from the Bloch equations [2]. *Gutowsky*, *McCall*, and *Slichter* [3] first published a solution of the Bloch equations corrected to account for the effects of chemical exchange of the nucleus between sites that are not equivalent in nuclear magnetic resonance. Later, *McConnell* published a mathematically simpler approach [4]. *Swift* and *Connick* [5] have published the most rigorous derivation of the equations relating NMR line shapes and lifetimes of ligands in paramagnetic environments for use where only the solvent resonance is observed. Their derivation proceeds after the method of *McConnell* in the following manner:

The first step is the addition of terms to the differential Bloch equations to include transfer of magnetization among three magnetically unequivalent species present in the solution. These species are the uncoordinated potential ligand present in the bulk solution (subscript a) and two possible types of coordinated ligands (subscripts b and c). The original Bloch equation for the rate of change of the magnetization of the uncoordinated species, G_a, is [2]:

$$\frac{dG_a}{dt} = -\frac{G_a}{T_{2a}} + iG_a\Delta\omega_a - i\gamma H_1 Mo_a \qquad (1)$$

In this equation $\Delta\omega_a = (\omega - \omega_a)$, where ω is the applied radiofrequency (customarily 40–60 Mc), and ω_a is the resonance frequency for species a. Mo_a is the maximum magnetization of species a in the direction of the high external magnetic field, γ is the gyromagnetic ratio of the proton, and H_1 is the low magnetic field strength of the applied radiofrequency. Also, T_{2a} is the transverse relaxation time for the species a. It may be regarded theoretically as being the mean lifetime of a spin state in the environment of a. Experimentally, T_{2a} is related to the line width ν_a at half peak height of the resonance signal for species a only:

$$\pi\nu_a = 1/T_{2a} \qquad (2)$$

The differential equation for the rate of change of G_a, corrected to account for chemical exchange is

$$\frac{dG_a}{dt} = i\gamma H_1 Mo_a + iG_a\Delta\omega_a - \frac{G_a}{T_{2a}} - \frac{G_a}{\tau_{ab}} - \frac{G_a}{\tau_{ac}} + \frac{G_b}{\tau_{ba}} + \frac{G_c}{\tau_{ca}} \qquad (3)$$

[1] A recent review article has covered the use of NMR spectroscopy in studying the kinetics of some of these reactions: *A. Loewenstein* and *T. M. Connor*, Ber. Bunsenges. physik. Chem. *67*, 280 (1963).

[2] A general discussion of the Bloch equations and the effects of chemical exchange is contained in *J. A. Pople*, *W. G. Schneider*, and *H. J. Bernstein*: High-resolution Nuclear Magnetic Resonance. McGraw-Hill, New York 1959, Chapter 10.

[3] *H. S. Gutowsky*, *D. W. McCall*, and *C. P. Slichter*, J. chem. Physics *21*, 279 (1953).

[4] *H. M. McConnell*, J. chem. Physics *28*, 430 (1958).

[5] *T. J. Swift* and *R. E. Connick*, J. chem. Physics *37*, 307 (1962).

where τ_{ab} is the lifetime for chemical exchange of "a" magnetization to b, τ_{ac} the lifetime for chemical exchange of "a" magnetization to c, τ_{ba} the lifetime for chemical exchange of "b" magnetization to a, and τ_{ca} the lifetime for chemical exchange of "c" magnetization to a.

There are two completely analogous equations for the rates of change of G_b and G_c.

The second step is the solution of the differential equations for the magnetization of the ligand free in solution. Chemical equilibrium and slow passage through resonance (slow variation of the high magnetic field) are assumed so that dG_a/dt, dG_b/dt, and $dG_c/dt = 0$. The assumption is also made that the uncoordinated species is present in large excess so that the total magnetization is essentially only that of the uncoordinated species. In such a dilute solution, the direct exchange of ligands between complexes would be rare and terms involving the lifetimes of such exchanges are dropped.

Finally, the complex equation for the magnetization of the uncoordinated species is solved for the imaginary component, which is proportional to the height of the NMR signal. The result is further simplified by the assumption that the resonance signal is being observed near the frequency of its maximum such that $\Delta\omega_a$ is nearly zero. The final equation for the NMR line shape is Lorentzian in form and may be solved for the line width at half height which is

$$\frac{1}{T_2} = \frac{1}{T_{2a}} + \sum_{j=b}^{c} \tau_{aj} \left[\frac{\frac{1}{(T_{2j})^2} + \frac{1}{T_{2j}\tau_{ja}} + \Delta\omega^2{}_j}{\left(\frac{1}{T_{2j}} + \frac{1}{\tau_{ja}}\right)^2 + \Delta\omega^2{}_j} \right] \quad (4)$$

In this equation, $1/T_{2_a}$ is the line width at half height in the absence of paramagnetic exchange, $1/T_{2j}$ is the much larger line width of the coordinated species b and c, τ_{ja} is the lifetime for chemical exchange of the coordinated ligand back into the solution, and $\Delta\omega_j$ is the chemical shift of species b or c from that of a. This equation is applicable to any number of paramagnetic components in the solution which may be included in the summation. The physical significance of the resultant equation is perhaps more easily seen from the simplified derivation by *Pearson* et al. [6]. This simplified equation assumes that only one paramagnetic environment is present in solution in small amount, and that $\Delta\omega_b$ as well as $\Delta\omega_a$ are small.

$$\frac{1}{T_2} = \frac{1}{T_{2a}} + \frac{P_b}{P_a}\left[\frac{1}{T_{2b} + \tau_{ba}}\right] \quad (5)$$

Here again $1/T_{2_a}$ is the line width of the signal of the uncoordinated ligand in the absence of chemical exchange, $1/T_{2_b}$ is the line width for the coordinated species, and P_b/P_a is the ratio of the molar concentration of the coordinated ligand to that of the uncoordinated ligand. It is seen that the line broadening produced by the paramagnetic species can be controlled by either the nuclear relaxation produced by the paramagnetism, if T_{2b} is greater than τ_{ba}, or by the length of time that the ligand spends in contact with the paramagnetism, if τ_{ba} is greater than T_{2b}. If the paramagnetism is relatively inefficient in producing line broadening (large T_{2b}), the line width will depend upon three laxation produced during the time of contact. If the paramagnetic relaxation is very efficient (small T_{2b}), the line width will depend upon the rate at which the paramagnetically relaxed nuclei are released into the bulk of the solution.

The NMR signal of the released ligand will be averaged with that of the uncomplexed and more abundant species. Measurement of the line broadening in solutions containing paramagnetic ions will, therefore, give at least the lower limit of the exchange rate.

It is possible to decide whether the observed line width is controlled by relaxation (T_{2b}) or chemical exchange (τ_{ba}) by temperature variation studies [6]. At a given concentration, $1/\tau_{ba}$ will behave as a (pseudo) first order rate constant and have a normal Arrhenius type temperature dependence. Hence, the line broadening (when dependent on τ_{ba}) will increase with increasing temperature. From the temperature variation, the value of the

$$1/\tau_{ba} = k = A\exp(-E_a/RT) \quad (6)$$

activation energy, E_a, can be found. A is a frequency factor which may be dependent on concentration.

The factor $1/T_{2b}$ will usually have a small temperature dependence, the correlation time being slightly dependent on temperature [*] [7]. However, $1/T_{2b}$ will be independent of changing concentrations since it is not a chemical rate constant.

3. Examples

a) Solvent as Ligand

The simplest chemical system to which the line broadening method can be applied is a solution of a paramagnetic salt in water. *Swift* and *Connick* [5] have applied the results of their derivation in detail to the ^{17}O line widths in aqueous solutions of manganous, cupric, nickel, cobaltous, and ferrous salts to determine the rates of solvation exchange in $M(H_2O)_6^{2+}$ ions as well as $\Delta H^{\neq}$ and $\Delta S^{\neq}$ of the exchange. The process involved is

$$M(H_2O)_6^{2+} + H_2O^* \rightleftharpoons M(H_2O^*)_6^{2+} + H_2O \quad (7)$$

Here, H_2O^* is a water molecule from the bulk of the solvent, M is a metal ion.

Since only two environments are considered [*i.e.* solvent (subscript H_2O) and complex (subscript M)] Equation (4) becomes:

$$\frac{1}{T_2} = \frac{1}{\tau_{H_2O}}\left[\frac{\frac{1}{(T_{2M})^2} + \frac{1}{T_{2M}\tau_M} + \Delta\omega_M^2}{\left(\frac{1}{T_{2M}} + \frac{1}{\tau_M}\right)^2 + \Delta\omega_M^2}\right] \quad (8)$$

[*] The correlation time is the average time that a molecule has before its position or condition with respect to the applied magnetic field changes. It may be the time of rotation of the molecule, the lifetime of a spin state of the unpaired electrons, or even the chemical exchange time. In general, whichever of these times is the shortest will be the correlation time. The relaxation time T_{2b} will be inversely proportional to the correlation time since the mechanisms for nuclear relaxation have a greater chance to operate during longer correlation times.

[6] *R. G. Pearson, J. Palmer, M. M. Anderson,* and *A. L. Allred,* Z. Elektrochem., Ber. Bunsenges. physik. Chem. *64,* 110 (1960).

[7] *R. A. Bernheim, T. H. Brown, H. S. Gutowsky,* and *P. E. Woessner,* J. chem. Physics *30,* 950 (1959).

Where τ_{ab} has been replaced by τ_{H_2O}, τ_{ba} by τ_M, T_{2b} by T_{2M}, and $\Delta\omega_b$ by $\Delta\omega_M$. Four possible cases arise for controlling factors in the line broadening:

1. $\Delta\omega_M^2 \gg 1/(T_{2M})^2 + 1/(\tau_M)^2$; $\quad 1/T_2 = 1/\tau_{H_2O}$

The relaxation of nuclear spins is caused by the large difference between the resonance frequencies in the coordinated state and in the bulk of the solution and is very rapid. In this case, the line broadening is controlled by the rate of exchange [$\tau_{ba} \gg T_{2b}$ in Equation (5)].

2. $1/(\tau_M)^2 \gg \Delta\omega_M^2 \gg 1/T_{2M}\tau_M$; $\quad 1/T_2 = P_M\tau_M\Delta\omega_M^2$

$P_M = \tau_M/\tau_{H_2O}$ proton fraction coordinated

The line broadening is controlled by the rate of relaxation through the change of resonance frequency, and the chemical exchange is rapid. This intermediate case is not covered by Equation (5).

3. $1/(T_{2M})^2 \gg \Delta\omega_M^2$ and $1/(\tau_M^2)$; $\quad 1/T_2 = 1/\tau_{H_2O}$

The relaxation is comparatively rapid and is controlled by the lifetime of the nuclear spin state. Therefore, the measured line width is controlled by the rate of chemical exchange [$\tau_{ab} \gg T_{2b}$ in Equation (5)].

4. $1/T_{2M}\tau_M \gg 1/(T_{2M})^2$ and $\Delta\omega_M^2$; $\quad 1/T_2 = P_M/T_{2M}$

The chemical exchange is comparatively rapid, $\Delta\omega_M$ is small and the line width is controlled by the nuclear spin relaxation in the complex [$T_{2b} \gg \tau_{ba}$ in Equation (5)].

Connick and *Swift* used the temperature dependence of the line width to determine which factors were controlling. Their results are shown in Table 1. *Pearson* et al. [6] utilized the fact that in ligands containing more than one kind of proton, the paramagnetic relaxation rate is inversely dependent upon the distance of the proton from the paramagnetic center. Therefore, if the line broadening is the same for two types of protons, it must be controlled by the exchange rate of the ligand.

Theoretical equations for the transverse relaxation rate, $1/T_{2M}$, have been given by *Solomon* [8] and *Bloembergen* [9]. There are two mechanisms, a dipole-dipole interaction and an isotropic contact interaction. The dipole-dipole interaction between an unpaired electron and a proton can operate over a certain distance. The contact interaction, on the other hand, depends upon coupling of the electron spin with the nuclear spin by the actual presence of the electron at the proton. It therefore requires close contact of the paramagnetic ion and the molecule containing the protons being studied. As a result some broadening of the NMR signal can occur due to dipole-dipole relaxation even for a molecule which is not directly coordinated to a paramagnetic ion. However, the effect does fall off with distance and is only significant when the molecule is in the layer right next to the coordinated layer. This line broadening is called "outer-sphere relaxation" and can be corrected for.

Table 1 gives some data for the rate of exchange of coordinated methanol [6] and ethylene glycol [10]. In these cases signals for CH and OH protons can be observed. Only for Ni^{2+} is the line broadening the same for both kinds of protons. In this case the rate of exchange is being measured. For the other metal ions the OH line broadening is greater than the CH line broadening. Hence, only a lower limit to the rate of exchange can be given using the OH data.

Table 1. Rate constants $1/\tau_M = k_{exchange}$ [sec^{-1}] for the exchange of water, methanol, and ethylene glycol coordinated to metal ions at 25 °C.

Metal ion	Water [a]	Methanol	Glycol[e]
Mn^{2+}	3×10^7	$>2.5\times10^5$ [c]	$>1.5\times10^6$
Fe^{2+}	3×10^6	—	$>2.5\times10^3$
Co^{2+}	1×10^6	1.8×10^4 [d]	$>3.4\times10^3$
Ni^{2+}	3×10^4	1.0×10^3 [d]	4.4×10^3
Cu^{2+}	2×10^8 [b]	1.0×10^4 [c]	$>1.5\times10^5$

[a] Data from reference [5].

[b] Some evidence for a second, slower reaction.

[c] From reference [6].

[d] From reference [12].

[e] From reference [10], temperature 27 °C.

The coordinated ligand can also give an NMR spectrum which can be seen in special cases. For example ethylenediamine coordinated to nickel(II) or cobalt(II) shows an NH_2 peak about 200 p.p.m. on the high-field side and a CH_2 peak about 100 p.p.m. on the low-field side with respect to water [11]. At 60 Mc for the resonance frequency these shifts, $\Delta\omega_M$, are of the order of 10^3 to 10^4 cps. Similar shifts can be found for coordinated OH protons.

Luz and *Meiboom* [12] have observed the resonance lines for the methyl and hydroxy groups of bound methanol separate from those of bulk solvent methanol in solutions containing $Ni(ClO_4)_2$ and $Co(ClO_4)_2$. Below −40 °C the exchange was sufficiently slow, so that the line width observed was completely caused by the coordinated ligand. Above −40 °C additional line broadening occurred due to chemical exchange. The rate of exchange could be calculated from the line width in the usual way.

When coordination of a paramagnetic ion to nitrogen occurs, the values of T_{2M} for the protons on the nitrogen atom are very small, about 10^{-5} to 10^{-7} seconds [10]. Coordination to oxygen produces values of T_{2M} which are much greater for bound protons, about 10^{-3} to 10^{-4} seconds [6, 12]. This difference is due to the greater polarizability of nitrogen compared to oxygen. Thus, a higher unpaired spin density due to the isotropic contact interaction will be found on nitrogen. By polarization this spin density will be transmitted to the proton bound to nitrogen and produce relaxation [13]. Since, moreover, τ_M is greater for nitrogen ligands than for oxygen ligands, this means that rates of exchange will be commonly measured for nitrogen-containing ligands, but not so often for oxygen ligands.

b) Solvent and Ligand Different

The results of Table 1 refer to cases in which the solvent is also the coordinated ligand. It is also possible to study the exchange of ligands, L, present in smaller amounts in a solvent such as water.

$$ML_n + L^* \underset{\tau_{ba}}{\overset{\tau_{ab}}{\rightleftharpoons}} ML_n^* + L \qquad (9)$$

[8] *J. Solomon*, Physical Rev. *99*, 559 (1955).

[9] *N. Bloembergen*, J. chem. Physics *27*, 572 (1957).

[10] *R. G. Pearson* and *R. D. Lanier*, J. Amer. chem. Soc. *86*, 765 (1964).

[11] *R. S. Milner* and *L. Pratt*, Discuss. Faraday Soc. *34*, 88 (1962).

[12] *Z. Luz* and *S. Meiboom*, J. chem. Physics *40*, 1058 (1964).

[13] *R. E. Benson*, *D. R. Eaton*, *A. D. Josey*, and *W. D. Phillips*, J. Amer. chem. Soc. *83*, 3714 (1961).

The NMR spectrum for free L will show the usual line broadening due to exchange. If the protons of L are being observed, as is usually the case, then it must be remembered that NH and OH protons of free L will very rapidly average with the solvent. Thus, if L is glycine ($gly^{\oplus} = NH_2CH_2COO^{\ominus}$), the NMR spectrum in water will show a CH_2 peak and a H_2O/NH_2 averaged peak. The glycine must be about 1 molar for easy observation, but a large portion of this can be in the form of $LH^{\oplus}$, or $^{\oplus}NH_3CH_2COO^{\ominus}$, since $NH_3^{\oplus}$ will also exchange rapidly with the solvent.

The experiments are done at a constant value of P_M (or P_b). This means a constant concentration of metal ion and a constant amount of $[L] + [LH^{\oplus}]$. The line broadening, $\Delta\nu$, is plotted as a function of [L], the concentration of free ligand, which is varied by changing the pH. Four kinds of results can be found as shown in Figure 1.

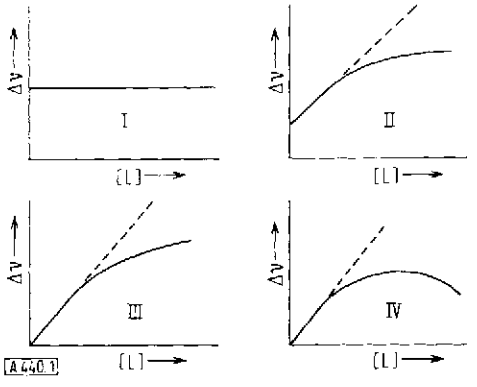


Fig. 1. Experimental results for plots of line broadening $\Delta\nu$ *vs.* concentration of free ligand [L].

For case I, there is no dependence of $\Delta\nu$ on [L]. Such results were found for some nickel complexes, where the rate of exchange is so slow that only a small broadening due to "outer-sphere relaxation" [6] was observed.

Case II has ligand dependence and a nonzero intercept. Thus, there is a line broadening process which is independent of the concentration of free ligand, L, and one which is directly proportional to the concentration of L. This suggests that there is a kinetically first-order exchange mechanism (independent of [L]) and a second-order exchange mechanism with a rate directly dependent on [L]. A positive temperature coefficient and near equality of the OH and CH line broadenings would be needed to confirm that exchange rates are controlling. Rate constants k_1 and k_2 would govern the first order and second order processes, respectively. The dashed line is for the case where T_{2M} remains small compared to τ_M at all concentrations of L used. Eventually, of course, τ_M must become smaller than T_{2M} with increasing [L] because of the relation

$$1/\tau_M = k_1 + k_2\,[L] \qquad (10)$$

Hence, at large [L], the curve must flatten out and reach a constant slope. It is possible, in principle, to obtain k_1, k_2, and T_{2M} in such cases.

The third case, III, involves dependence on [L] and a zero intercept. This indicates that only a second order exchange reaction is occurring, k_1 in Equation (10) being zero. Curvature will occur when [L] becomes large enough so that T_{2M} is greater than τ_M. Equation (10), with $k_1 = 0$, Equation (2), and Equation (5) can be combined to give

$$\pi\nu = \pi\nu_a + \frac{P_b}{P_a}\left[\frac{1}{T_{2b} + 1/k_2\,[L]}\right] \qquad (11)$$

Accordingly, a plot of the reciprocal of the line broadening, $\Delta\nu$, against the reciprocal of the concentration, [L], gives a straight line from which T_{2b} and k_2 can be found.

The plot for case IV shows a maximum. This is due to a change in the concentration of species contributing differently to the line broadening. Some copper(II) systems show this behavior. For example, Cu^{2+}/NH_3 gave such a result because $Cu(NH_3)_5^{2+}$ formed at high concentration of NH_3 is inefficient at line broadening.

Table 2 shows some data obtained for metal ion/ligand systems in aqueous solution. The results can be confirmed by information from other sources in several instances. For example, data on the rate of dissociation of $Ni(en)_3^{2+}$ ($k_1 = 3\ sec^{-1}$) and of $Ni(gly)_3^-$ ($k_1 = 10\ sec^{-1}$) [14] show that the rates are too small to be measured by NMR line broadening methods. They can be measured by flow methods however [14]. Thus, the rate of acid catalysed dissociation was found to be some 20–30 times faster than ligand exchange since only one end of the chelate needs to be free for acid dissociation, but both ends must be free for ligand exchange.

It will be noted that rates of exchange in Table 2 calculated from the averaged OH/NH signals are usually

Table 2. Rate limits for the ligand exchange in complexes at 27 °C. en = ethylenediamine, gly = glycine, sarc = N-methylglycine (sarcosine), dmg = *N,N*-dimethylglycine.

Complex	k_1 [sec^{-1}] or k_2 [M^{-1} sec^{-1}]	Temperature dependence
$Cu(en)_2^{2+}$	$kOH = 2.6\times10^6\ M^{-1}\ sec^{-1}$	$E_a = 7$ kcal/mole
	$kCH_2 = 1.8\times10^6\ M^{-1}\ sec^{-1}$	$E_a = 7$ kcal/mole
$Ni(en)_3^{2+}$	$kOH < 1\times10^3\ sec^{-1}$	None
	$kCH_2 < 2\times10^2\ sec^{-1}$	Small
$Co(en)_3^{2+}$	$kOH = 4.8\times10^3\ sec^{-1} + 3.3\times10^3\ M^{-1}\ sec^{-1}$	$E_a = 10.5$ kcal/mole
	$kCH_2 = 2.5\times10^3\ M^{-1}\ sec^{-1}$	$E_a = 10.5$ kcal/mole
$Cu(gly)_2$	$kOH = 8.2\times10^6\ M^{-1}\ sec^{-1}$	$E_a = 6$ kcal/mole
	$kCH_2 = 2.6\times10^6\ M^{-1}\ sec^{-1}$	$E_a = 6$ kcal/mole
$Ni(gly)_3^-$	$kOH < 1\times10^3\ sec^{-1}$	Negative
	$kCH_2 < 3\times10^2\ sec^{-1}$	Positive
$Co(gly)_3^-$	$kOH = 5.7\times10^3\ sec^{-1} + 4.8\times10^3\ M^{-1}\ sec^{-1}$	$E_a = 10$ kcal/mole
	$kCH_2 = 5.7\times10^3\ sec^{-1} + 3.8\times10^3\ M^{-1}\ sec^{-1}$	$E_a = 10$ kcal/mole
$Mn(gly)_2$	$kOH > 1\times10^3\ sec^{-1}$	Negative
	$kCH_2 > 1\times10^4\ sec^{-1}$	Negative
$Fe(gly)_2$	$kOH = 2.2\times10^4\ sec^{-1} + 5\times10^4\ M^{-1}\ sec^{-1}$	$E_a = 9.5$ kcal/mole
	$kCH_2 = 2.2\times10^4\ sec^{-1} + 3.2\times10^4\ M^{-1}\ sec^{-1}$	$E_a = 9.5$ kcal/mole
$Cu(sarc)_2$	$kOH = 6\times10^5\ M^{-1}\ sec^{-1}$	$E_a = 7$ kcal/mole
$Ni(sarc)_3^-$	$kCH_2 = 60\ sec^{-1} + 1\times10^2\ M^{-1}\ sec^{-1}$ [a]	Positive
$Co(sarc)_3^-$	$kOH = 6.7\times10^2\ sec^{-1} + 3.3\times10^3\ M^{-1}\ sec^{-1}$	$E_a = 13$ kcal/mole
	$kCH_2 = 4.2\times10^2\ sec^{-1} + 2.1\times10^3\ M^{-1}\ sec^{-1}$	$E_a = 13$ kcal/mole
$Cu(dmg)_2$	$kCH_2 = 1.3\times10^4\ M^{-1}\ sec^{-1}$	$E_a = 9.5$ kcal/mole
$Ni(dmg)_3^-$	$kCH_2 = 70\ sec^{-1} + 4.7\times10^2\ M^{-1}\ sec^{-1}$	$E_a = 17$ kcal/mole
$Co(dmg)_3^-$	$kCH_2 = 3.2\times10^3\ sec^{-1} + 7.3\times10^3\ M^{-1}\ sec^{-1}$	Positive

[a] Rate constant at 54 °C.

[14] *R. G. Wilkins* and *A. K. Shamsuddin-Ahmed*, J. chem. Soc. (London) *1959*, 3700; *1960*, 2901; *P. Ellis* and *R. G. Wilkins*, ibid. *1959*, 299.

somewhat larger than those from the CH signals. This is expected because release of the NH end of the chelate will lead to an acid-base proton exchange which will broaden the OH peak only. The extreme case is $Co(en)_3^{2+}$ where the OH peak gives a k_1 of 3.3×10^3 sec^{-1} and the CH peak shows $k_1 = 0$. If k_1 is entirely due to one end only being released and if *Wilkins'* factor [14] of 30 is valid, then the contribution of a first-order process for the complete dissociation of the group en would be too small to be measured from the CH signal.

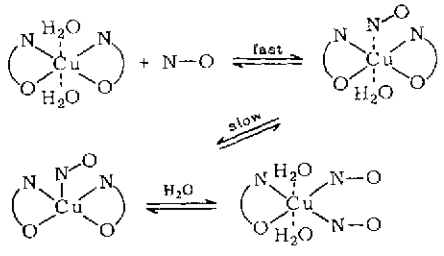
The difference between the rate constants derived from the OH and CH signals is small for glycine and sarcosine. In these cases it is probably the carboxylate end which is released first. This does not lead to proton exchange and hence k_1 and k_2 calculated from the CH and OH signals should be the same. Copper gives the largest difference in k_2 values between the two signals for glycine. This may be due to an additional exchange of a glycine ion coordinated through the amine group only to one of the axial positions above and below the plane of $Cu(gly)_2$ [15]. It is known [5] that groups held in the axial position are very labile. Hence, τ_{ba} in Equation (5) is very small compared to T_{2b}. Since the coordinated NH_2 group is closer to the copper ion than the CH_2 group, its signal would be broadened more.

Copper, manganese, and iron(II) have two water molecules still coordinated in most of the complexes studied. Presumably these molecules are labile and could cause OH line broadening. However, a consideration of the high rates of exchange of such water molecules and the low rates of relaxation of protons bonded to oxygen [16] suggests that the contribution of such a process to the overall line broadening would be small. Manganese(II) would possibly be an exception, since it gives higher rates of relaxation, and part of the difference between the OH and CH signals for this ion in Table 2 could be due to water exchange. Otherwise, it should be noted that the approximate activation energies listed in Table 2 are the same for both OH and CH signals. This suggests that the same process is rate determining for both.

In all cases the order of exchange reactivity found, $Mn(II) > Fe(II) > Co(II) > Ni(II) \ll Cu(II)$, agrees with previous observations for the same series [17]. An explanation has been given in terms of crystal field theory, in which the important factor is the different loss of crystal field stabilization energy in going from the ground state to the transition state for each metal ion. To use such a theory, it is necessary to assume a mechanism and a structure for the transition state as well as for the ground state.

The data are in agreement with a number of possible mechanisms. They are best considered in combination with available information on substitution reactions of other complex ions. It is safe to assume that the complexes of Mn(II), Fe(II), Co(II), and Ni(II) are octahedral, or slightly distorted octahedral, structures. Cu(II) complexes have such a serious tetragonal distortion that they may be considered essentially as planar. It has been found that octahedral complexes react by mechanisms which are, or strongly resemble, S_N1 or dissociation mechanisms [17]. Planar complexes, however, have always been found to react by S_N2 or displacement mechanisms in their substitution reactions [17, 18].

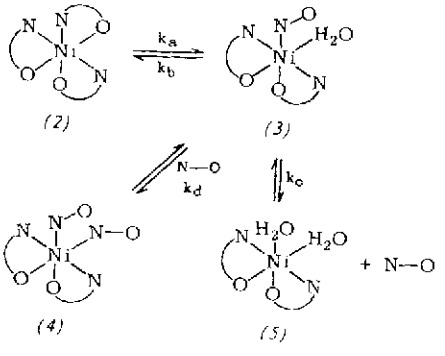
It is significant that in Table 2 copper always reacts by a totally second-order process, where exchange rates are being measured. This suggests an S_N2 mechanism for copper(II) complexes in agreement with their structures. By analogy with complexes of platinum(II) and palladium(II) [18], the first step in the reaction would be the facile replacement of an axial water molecule by the substituting ligand. This would be followed, probably, by rearrangement to a trigonal bipyramid structure, expulsion of one end of the coordinated ligand, and return to a planar structure *(1)* containing two unidentate ligands. (In the formulae N–O is a glycinate anion.) At



(1)

this point exchange has been assured since the ligand originally in solution has taken up a position identical with that of the ligand originally present in the complex. The rate of exchange would be equal to the rate of formation of *(1)*, *i.e.* it would be second order, depending on the concentrations of the complex and of the free ligand. A corresponding first-order reaction in which water is the nucleophilic reagent would be too slow to be detectable because planar complexes are very sensitive to the reactivity of the nucleophile [18].

Octahedral complexes with three bidentate ligands are not as easily accessible for an incoming ligand molecule. Instead, by a mechanism which may be described as a dissociation assisted by water (see below), one end of a bound chelate is replaced by a water molecule in a readily reversible process. After releasing one end of the chelate, the intermediate *(3)* could reclose the chelate, could



(2) *(3)* *(4)* *(5)*

[15] The third en group of $Cu(en)_3^{2+}$ is attached as a unidentate ligand: *J. Bjerrum*, Acta chem. scand. *2*, 297 (1948).

[16] *L. O. Morgan* and *A. W. Nolle*, J. chem. Physics *31*, 365 (1959).

[17] *F. Basolo* and *R. G. Pearson*: Mechanisms of Inorganic Reactions. Wiley, New York 1958; *R. G. Pearson*, J. chem. Educat. *38*, 164 (1961); *R. G. Wilkins*, Quart. Rev. (chem. Soc. London) *16*, 316 (1962).

[18] *F. Basolo* and *R. G. Pearson* in *F. A. Cotton*: Progress in Inorganic Chemistry. Interscience, New York 1962, Vol. 4.

react by the same dissociation mechanism to release both ends of the chelate, or could have the coordinated water replaced by an external ligand molecule. Either of the last two events would lead to exchange. The rate of exchange would be given by

$$\text{rate} = \{k_c + k_d [L]\} [(3)] \qquad (12)$$

Applying the steady-state treatment to *(3)* and assuming the concentrations of *(4)* and *(5)* to be very small, gives for the rate of exchange

$$\text{rate} = \frac{\{k_c + k_d [L]\} k_a [NiL_2]}{k_b + k_c + k_d [L]} \qquad (13)$$

If $k_d[L]$ is small compared to $(k_b + k_c)$, then the observed rate constant for exchange will be the sum of a first-order term and a second-order term, in agreement with the experimental results.

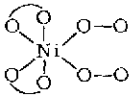
This mechanism can be tested because, first of all, it should be true that k_b is 20–30 times as large as k_c, as mentioned above for $Ni(en)_3^{2+}$ and $Ni(gly)_3^-$. Secondly, let us assume that $(k_b + k_c)$ is large compared to $k_d[L]$. The denominator of Equation (13) is then simply a constant since $k_d[L]$ can be ignored. This means the equation is of the same form as Equation (10), found experimentally. We can now identify k_1 as $k_a k_c/(k_b + k_c)$ or $k_a k_c/k_b$, since $k_b \gg k_c$. In the same way k_2 becomes $k_a k_d/k_b$. An examination of Table 2 shows that in no case does $k_2[L]$ become as much as ten times k_1 for the highest [L] used. This means that $(k_b + k_c)$ will indeed be large compared to $k_d[L]$, as assumed. Some leveling of the rate with increasing [L] may occur but would ordinarily be obscured by the normal curvature of plots of line broadening *vs.* [L] due to relaxation control superseding exchange control. A similar mechanism can be written for octahedral chelates containing two bidentate ligands and, in addition, a second-order path in which the reverse process *(5)* → *(3)* occurs can be visualized.

There is no absolute reason why a mechanism involving an S_N2 attack on the metal by the incoming ligand should not account for the second-order rateconstants for exchange in the octahedral systems. The chief evidence against such a process is the general failure to detect nucleophilic displacement reactions with octahedral complexes of transition metals [19]. It is significant that it is the "special mechanism for chelate compounds" [17] which causes second-order kinetics without a true bimolecular reaction. In the dissociation of any chelate ligand (bidentate or polydentate), it is necessary that one point of attachment be broken at a time. Almost invariably a water molecule will replace the released part of the ligand. Since other ligands can replace water, it is now possible for the rates of ligand substitution or exchange to depend on the concentration of the new ligand. When unidentate ligands such as NH_3 or CNS^- are exchanging, only first-order exchange is observed [20].

The rate sequence glycine > sarcosine > dimethylglycine observed for copper(II) complexes is expected for an S_N2 mechanism and may be attributed to steric hindrance to the approach of the nucleophile. Similar cases are known for platinum(II) complexes [18]. For octahedral cobalt(II) and nickel(II) complexes the opposite order is found: dimethylglycine > sarcosine > glycine. This is readily explained as steric acceleration of the dissociation mechanism and has been observed for other octahedral systems, too [17]. *Wilkins* [21] has found the same order for the rate of dissociation of *N*-methylethylenediamine complexes of nickel(II).

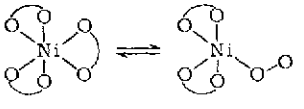
The water-assisted dissociations, *i.e.* the steps with rate constants k_a and k_c, are visualized as requiring a critical extension of the metal-ligand bond and the partial coordination of a water molecule before the bond is completely broken. This follows from the improbability for energetic reasons of a five-coordinated intermediate with a square pyramid structure [22]. Rearrangement to a trigonal bipyramid structure might occur instead in certain cases, for example, where there is no crystal field stabilization energy or where π-bonding is important. If a water molecule is required, then the transition state will be seven-coordinated, with five groups in the original octahedral positions and two groups, water and the leaving group, adjacent to each other and somewhat further away [23].

The results for glycol exchange given in Table 1 call for some special comment. First of all, the rates of exchange of this chelate ligand are about the same as those for the unidentate methanol. This is understandable in terms of the mechanism of a solvent-assisted dissociation. The intermediate *(6)* guarantees exchange after only one end



(6)

of the chelate has dissociated. A five-coordinated intermediate, *(7)*, would lead to a greatly reduced exchange rate for glycol compared to methanol because of rapid reclosing of the chelate ring.



(7)

4. Other Methods

Another NMR line broadening method not using paramagnetic metal ions has been developed chiefly by *Hertz* [24]. Here, advantage is taken of the fact that a halide ion coordinated to any metal ion has a high rate of magnetic relaxation, due to coupling of the nuclear quadrupole moment of the halide ion with the asym-

[19] *R. G. Pearson, D. N. Edgington*, and *F. Basolo*, J. Amer. chem. Soc. *84*, 3233 (1962).

[20] *J. P. Hunt, H. W. Dodgen*, and *F. Klanberg*, Inorg. Chem. *2*, 478 (1963).

[21] *R. G. Wilkins*, J. chem. Soc. (London) *1962*, 4475.

[22] See reference [17], pp. 98–101 and p. 165.

[23] *R. Dyke* and *W. C. E. Higginson*, J. chem. Soc. (London) *1963*, 2788; *S. A. Johnson, F. Basolo*, and *R. G. Pearson*, J. Amer. chem. Soc. *85*, 1741 (1963).

[24] *H. G. Hertz*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *64*, 53 (1960); *65*, 36 (1961).

metric electric field produced at the halide nucleus by the metal ion. Rates of reactions such as

$$Cd(H_2O)_6^{2+} + Br^- \rightleftharpoons Cd(H_2O)_5Br^+ + H_2O$$

can be evaluated.

Finally, it is of interest to mention that rates of rapid exchange reactions can also be measured by using the line broadening in EPR or ESR spectra [25]. Since the time scale of EPR is some 10^3 times larger than that of NMR (the frequency used is of the order 10^{10} cps rather than 10^7 cps) only very rapid reactions can be studied. Half-lives of 10^{-6}–10^{-9} seconds are most convenient.

It has been possible to study rates of outer-sphere complex formation between paramagnetic cations and a paramagnetic anion, the nitrosyldisulfonate ion. Such outer-sphere reactions are very rapid, being diffusion controlled [26]. It is also possible to study rates of inner-sphere complex conversions by selecting a cation the complexes of which are very labile, for example Mn(II), and going to high temperatures where the rates become sufficiently rapid [27].

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German version: Angew. Chem. 77, 361 (1965)

[25] *R. G. Pearson* and *T. Buch*, J. chem. Physics *36*, 1277 (1962).

[26] *M. Eigen* and *K. Tamm*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *66*, 93, 107 (1962).

[27] *R. G. Hayes* and *R. J. Myers*, J. chem. Physics *40*, 877 (1964).

Formation and Reactivity of Phosphonium Salts in the Vitamin A Series

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For syntheses in the carotenoid field using the Wittig reaction, particularly on the technical scale, it was necessary to carry out extensive studies on the preparation and properties of the intermediates. Here the part of this work is discussed which dealt with quaternary phosphonium compounds of trimethylcyclohexene derivatives.

1. Formation of Phosphonium Salts

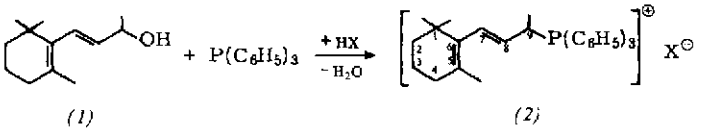
The well-known reaction of tertiary phosphines with organic halides to form quaternary phosphonium compounds [1] is unsatisfactory in the vitamin A series, since here the halogen compounds are extremely unstable. However, this difficulty has been overcome by a new method for the preparation of quaternary phosphonium salts [2].

When alcohols are treated simultaneously with tertiary phosphines and acids, they give high yields of quaternary phosphonium salts [3]:

$$R\text{-}OH + PR'_3 + HX \rightarrow [R\text{-}PR'_3]^{\oplus}\,X^{\ominus} + H_2O \qquad (a)$$

Suitable starting materials include primary and secondary alcohols; substituted allyl alcohols react particularly smoothly.

Thus, β-ionol *(1)* reacts with triphenylphosphine [*] and an acid HX to give the β-ionyltriphenylphosphonium salt *(2)*; similarly β-ionylidene-ethanol *(3)* gives the β-ionylidene-ethyltriphenylphosphonium salt *(6)*.



(1) *(2)*

We assume an ionic mechanism for the formation of the quaternary phosphonium salt from alcohol, phosphine, and acid. Under the action of the proton, the alcohol R–OH forms the carbonium ion $R^{\oplus}$, which then alkylates the tertiary phosphine to yield the quaternary salt. In support of this mechanism, replacement of β-ionylidene-ethanol *(3)* by its isomer 9-vinyl-β-ionol *(4)* leads to the same β-ionylidene-ethyltriphenylphosphonium salt *(6)* [4].

[1] *G. M. Kosolapoff*: Organophosphorus Compounds. Wiley, New York 1950.

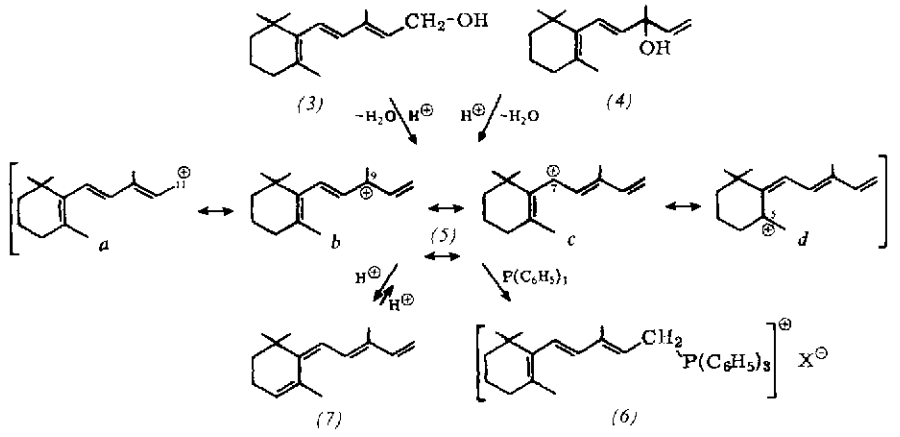
[2] *H. Pommer*, Angew. Chem. *72*, 811, 911 (1960).

[3] German Patent 1046046 (June 29th, 1956), BASF; inventors: *W. Sarnecki* and *H. Pommer*; Chem. Zbl. *1959*, 13003.

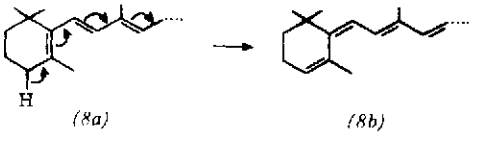
[*] The tertiary phosphine used here and throughout this work is triphenylphosphine, the preferred reagent for the Wittig olefination. The components $(C_6H_5)_3P$ and HX can be replaced by the quaternary phosphonium salt $[(C_6H_5)_3PH]^{\oplus}X^{\ominus}$.

[4] German Patent 1060386 (Sept. 3rd, 1957), BASF; inventors: *W. Sarnecki* and *H. Pommer*; Chem. Zbl. *1960*, 13777.

Compounds *(3)* and *(4)* apparently react with the acid to give the same carbonium ion *(5)*, which has a number of resonance structures *(5a)–(5d)*. This carbonium ion is normally stabilized by loss of a proton with formation



of the hydrocarbon *(7)*, which exists in the so-called retro-configuration. The "retro-ionylidene rearrangement", which was first described by *Oroshnik* et al. [5] and by *Huisman* et al. [6], always takes place when a carbonium ion is formed in the α-position relative to a ring double bond or in a position vinylogous thereto. However, if a tertiary phosphine is present, the cation *(5)* reacts preferentially with this nucleophile, instead of assuming the retro-configuration.



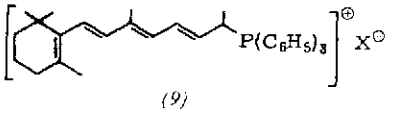
The retro-configuration *(8b)* is energetically more favorable than the trimethylcyclohexene configuration *(8a)*. With a few exceptions, the retro-ionylidene rearrangement is irreversible. Thus, one of the major tasks in carotenoid chemistry is the search for synthetic routes and reaction conditions under which the retro-ionylidene rearrangement either does not take place at all, or can be suppressed.

2. Reconversion of the Retro-Form into the Trimethylcyclohexane Configuration

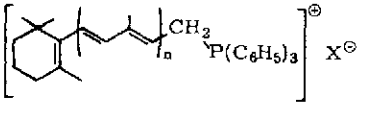
We found that the "rcto-hydrocarbon" *(7)* could be transformed to the trimethylcyclohexene configuration by the combined action of phosphines and acids. For example, a proton from the acid and the phosphorus atom of the phosphine yield the phosphonium salt *(6)* by 1,8-addition to the conjugated system of the retro-hydrocarbon *(7)* [7]. First, the proton adds onto the retro-hydrocarbon *(7)* to reform the carbonium ion *(5)*, which then reacts with the triphenylphosphine to give the β-ionylidene-ethyltriphenylphosphonium salt *(6)*. This reaction occurs with all retro-hydrocarbons in the carotenoid series.

In the vitamin A series, this method is an excellent alternative to the formation of phosphonium salts from alcohols. It proceeds more slowly than the formation of phosphonium salts by direct alkylation of the tertiary phosphine; consequently, the phosphonium salt is always accompanied by a small quantity of retro-hydrocarbon, which disappears only after very long reaction times.

The reaction mechanism discussed above can be applied to the formation of the vinylogous salts *(9)*, *(10)*, and



(9)

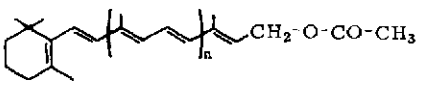


(6a): n = 0 *(10)*: n = 2
(6): n = 1 *(11)*: n = 3

(11) from the corresponding alcohols; competing reactions again lead to the formation of small amounts of the retro-hydrocarbon.

3. Other Syntheses of Phosphonium Salts

Quaternary phosphonium salts can also be synthesized by the combined action of triphenylphosphine and an acid on esters of alcohols in the vitamin A series. Thus, the β-ionylidene-ethyltriphenylphosphonium salt *(6)* can be obtained from β-ionylidene-ethyl acetate *(12)*, and the axerophthyltriphenylphosphonium salt *(10)* from vitamin A acetate *(13)* [8]. The ester can be replaced by



(12): n = 0
(13): n = 1

$\xrightarrow[-CH_3COOH]{P(C_6H_5)_3,\ HX}$

(6): n = 0
(10): n = 1

[5] *W. Oroshnik, G. Karmas*, and *A. D. Mebane*, J. Amer. chem. Soc. *74*, 295, 3807 (1952).

[6] *H. O. Huisman, A. Smit, S. Vromen*, and *L. G. M. Fischer*, Recueil Trav. chim. Pays-Bas *71*, 899 (1952); *75*, 977 (1956).

[7] German Patent 1046612 (Oct. 23rd, 1957), BASF; inventors: *H. Pommer* and *W. Sarnecki*; Chem. Zbl. *1960*, 6928.

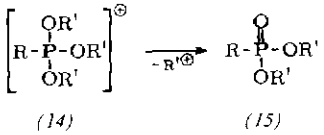
[8] German Patent 1155126 (May 23rd, 1962), BASF; inventors: *W. Sarnecki, A. Nürrenbach*, and *W. Reif*.

the ether with equal success. These results are again explained by the formation of a carbonium ion by the action of a proton on the ester or ether.

The main product in all our experiments was the terminal phosphonium salt. Salts derived from the resonance structures *(5b)*–*(5d)*, *i.e.* with the phosphorus attached to non-terminal carbon atoms, could be detected either only in traces or not at all. It is obvious that salts derived from structures *(5b)* or *(5c)*, in which the conjugation is interrupted, are energetically less favored than the terminal phosphonium salt *(6)*. On the other hand, energy considerations suggest that *(5d)* should take part in the reaction as well as *(5a)*, since the resulting systems have an equal number of conjugated double bonds. Thus, the nucleophilic reagent must be partly responsible for the fact that only *(6)* is formed. It can be shown with Stuart models that *(6)* is the only isomer with an unstrained structure. The molecule becomes strained, if the triphenylphosphine is attached to carbons 9, 7, or 5.

4. Quasi-Phosphonium Salts and Phosphonates

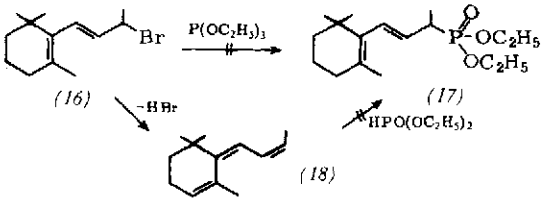
During attempts to synthesize phosphonates *(15)* instead of the quaternary phosphonium salts of type *(6)*, we found that the resonance forms *(5a)* and *(5b)* of the carbonium ion intermediate react with the nucleophile. Like the Michaelis-Arbusow reaction [2,9], the synthesis proceeds *via* a quasi-phosphonium salt *(14)*, which differs from the "normal" phosphonium salts in that three alkyl or aryl residues have been replaced by RO groups.



(14) *(15)*

Despite their low stability – they readily lose a cation $R'^{\oplus}$ with formation of the phosphonate grouping *(15)* [10] – the quasi-phosphonium salts are formed by the same mechanism as normal phosphonium salts.

We then attempted to synthesize the phosphonates, in which we were interested, using the Michaelis-Arbusow reaction. However, the reaction of β-ionyl bromide *(16)* with triethyl phosphite did not yield the desired product *(17)*. Instead, the retro-hydrocarbon *(18)* was formed



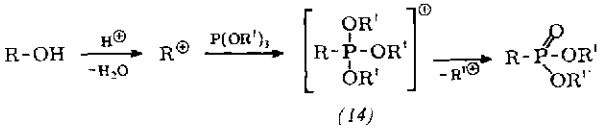
(16) *(17)* *(18)*

[9] Cf. *H. Freyschlag, W. Reif,* and *H. Pommer,* Communication to the IUPAC Symposium on Organic Phosphorus Compounds, Heidelberg (Germany), May 20th, 1964.

[10] *K. Dimroth* and *A. Nürrenbach,* Chem. Ber. *93*, 1649 (1960).

by elimination of HBr, even at temperatures much lower than those required for the Michaelis-Arbusow reaction, *i.e.* a quasi-phosphonium salt is not formed. Addition of hydrogen phosphites onto retro-hydrocarbons was also unsuccessful.

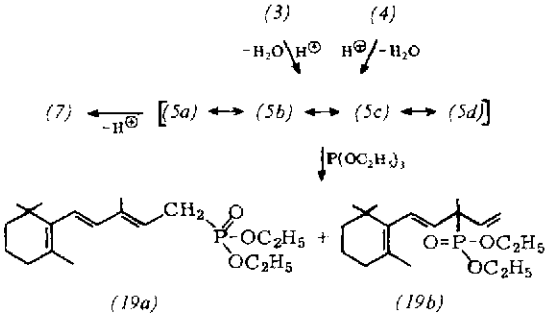
In contrast to tertiary phosphines, tertiary phosphites are not stable toward acids, being rapidly decomposed, even in the absence of water. We were therefore surprised to find that the desired phosphonates could be prepared from alcohols and a phosphite in the presence of proton donors; we assume the mechanism to be as follows: The phosphite reacts with carbonium ion $R^{\oplus}$ formed first to yield the quasi-phosphonium salt *(14)*,



(14)

which is stabilized by elimination of a carbonium ion $R'^{\ominus}$ and formation of the phosphonate grouping. The yield of phosphonate is high only when the phosphite is used in an excess of at least one mole. Diethyl β-ionylphosphonate *(17)* could be obtained in this way from β-ionol *(1)* and triethyl phosphite.

For the preparation of the vinylogous phosphonate by the same method, it should be immaterial wheter the starting material is β-ionylidene-ethanol *(3)* or 9-vinyl-β-ionol *(4)*. With either compound, the first step leads to the cation *(5)*, which can react further either by elimination of a proton to form the retro-hydrocarbon *(7)*, or by alkylation of the phosphorus atom.



(19a) *(19b)*

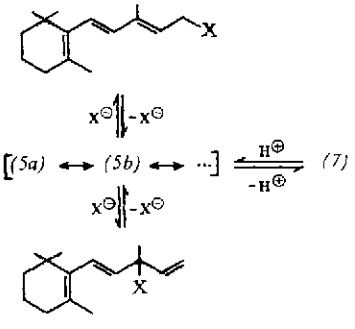
In contrast to the reaction leading to the phosphonium salts *(6)*, however, the formation of the retro-hydrocarbon during the preparation of the phosphonate is irreversible. Probably reformation of the carbonium ion *(5)* from the retro-hydrocarbon *(7)* is relatively slow in comparison with the decomposition of the phosphite by acid. The competing reaction leading to the retro-hydrocarbon must therefore be suppressed here by the use of excess phosphite. In this way, the carbonium ion *(5)* formed as the first intermediate is intercepted as the quasi-phosphonium salt.

Another difference between this reaction and the formation of phosphonium salts is the occurrence of two isomers: a primary phosphonate *(19a)* formed by reaction of the carbonium ion *(5a)* with the phosphite, and a tertiary phosphonate *(19b)* derived from the reso-

nance structure *(5b)*. Phosphonates derived from resonance structures *(5c)* and *(5d)* could not be detected. It can be shown with Stuart models that triethyl phosphite, unlike triphenylphosphine, can be attached to carbon 9 without steric hindrance, but not to carbons 7 or 5.

5. Rearrangement Mechanisms

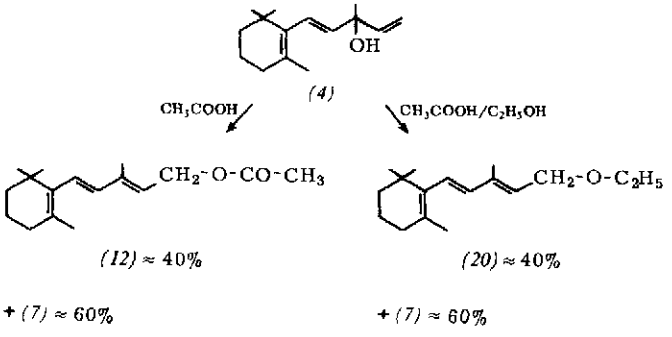
The mechanism proposed for the formation of the retro-hydrocarbon by elimination of a proton from a carbonium ion intermediate also explains why attempts to rearrange 9-vinyl-β-ionol *(4)* to β-ionylidene-ethanol *(3)* have so far met with failure [5,6,11,12]. Evidently, the rearranged compound is converted into the cationic intermediate as easily as the starting material, under the reaction conditions used. Since the conversion of the cation into the retro-compound is the only reaction involved which is almost irreversible [*], the most stable product is the retro-compound. During the formation of phosphonium salts, on the other hand, an allylic rearrangement becomes possible (see Scheme 1) because of the stability of the new P–C bond.



Scheme 1.

Thus, the normal allylic rearrangement should always take place when the reaction of the carbonium ion intermediate with the nucleophile is favored over the reverse reaction. The retro-hydrocarbon can be formed if the carbonium ion intermediate arises equally readily from both allylic isomers. However, if none of these steps is particularly favored, the reaction should lead to a mixture of the products of the allylic rearrangement and of the retro-rearrangement.

Thus, if 9-vinyl-β-ionol *(4)* is treated with glacial acetic acid, the product contains β-ionylidene-ethyl acetate *(12)*, together with the retro-hydrocarbon *(7)*. If the reaction is carried out in an acetic acid/ethanol mixture, on the other hand, it is ethyl β-ionylidene-ethyl ether *(20)* that is formed together with the retro-compound *(7)*, although traces of the acetate *(12)* are also found. These results disagree with the findings of earlier workers [5,6,11,12] but can be readily explained by assuming that the hydroxy group is removed from 9-vinyl-β-ionol and β-ionylidene-ethanol derivatives after protonation more easily than acetoxy or alkoxy groups. This also explains the lability of the halogen derivatives in this series, and the difficulty encountered in preparing them from the alcohols.

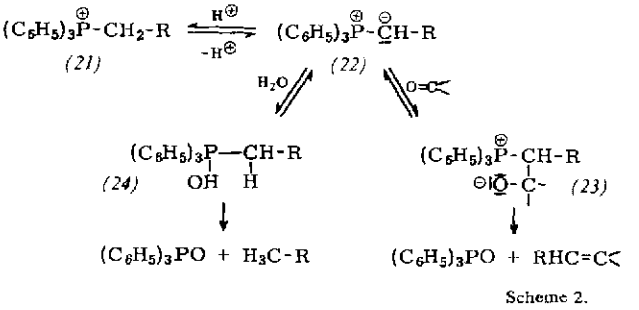


(12) ≈ 40% + *(7)* ≈ 60%

(20) ≈ 40% + *(7)* ≈ 60%

6. Reactivity of the Phosphonium Salts

After we had succeeded in synthesizing all the desired phosphonium salts of the vitamin A series, using the methods described above, we proceeded to study their stability and reactivity [13]. Among the isoprenologous phosphonium salts [cyclogeranyl- *(6a)*, β-ionylidene-ethyl- *(6)*, axerophthyl- *(10)*, and homoisoprenoaxerophthyl-triphenylphosphonium salts *(11)*], *(6a)* reacts only sluggishly with carbonyl compounds when an alkali metal hydroxide is used for ylide formation or when water is present. Elevated temperatures are required for carbonyl olefination, even in absolutely anhydrous solvents and when sodium methoxide is used. On the other hand, the isoprenologous salts *(6)*, *(10)*, and *(11)* react with carbonyl groups even in aqueous solution and with only alkali metal hydroxide as proton acceptor. It was surprising to find that these salts react in aqueous solution, since the Wittig reaction generally proceeds only in the absence of water. The phosphonium ion *(21)* gives up a proton to the base, in accordance with a reaction scheme formulated by *Wittig* (Scheme 2). The resulting ylide *(22)* readily adds on polar substances: addition of carbonyl compounds leads to the betaine *(23)* by the normal olefination reaction, while addition of water leads to the phosphonium hydroxide *(24)* as a hydrolysis intermediate [14,15].



Scheme 2.

[11] *J. G. Baxter*, Fortschr. Chem. org. Naturstoffe *9*, 41 (1952).

[12] *P. Karrer* and *J. Kebrle*, Helv. chim. Acta *35*, 2570 (1952).

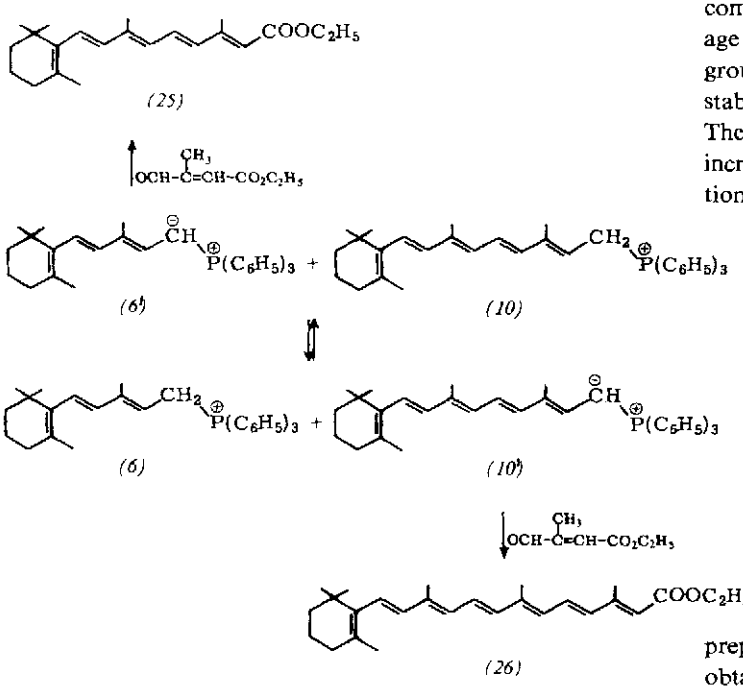
[*] The reverse reaction, *i.e.* the addition of a proton onto the retro-hydrocarbon, is so slow that the formation of the retro-configuration can be regarded as being "almost irreversible" in this case.

[13] Cf. *W. Sarnecki* and *A. Nürrenbach*, Communication to the IUPAC Symposium on Organic Phosphorus Compounds, Heidelberg (Germany), May 20th, 1964.

[14] *D. D. Coffmann* and *C. S. Marvel*, J. Amer. chem. Soc. *51*, 3496 (1929).

[15] *G. W. Fenton* and *C. K. Ingold*, J. chem. Soc. (London) *1929*, 2342.

Addition of water onto, and hence hydrolysis of, the isoprenologous salts should be more difficult owing to the increased stabilization by resonance of the corresponding ylides; this enhancement of the ylide stability can be detected experimentally. If the phosphonium ion *(21)* and its ylide *(22)* are regarded as a conjugate acid-base pair, the equilibrium established between an ylide and the phosphonium ion of a second compound will always be displaced towards the weaker acid and the weaker base [16]. Thus, a mixture of the ylide *(6')* and a stoichiometric quantity of phosphonium salt *(10)* react with ethyl β-formylcrotonate to form only the ethyl heptaenoate *(26)*; no ester of vitamin A acid *(25)* is formed. It follows, therefore, that the ylide *(10')* must be a weaker base than the ylide *(6')*, *i.e.* the phosphonium ion *(6)* is a weaker acid than the phosphonium ion *(10)*. Thus, any increase in the number of double bonds is accompanied by an increase in the acidity of the phosphonium ions, and a decrease in the basicity of the ylides. However, measurement of the rates of hydrolysis of the



ylides [*] showed that hydrolysis is by no means retarded by the increasing resonance stabilization. Contrary to our original assumption, the rate of hydrolysis actually increases with the number of conjugated double bonds. The cyclogeranyltriphenylphosphonium salt *(6a)* undergoes practically no hydrolysis at room temperature, whereas the salt *(11)* is hydrolysed fairly rapidly. The hydrolysis is strongly dependent on temperature; with the β-ionylidene-ethyltriphenylphosphonium salt *(6)*, for example, it ceases at about 0 °C (cf. Fig. 1).

Thus, olefination in the presence of water can proceed in high yield only when the reaction is carried out below the temperature at which hydrolysis ceases.

[16] *H. Bestmann*, Chem. Ber. *95*, 58 (1962).

[*] The hydrolysis to $(C_6H_5)_3PO$ is accompanied by a corresponding consumption of base. Thus, after reaction of the phosphonium salts with sodium methoxide in methanol to form the ylides, followed by addition of water, determination of the sodium methoxide consumption provides a simple titrimetric method of determining the rate of hydrolysis (Fig. 1).

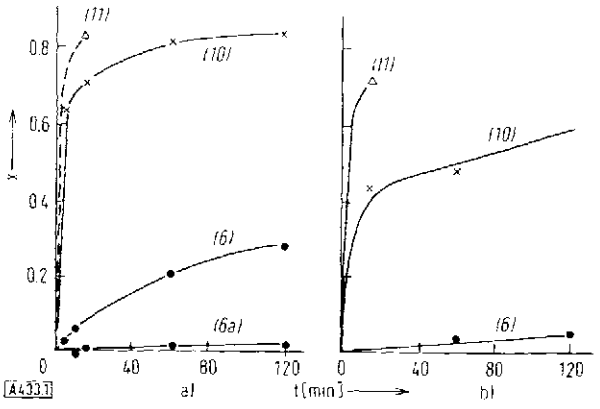
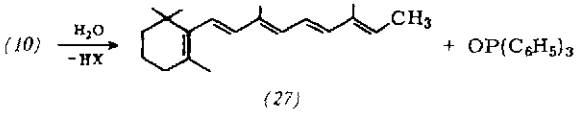


Fig. 1. Hydrolysis of C_{10}, C_{15}, C_{20}, and C_{25} ylides ($c = 275 \times 10^{-3}$ mole/l) in a 4:5 methanol/water mixture at a) 26 °C; b) 4 °C.
Ordinate: Moles of base consumed per mole of phosphonium salt.
Abscissa: Hydrolysis time [min].

No decomposition of phosphonium salts in anhydrous alcohols in the presence of alkoxides was observed in the vitamin A series. This is in contrast to the thermal decomposition of phosphonium alkoxides [17,18]. Cleavage occurred only on addition of water, and the leaving group was always that which was able to form the most stable anion, *i.e.* the trimethylcyclohexene group [*]. The attachment of these groups becomes less firm with increasing chain length, owing to resonance stabilization. The ease of cleavage can be used to advantage in preparative work. For example, axerophthene *(27)* is obtained in a smooth reaction from the axerophthyltriphenylphosphonium salt *(10)*. Other carotenoid hydrocarbons can also be obtained in good yields by a similar method.



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German version: Angew. Chem. 77, 277 (1965)
Translated by Express Translation Service, London

[17] *L. Hey* and *C. K. Ingold*, J. chem. Soc. (London) *1933*, 531.

[18] *M. Grayson* and *P. T. Keough*, J. Amer. chem. Soc. *82*, 3919 (1960).

[*] *Horner* [19], *Zanger* [20], and *Schlosser* [21] have reported similar results in the cleavage of quaternary phosphonium salts.

[19] *L. Horner, H. Hoffmann, H. G. Wippel*, and *G. Hassel*, Chem. Ber. *91*, 52 (1958).

[20] *M. Zanger, C. A. van der Werf*, and *W. E. McEwen*, J. Amer. Chem. Soc. *81*, 3806 (1959).

[21] *M. Schlosser*, Angew. Chem. *74*, 291 (1962); Angew. Chem. internat. Edit. *1*, 266 (1962).

New Methods in the Chemistry of Pyridazones

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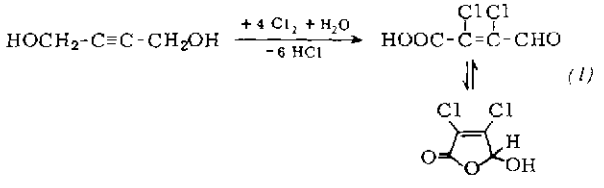
A new synthesis of mucochloric acid by chlorination of butynediol has facilitated the preparation of a series of 4,5-dichloropyridazones. The high reactivity of these compounds has been investigated and applied in several ways. New classes of compounds, some with biological activity, were obtained by displacement of the chlorine atoms. New heterocyclic systems were prepared by condensation and rearrangement reactions.

1. Introduction

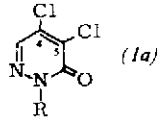
Mucochloric acid *(1)* has recently become readily available by chlorination of 2-butyne-1,4-diol, which is produced in large quantities by Reppe reactions [1].



(1)

This polyfunctional γ-aldehydo-acid is extremely reactive. The most interesting of its many reactions are those which lead to cyclic compounds. In particular, its reaction with hydrazine or hydrazine derivatives to form pyridazones might lead to physiologically active substances analogous to the pyrazolones [2]. A number of pyridazones possessing interesting phytophysiological properties have, in fact, been discovered and reported elsewhere [3].

Only a few derivatives of the parent 4,5-dichloropyridazone *(1a)* [4] were previously known. At the turn of the century, *Bistrycki* et al. [5] achieved the first synthesis of 4,5-dihalogenopyridazones, *i.e.* of 4,5-dibromopyridazone and its 1-phenyl derivative, by treating mucobromic acid with hydrazine hydrate or phenylhydrazine, respectively. Ring closure with elimination of two molecules of water to form the pyridazone derivative proceeded so readily that the open-chain phenylhydrazone initially formed could be isolated only with difficulty. The semicarbazone of mucobromic acid also reacts readily on heating in glacial acetic acid, with loss of the amido group to give a quantitative yield of the pyridazone with no substituent in the 1-position. The analogous 4,5-dichloropyridazone and its 1-phenyl derivative were discovered much later [6, 7], as was the corresponding 1-methyl derivative [8].



(1a)

2. Synthesis of Dichloropyridazones

4,5-Dichloropyridazones are prepared by the reaction of mucochloric acid with hydrazine or its monoalkyl or monoaryl derivatives.

The condensation generally proceeds smoothly with elimination of two molecules of water. The latter may be distilled off azeotropically with a solvent [9], or the mixture can be heated in an organic acid. An elegant variant of the synthesis of 4,5-dichloropyridazones discovered by *Hensel* and *Baumann* [10] entails condensation of the reactants in dilute mineral acid. The hydrazine salts resulting from reduction of the corresponding diazonium salts are used directly in this procedure. The yields of 4,5-dichloropyridazones obtained are generally excellent. The intermediate hydrazones of mucochloric acid can be isolated only under mild conditions, *e.g.* in alcohol at room temperature; even on only slight warming, they readily lose a second molecule of water to form the pyridazones.

The phenylhydrazone of mucochloric acid *(2)* is formed from *(1)* and phenylhydrazine in alcohol at room temperature. It is a bright yellow compound, m. p. 126 °C, which even on gentle heating, neat or in solution, loses water to form colorless 4,5-dichloro-1-phenylpyridazone *(3)*, m. p. 162 °C.

[1] *K. Dury*, Angew. Chem. *72*, 864 (1960).

[2] Cf. *E. Jucker* and *R. Süess*, Helv. chim. Acta *42*, 2506 (1959); *Y. Nitta, F. Yoneda, T. Ohtaka*, and *T. Kato*, Chem. pharmac. Bull. (Tokyo) *12*, 69 (1964).

[3] *K. Dury* and *A. Fischer:* 100 Jahre BASF – Aus der Forschung, BASF, Ludwigshafen 1965, p. 307.

[4] The numbering used in this paper is that suggested by analogy with the pyrazolones; cf. *E. Jucker* and *R. Süess* [2].

[5] *A. Bystrycki* and *H. Simonis*, Ber. dtsch. chem. Ges. *32*, 534 (1899); *A. Bystrycki* and *C. Herbst*, Ber. dtsch. chem. Ges. *34*, 1010 (1901).

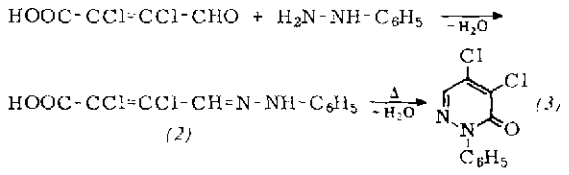
[6] *D. T. Mowry*, J. Amer. chem. Soc. *75*, 1909 (1953); U.S. Patent 2628181 (April 13th, 1949), Monsanto, inventor: *D. T. Mowry*; Chem. Zbl. *1954*, 4244.

[7] *T. Kuraishi*, Chem. pharmac. Bull. (Tokyo) *4*, 497 (1956).

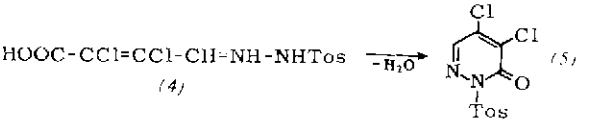
[8] *L. F. Wiggins*, J. chem. Soc. (London) *1948*, 2194.

[9] German Patent 1086238 (Febr. 3rd, 1959), BASF, inventors: *F. Reicheneder* and *K. Dury;* Chem. Zbl. *1960*, 17250.

[10] U.S. Patent 3045014 (June 20th, 1960; German priority June 23rd, 1959), BASF, inventors: *H. R. Hensel* and *H. Baumann;* Chem. Zbl. *1964*, 32–2063.

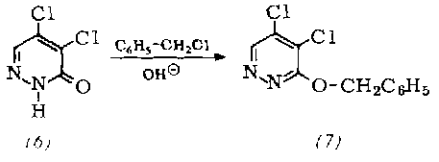


The reaction of acylhydrazines with mucochloric acid generally leads to open-chain hydrazones [11,12], whereas sulfonylhydrazones readily undergo cyclization. Thus, tosylhydrazine is converted, *via* the hydrazone *(4)*, into the cyclic compound *(5)*.

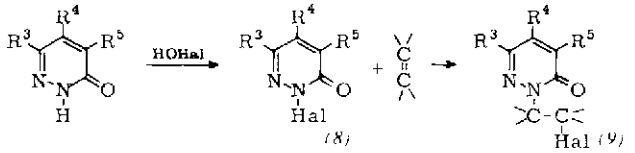


A number of 1-arylsulfonyl-4,5-dichloro-6-pyridazones have been prepared in this way; some of these exhibit strong fungicidal properties.

The synthesis of 4,5-dichloropyridazones has been extended by 1-alkylation of unsubstituted 4,5-dichloropyridazone *(6)* with dialkyl sulfates or reactive halogeno compounds [14–17]. It has frequently been possible by comparison of the product of alkylation of *(6)* with the product obtained from the corresponding alkylhydrazine and mucochloric acid to prove that alkylation had in fact taken place on the 1-nitrogen of the pyridazone ring. Occasionally the isomeric 6-alkoxypyridazone [*e.g.* *(7)*, m.p. 197–198 °C] formed by *O*-alkylation has been isolated as a by-product.



A new method of preparing 1-substituted pyridazones is the addition of 1-halogenopyridazones *(8)* onto olefinic double bonds [18], *e.g.* in cyclohexene, with formation of *(9)*. The *N*-halogenopyridazones are readily formed by treating pyridazones containing a hydrogen atom on the 1-nitrogen with hypohalites [19]. These products were previously unkown but are surprisingly stable, especially in the pure form.



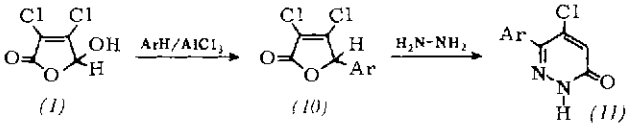
R^3 = H, O-Alk, C_6H_5; R^4 = Halogen; R^5 = OR, H; Hal = Cl, Br

Whereas normally the first step in pyridazone chemistry is the preparation of the halogen-free parent compound, which then has to be halogenated (usually with phosphorus pentachloride) before further reaction [20], halogenated pyridazones are obtained directly by the new method.

A list of 4,5-dichloropyridazones prepared by the various methods is given in Table 1.

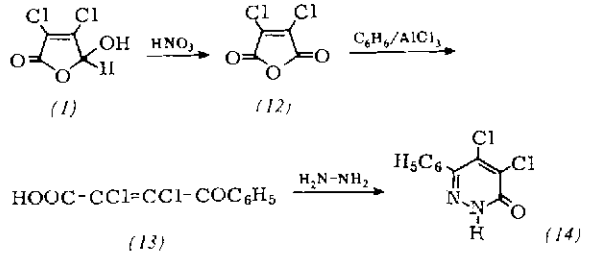
Other halogenated pyridazones can be obtained indirectly from mucochloric acid:

a) Friedel-Crafts alkylation of aromatic compounds with mucochloric acid *(1)* leads to γ-aryldichlorocrotonolactones *(10)* [21]. These compounds react in a complex manner with hydrazine hydrate, with elimination of one atom of chlorine, to afford high yields of 3-aryl-4-chloropyridazones *(11)* [22].



These compounds can be alkylated or tosylated in the 1-position. Since the chlorine in the 4-position is easily replaceable, a series of further derivatives can be prepared.

b) Friedel-Crafts acylation of benzene with dichloromaleic acid or its anhydride *(12)* (obtained by oxidation of mucochloric acid with nitric acid [23]) yields phenylmucochloric acid *(13)*, which reacts with hydrazine hydrate to give 4,5-dichloro-3-phenyl-6-pyridazone *(14)*. This compound exhibits the same reactivity as the pyridazone with no substituent in the 3-position.



[11] Cf. however *A. Bystrycki* and *C. Herbst* [5].

[12] This behavior finds a certain parallel in the chemistry of pyrazolones, where the preparation of 1-benzoyl-3-methylpyrazolone by direct reaction of benzoylhydrazine with acetoacetic ester has also been unsuccessful [13].

[13] *J. Renault, C. Fauran,* and *F. Pellerin,* Bull. Soc. chim. France *1963*, 2742.

[14] U.S. Patent 2832780 (Sept. 4th, 1955), Warner-Lambert Pharm. Co., inventor: *J. A. King*; Chem. Abstr. *52*, 14701 h (1958).

[15] Austrian Patent 205036 (Dec. 21st, 1957), Österr. Stickstoffwerke, inventors: *L. Holzer* and *R. Schönbeck*; Chem. Zbl. *1961*, 5586.

[16] Austrian Patent 217467 (Aug. 25th, 1959), Österr. Stickstoffwerke, inventors: *R. Schönbeck* and *E. Kloimstein*; Chem. Zbl. *1964*, 14–1588.

[17] *R. Schönbeck, T. Kato* et al., Chem. pharmac. Bull. (Tokyo) *12*, 69 (1964).

[18] French Patent 1330399 (July 19th, 1962; German priority July 19th, 1961), BASF, inventors: *F. Reicheneder* and *K. Dury*; Chem. Abstr. *59*, 14005 d (1963).

[19] German Patent 1122069 (Dec. 30th, 1960), BASF, inventors: *F. Reicheneder* and *K. Dury*; Chem. Zbl. *1962*, 12841.

[20] According to *F. Ach*, Liebigs Ann. Chem. *253*, 44 (1889), the halogen atom enters preferentially at the 5-position.

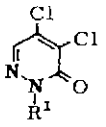
[21] *V. Ettel, M. Semonsky,* and *V. Zikan*, Chem. Listy *46*, 232, 634 (1952).

[22] Belgian Patent 630379 (March 29th, 1963; German priority March 29th, 1962), BASF, inventors: *F. Reicheneder* and *K. Dury*.

[23] *A. Salmony* and *H. Simonis*, Ber. dtsch. chem. Ges. *38*, 2588 (1905).

c) After *Druey* et al. [24,25,30] had condensed maleic acid and its monochloro derivative with hydrazines in hydrochloric acid to obtain pyridazone derivatives, we condensed dichloromaleic acid (or its anhydride) with hydrazines in the same way to form 4,5-dichloro-3-hydroxy-6-pyridazones *(15)*; these in turn can be used as starting materials in various syntheses. Reaction of *(15)* with amines yields compounds of formula *(16)*, while 3,4,5-trichloropyridazones *(17)* are obtained by halogenation of *(15)*, *e.g.* with phosphorus oxide chloride.

Table 1. 4,5-Dichloropyridazones.

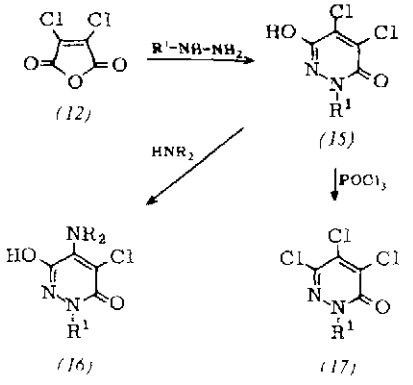


R^1	M.p. (uncorr.) [°C]
H [a]	203–204
CH_2–OH	104–105
CH_2–Cl	70–71
CH_2–OAc [a, b]	87–89
CH_2–OOC–C_6H_5 [a, b]	97–99
CH_2–(*N*-morpholino)	125
CH_2–NH–C_6H_5	62–63
CH_2–NH–3,4-dichlorophenyl	165–166
CN [b]	103–104
CH_2–N–4,5-dichloro-6-oxopyridazinyl	221–222
CH_3 [a, b]	134–144
C_2H_5 [a, b]	49–51
CH_2–CH_2–OH [a]	54–55
CH_2–CH_2–NH_2·HCl [a]	248 (decomp.)
CH_2–CH_2-pyrrolidinyl [b]	80–81
CH_2–$COOC_2H_5$ [b]	91–92
$CH(CH_3)_2$ [a]	69–70
CH_2–CH_2–CN [a]	102–103
CH_2–CH_2–$CONH_2$	166–168
CH_2–CH_2–CO–$NHCH_3$	146–148
CH_2–CH_2–COOH	128–130
CH_2–CH_2–CO–C_6H_5	100–101
CH=CH–CO–C_6H_5	161–162
$\underset{CH_3}{CH}$–$COOC_2H_5$ [b]	25–27
n-Butyl [a]	liquid
Isobutyl [a]	37–38,5
s-Butyl [a]	34–36
t-Butyl [a]	67–68
Tetra-*O*-acetylglucosyl [b]	164–165
Cyclopentyl [a]	62–63
Cyclohexyl [a]	89–90
4-Methylcyclohexyl [a]	70–71
Cycloheptyl [a]	47–48
Cyclooctyl [a]	58–59
Perhydro-4,7-methanoindenyl [a]	92–100
–CH_2–C_6H_5 [a, b]	87–89
–CH_2–CH_2–C_6H_5 [a]	124–125
CH_2-furfuryl [a]	78–80
Phenyl [a]	161–162
m-Cl–C_6H_4 [a]	199–200
p-Cl-C_6H_4 [a]	270
m-NO_2–C_6H_4 [a]	210–212
m-$NaSO_3$–C_6H_4 [a]	–
p-HSO_3–C_6H_4 [a]	270
p-NH_2SO_2–C_6H_4 [a]	267–268
3,4-$Cl_2C_6H_3$ [a]	223 (decomp.)
p-Tolyl [a]	147
m-Tolyl [a]	119–120
α-Naphthyl [a]	198
2-Chlorocyclohexyl [c]	133–134
4-Chlorotricyclo[2.2.1.$0^{2,6}$]hept-3-yl [c]	118–121
2-Chlorocyclooctyl [c]	96–97
2-Bromocyclooctyl [c]	162–163
2-Chlorocyclooct-5-enyl [c]	151–153
2-Chlorocyclododecyl [c]	87–89
N-Methyl-4-piperidinyl·HCl [a]	310
N-Methyl-4-piperidinyl·CH_3I [a]	280
2-Benzimidazolyl [a]	259–260
2-Benzthiazolyl [a]	216–218

[a] Prepared from hydrazine and mucochloric acid.

[b] Prepared by alkylation of a pyridazone with the 1-position free.

[c] Prepared by addition of a 1-halogenopyridazone onto an olefin.



3. Reactions of 4,5-Dichloropyridazones

4,5-Dichloropyridazones contain the characteristic –CO–C(Cl)=C(Cl)–Cl grouping of β-chlorovinyl ketones. They are cyclic vinylogous acid chlorides, and have a *trans*-configuration [26]; consequently, the chlorine in the 4-position readily undergoes nucleophilic substitution. Owing to the high reactivity of this chlorine atom, the 4,5-dichloropyridazone residue can be used as the reactive component in novel reactive dyes [27,28].

We have prepared a series of aminochloropyridazones (see Table 2) by the reaction of 4,5-dichloropyridazones with ammonia or primary or secondary amines.

These amino compounds are only very weakly basic. Although they react with concentrated acids to form salts, the latter are more like addition compounds, and readily dissociate to reform the starting materials. Thus, the hydrochloride of *(18)* can be prepared in concentrated hydrochloric acid, but attempts to isolate the salt result in elimination of HCl and regeneration of the free base.

On synthesis of aminochloro-1-phenylpyridazone from 4,5-dichloro-1-phenylpyridazone, two isomeric products are obtained: 4-amino-5-chloro- and 5-amino-4-chloro-1-phenylpyridazone. Reductive dehalogenation by the method of *Grundmann* [29] converts the predominant isomer, which melts at 205–206 °C, into 4-amino-1-phenyl-6-pyridazone *(19)*, which is also the product of dehalogenation of 4-amino-3-chloro-1-phenyl-6-pyridazone *(20)* [30]. The structure of the main isomer was thus established as *(18)*. Morover, this

[24] *K. Eichenberger, A. Staehelin,* and *J. Druey,* Helv. chim. Acta *37*, 837 (1954).

[25] Belgian Patent 566178 (Sept. 29th, 1958; Swiss priority March 29th, 1957; Mady 23r, 1957; Oct. 23rd, 1957; Jan. 27th, 1958), Ciba, inventors: *J. Druey* et al.; Chem. Zbl. *1961*, 9520.

[26] *W. R. Benson* and *A. E. Pohland,* J. org. Chemistry *29*, 385 (1964).

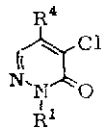
[27] Cf. *H. R. Hensel* and *G. Lützel,* Angew. Chem. *77*, 303 (1965); Angew. Chem. internat. Edit. *4*, 312 (1965).

[28] German Patent 1135115 (June 25th, 1959), BASF, inventors: *H. R. Hensel, H. Baumann, K. Dury,* and *W. Federkiel*; Chem. Abstr. *58*, 2526a (1963).

[29] *Ch. Grundmann,* Chem. Ber. *81*, 1 (1948).

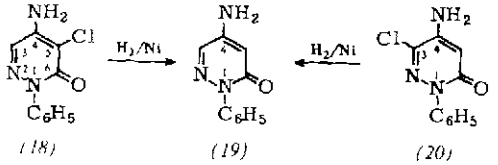
[30] *K. Meier, B. H. Ringier,* and *J. Druey,* Helv. chim. Acta *37*, 523 (1954).

Table 2. 4-Amino-5-chloropyridazones.



R^1	R^4	M.p. (uncorr.) [°C]
H	NH_2	352
CH_3	NH_2	203–204
C_2H_5	NH_2	217
CH_2-CH_2-CN	NH_2	195–198
CH_2-COOH	NH_2	253–255
CH_2-CH_2-OH	NH_2	178–180
$(CH_2)_3-O-CH_3$	NH_2	137–138
Phenyl	NH_2	205–206
m-Cl–C_6H_4	NH_2	214–216
p-Cl–C_6H_4	NH_2	254–256
p-Tolyl	NH_2	226
2-Amino-4-tolyl	NH_2	220–222
p-$H_3CO-C_6H_4$	NH_2	279–280
p-HOOC–C_6H_4	NH_2	--
p-$NH_2-SO_2-C_6H_4$	NH_2	–
p-$NHCH_3SO_2-C_6H_4$	NH_2	262–264
α-Naphthyl	NH_2	207–209
Cyclohexyl	NH_2	224–225
Cyclooctyl	NH_2	178–179
N-Methylpiperidyl·HCl	NH_2	296–297
Glucosyl	NH_2	178–180
H	NH–CH_3	252–253
H	NH–C_2H_5	198–200
H	NH–C_6H_5	246–247
H	p-Toluidino	203–206
H	NH–C_6H_4–OCH_3-p	242–243
H	NH-Cyclohexyl	
CH_2-CH_2-CN	NH-iso-C_3H_7	91–92
C_6H_5	NH-Cyclooctyl	80–81
H	$N(CH_3)_2$	200–201
H	$N(C_2H_5)_2$	119
H	$N(CH_3)-CH_2-C_6H_5$	172–173
CH_3	Morpholino	104–106
C_6H_5	$N(C_2H_5)_2$	107–108
C_6H_5	Pyrrolidinyl	148–149
C_6H_5	1-Piperazinyl	143–144
C_6H_5	2,6-Dimethylmorpholino	126

reaction shows that the chlorine atom in the 4-position is more reactive than that in the 5-position.



(18) (19) (20)

The amine *(18)* and a number of other aminochloropyridazones exhibit phytophysiological activity [3, 31]. This fact induced us to investigate some modifications of the active molecule, *e.g.* several acyl derivatives [32]. These can be prepared from the aminopyridazones with acid chlorides or anhydrides, despite the rather weak basicity of the amino group.

Finally, a series of amidines was prepared by condensation of the aminopyridazones with amides in the presence of phosphorus oxide chloride [33].

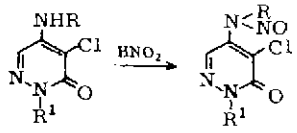
[31] German Patent 1105232 (Nov. 21st, 1958), BASF, inventors: *F. Reicheneder, K. Dury*, and *A. Fischer*; Chem. Zbl. *1961*, 14805.

[32] German Patent 1107998 (March 19th, 1960), BASF, inventors: *F. Reicheneder, K. Dury, H. Stummeyer*, and *A. Fischer*; Chem. Zbl. *1961*, 16982.

[33] Belgian Patent 615519 (Sept. 24th, 1962; German Priority March 25th, 1961 and Nov. 17th, 1961), BASF, inventors: *F. Reicheneder, K. Dury, H. Stummeyer*, and *A. Fischer*. – With regard to the method, cf. *H. Bredereck, R. Gompper, K. Klemm*, and *H. Rempfer*, Chem. Ber. *92*, 837 (1959).

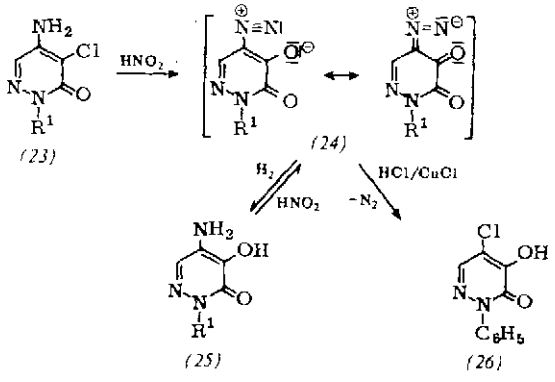
4. Diazoniumpyridazones

Although 4-monoalkylaminopyridazones *(21)* react smoothly with nitrous acid to form the *N*-nitroso derivatives *(22)*, the product obtained from unsubstituted 4-amino-5-pyridazones *(23)*, with HNO_2 is completely different. As a result of a reaction which was formerly known only with aromatic compounds, the amines *(23)*



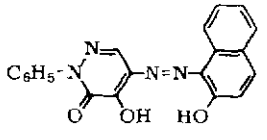
(21) (22)

lose the chlorine adjacent to the amino group (by analogy to the formation of hydrazonoquinones) to yield yellow 4-diazonium-5,6-dioxo compounds *(24)* [34]. The analogy with the formation of hydrazonoquinones extends further in that adjacent groups other than halogen, *e.g. O*-alkyl residues, are also eliminated during this diazotization [35]. Similarly, the 5-amino compounds give the isomeric diazonium enolbetaines which, like *(24)*, crystallize well and are surprisingly stable.



(23) (24) (25) (26)

Reduction of the diazonium compounds *(24)* yields 4-amino-5-hydroxypyridazones *(25)*, which can be reconverted into the 4-diazoniumpyridazones by reaction with nitrous acid. The Sandmeyer reaction leads to 4-halogeno-5-hydroxypyridazones, *e.g.* the 4-chloro-5-hydroxy-1-phenylpyridazone *(26)* obtained from *(24)* with R = C_6H_5. Like aromatic diazonium salts, the diazonium compounds *(24)* couple with phenols, to form a new type of *o*-hydroxyazo dyes. Coupling of *(24)*, R = C_6H_5, and β-naphthol, for example, gives the purple dye *(27)*, which can be converted into a light-fast dye by subsequent metallation [36].



(27)

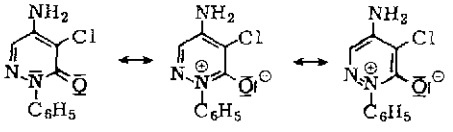
[34] German Patent 1102162 (April 28th, 1959), BASF, inventors: *F. Reicheneder* and *K. Dury*; Chem. Zbl. *1961*, 11903.

[35] Cf. *K. Holzach*: Die aromatischen Diazoverbindungen. Enke, Stuttgart 1947, p. 84.

[36] French Patent 1352341 (Feb. 22nd, 1963; German priority Feb. 24th, 1962), BASF, inventors: *O. Kaufmann* and *K. Dury*.

Diazotization and coupling of the 4-amino-5-halogeno-pyridazones can be used as a sensitive color reaction for detecting them, even in biological material [37].

In order to form stable diazonium compounds which are capable of coupling, the aminohalogenopyridazones must possess a certain degree of aromaticity. This concurs with *Arndt's* theory of the aromaticity of "carboxamide-containing six-membered rings" [38]. 4-Amino-5-chloro-1-phenyl-6-pyridazone may be assumed to have the polar resonance structures *(28)–(30)*.

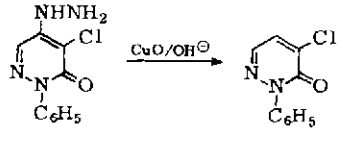


(28) *(29)* *(30)*

5. Hydrazino and Azido Derivatives

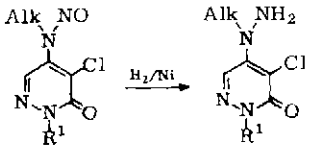
Gentle heating of 4,5-dichloropyridazones in the presence of hydrazine hydrate leads to the formation of 5-chloro-4-hydrazino-6-pyridazones, which react with aldehydes or ketones to form crystalline hydrazones. As expected, the hydrazino group is introduced at the 4-position. The 4-hydrazinopyridazones react smoothly with nitrous acid to form the corresponding 4-azido-5-chloropyridazones, which are pale yellow photosensitive substances. The same compounds can be obtained directly from the dichloropyridazones with sodium azide in either acetone/water or dimethylformamide/water. The constitution of the azides is established by the fact that careful hydrogenation of the azido group leads to the well known 4-amino-5-chloropyridazones *(23)*.

Whereas 2,3-dichloronaphthoquinone readily exchanges both of its chlorine atoms for azide groups when treated with sodium azide [39], it has not been possible to replace the second chlorine atom (in the 5-position) of the 4,5-dichloropyridazones by the azido residue. If 5-chloro-4-hydrazino-pyridazones are gently heated with cupric oxide in sodium carbonate solution [40], nitrogen is eliminated and the hydrazino group is replaced by hydrogen. 5-Chloro-1-phenyl-6-pyridazone *(32)* is readily formed in this manner from 5-chloro-4-hydrazino-1-phenyl-6-pyridazone *(31)*.



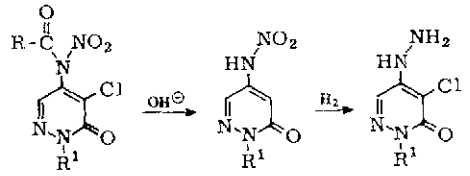
(31) *(32)*

N-Alkylhydrazino derivatives of the pyridazones *(34)* can be prepared from the 4-monoalkylaminopyridazones by reduction of their *N*-nitroso derivatives *(33)*.



(33) *(34)*

Finally, 4-hydrazinopyridazones are also obtained by the reaction of 4-acylaminopyridazones with strong nitric acid to form the corresponding acylnitramines *(35)* followed by reduction of the free nitraminopyridazones *(36)* resulting from hydrolysis of *(35)*.

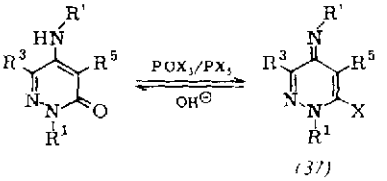


(35) *(36)*

The 5-chloro-4-hydrazinopyridazones exhibit remarkable plant-physiological properties [41], especially when they contain a phenyl or cycloalkyl residue at the 1-position. *Castle* et al. [42] recently examined a number of 4-hydrazinopyridazones and the products of their reactions with aldehydes and ketones, in order to check their activity against tumors.

6. Iminopyridazones

Just as 4-halogeno-6-pyridazones may be regarded as either cyclic β-chlorovinyl ketones or cyclic vinylogous acid chlorides, 4-aminopyridazones may be regarded as cyclic vinylogous amides. Corresponding to the formation of imido chlorides from amides, cyclic vinylogous imido chlorides *(37)*, *i.e.* 4-imino-6-halogenopyridazones are formed from 4-amino-6-pyridazones by the action of phosphorus pentahalides or oxide halides [43]. The halogen atom in position 6, which is the last to enter, is



(37)

extremely reactive in these 6-halogeno-4-imino- and 5,6-dihalogeno-4-iminopyridazones. The chemical behavior of these new compounds is very similar to that of imido chlorides. Hydrolysis leads to regeneration of the starting pyridazone. The halogen readily undergoes nucleophilic substitution with ammonia, primary and secondary amines, hydrazines, alcohols, and thiols. The 6-halogen can also be replaced by a nitro group on reaction with nitrites. Another remarkable feature of the

[37] *N. Drescher:* 100 Jahre BASF – Aus der Forschung. BASF, Ludwigshafen 1965, p. 317.

[38] *F. Arndt, L. Loewe,* and *L. Ergener,* Rev. Fac. Sci. Univ. Istanbul *13 A,* 103 (1948); Chem. Abstr. *43,* 579a (1949); cf. *J. Druey* [24].

[39] *K. Fries* and *P. Ochwat,* Ber. dtsch. chem. Ges. *56,* 1299 (1923).

40] *L. F. Armarego,* J. appl. Chem. *11,* 70 (1961).

[41] French Patent 1321672 (March 24th, 1962; German priority March 25th, 1961, Nov. 17th, 1961), BASF, inventors: *F. Reicheneder, K. Dury,* and *A. Fischer.*

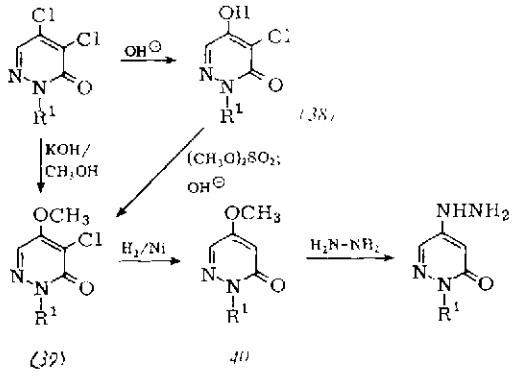
[42] *R. N. Castle, W. M. Osner,* and *D. L. Aldons,* J. pharm. Sci. *52,* 539 (1963).

[43] Belgian Patent 645360 (March 18th, 1964; German priority March 19th, 1963), BASF, inventors: *F. Reicheneder* and *K. Dury.*

6-halogeno-4-iminopyridazones is their stronger basicity compared with the parent aminopyridazones, by virtue of which they are able to form well defined salts.

7. Introduction of Other Groups

As in the reaction with ammonia and amines, the chlorine in the 4-position of the pyridazone ring is very readily replaced by hydroxy *(38)* or alkoxy groups *(39)* on treatment with aqueous bases or alcohols. We have prepared a large number of such derivatives with a view to investigating their phytophysiological action [44]. Reductive dehalogenation yields halogen-free 4-hydroxy- and 4-alkoxypyridazones *(40)*, which are completely free from phytotoxic activity.

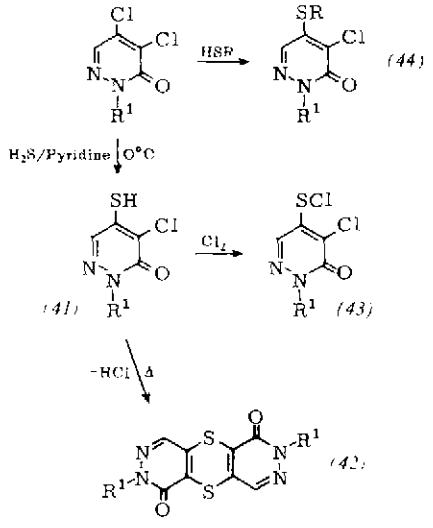


(38) *(39)* *(40)*

Nucleophilic substitution of the chlorine proceeds even more readily with hydrogen sulfide or thiols [45]. For example, 4,5-dichloro-1-phenyl-6-pyridazone and sodium sulfide react smoothly in pyridine/water with cooling to give a high yield of 5-chloro-4-mercapto-1-phenyl-6-pyridazone *(41)*. Under more vigorous conditions, however, further substitution takes place in the 5-position as well. This readily leads (as does the reaction with sodium thiocyanate, sodium thiosulfate, or thiourea) to interlinkage of two pyridazone rings by sulfur bridges to form a dipyridazo[4,5-*b*:4,5-*e*]-1,4-dithiine-1,6-dione *(42)*. Such "dithiine pyridazones" have recently also been prepared by *Castle* et al. [46,47] by the reaction of dichloropyridazones with sodium sulfide. The mercaptopyridazone *(41)* forms stable heavy metal salts.

Compound *(41)* is converted by chlorine into the 4-sulfenylchloride *(43)*.

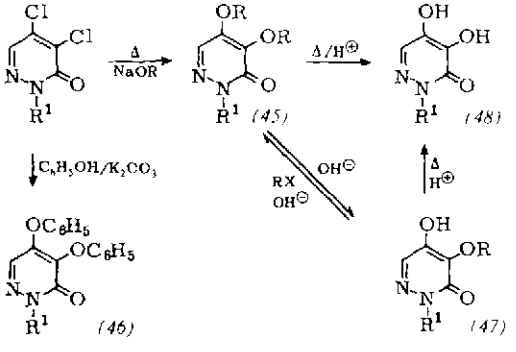
Similarly, careful reaction of thiols and thiophenols with dichloropyridazones yields 4-alkylthio-5-chloropyridazones and the 4-phenylthio-5-chloropyridazones *(44)*, R = alkyl and aryl, respectively. Under more vigorous conditions, both chlorine atoms are readily eliminated from 4,5-dichloro-6-pyridazones to form the 4,5-bisalkylthio or 4,5-bisarylthio compounds.



(44) *(41)* *(43)* *(42)*

In a similar manner, but under much more vigorous conditions, 4,5-dichloropyridazones react with excess alkoxide or phenoxide to form the 4,5-dialkoxy *(45)* or 4,5-diphenoxy compounds *(46)*. The formation of the 4,5-dialkoxypyridazones is often accompanied by that of 5-alkoxy-4-hydroxypyridazones *(47)*.

Alkylation of 5-alkoxy-4-hydroxypyridazones also yields 4,5-dialkoxypyridazones *(45)*. Compounds with different alkoxy residues in the 4- and 5-positions can also be



(45) *(48)* *(46)* *(47)*

prepared in this manner. Examination of the phytotoxicity of these gives insight into the relationship between structure and activity.

4,5-Dialkoxypyridazones *(45)* can be hydrolysed to form 4,5-dihydroxypyridazones *(48)* which may be regarded as reductones of the pyridazone series. This viewpoint is strongly supported by their properties, particularly their pronounced reactivity.

4,5-Dichloropyridazones react even more readily with phenols than with alcohols, both halogen atoms being eliminated. Thus, 4,5-dichloro-1-phenylpyridazone is readily diphenoxylated on heating in excess phenol containing potassium carbonate, the product being 4,5-diphenoxy-1-phenyl-6-pyridazone *(46)*.

Replacement of both halogen atoms by primary or secondary amines to give 4,5-diaminopyridazones *(49)* is more difficult and requires very high temperatures and

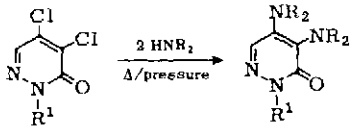
[44] Belgian Patent 607934 (Sept. 7th, 1961; German priority Sept. 9th, 1960), BASF, inventors: *F. Reicheneder, K. Dury, A. Fischer*, and *H. Stummeyer*.

[45] We believe that this enhanced reactivity towards thiols is a possible cause of the bactericidal and fungicidal action of 4,5-dichloropyridazones; these compounds probably block thiol groups of microbial or fungal enzymes [6].

[46] *R. N. Castle* and *K. Kaji*, Naturwissenschaften *51*, 38 (1964).

[47] Cf. *R. N. Castle* and *K. Kaji*, Tetrahedron Letters *1962*, 393.

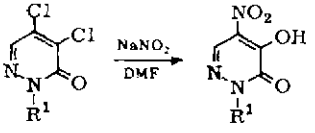
pressures. However, the parent compound of this class, 4,5-diaminopyridazone, cannot be obtained in this way [48]. It is prepared by another method.



(49)

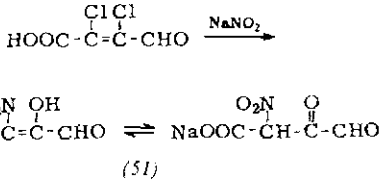
8. Hydroxynitropyridazones

The reaction of 4,5-dichloropyridazones with sodium nitrate in dimethylformamide (DMF) proceeds extremely readily with elimination of both chlorine atoms to yield 5-hydroxy-4-nitropyridazones *(50)*.



(50)

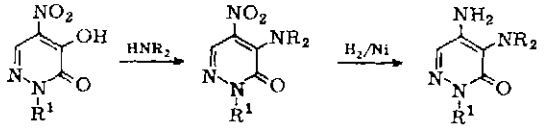
There is clearly some analogy with mucochloric acid, which reacts with sodium nitrite to give sodium 3-formyl-2-nitro-3-oxopropionate *(51)* [49].



(51)

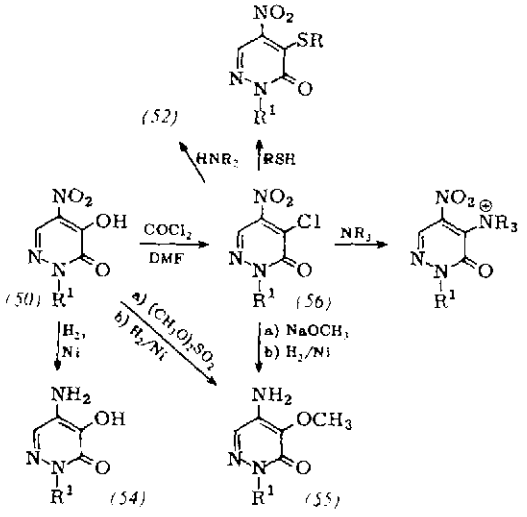
In the halogenoquinone series, chloranil, for example, also reacts with sodium nitrite to form so-called "nitranilic acid", *i.e.* 3,6-dihydroxy-2,5-dinitro-1,4-benzoquinone [50].

5-Hydroxy-4-nitropyridazones *(50)* are strongly acidic enols and readily form salts. The salts formed with ammonia and some amines are converted on heating into 5-amino-4-nitro compounds *(52)*, which can then be reduced, either catalytically or with zinc dust, to 4,5-diamino-6-pyridazones *(53)*. We have obtained a series of diaminopyridazones in this way.



(50) *(52)* *(53)*

4-Amino-5-hydroxypyridazones *(54)* and 4-amino-5-methoxypyridazones *(55)* can be easily prepared by the reduction of 5-hydroxy-4-nitropyridazones. Replacement of the hydroxy group by chlorine then leads to the 5-chloro-4-nitro compounds *(56)*. Owing to the reactivity of the strongly activated halogen atom, these compounds can undergo further reactions.



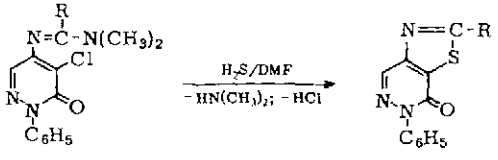
(50) *(52)* *(54)* *(55)* *(56)*

It is interesting that chlorination of 5-hydroxy-4-nitro-1-phenylpyridazone *(50)*, R = C_6H_5, followed by reduction of the resulting chloronitropyridazone *(56)* and reaction of the product with sodium methoxide, leads to two isomeric aminomethoxypyridazones which on diazotization yield a 4-diazoniumpyridazone and a 5-diazoniumpyridazone, respectively. These can also be obtained from 4-amino-5-chloro-1-phenylpyridazone and 1-phenyl-5-amino-4-chloro-1-phenylpyridazone, respectively. This indicates that the starting material *(50)* itself must contain a small quantity of the isomeric 4-hydroxy-5-nitro compound.

9. Heterocyclic Systems

By treating acyl derivatives of 4-amino-5-chloropyridazones with hydrogen sulfide, we obtained a new heterocyclic system, namely the pyridazothiazole system.

Amidines react readily with hydrogen sulfide to form thiocarboxamides [51]. Reaction of an amidine of 4-amino-5-chloro-1-phenyl-6-pyridazone, *e.g.* 5-Chloro-4-(dimethylaminomethyleneamino)-1-phenyl-6-pyridazone *(57)*, R = H, with hydrogen sulfide in dimethylformamide (DMF) leads by thiolysis and simultaneous elimination of hydrogen chloride to the thiazolo derivative *(58)*.



(57) R = H, CH_3, C_6H_5 *(58)*

The thiazolopyridazone isomeric with *(58)* can be prepared from 5-amino-4-chloropyridazone, again by thiolysis of an amidine. The action of hydrogen sulfide on the corresponding amidrazone *(59)*, on the other hand,

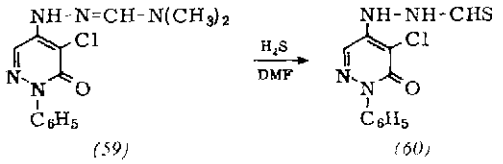
[48] *R. N. Castle* and *W. S. Seese*, J. org. Chemistry *23*, 1534 (1958).

[49] *P. E. Fanta, R. A. Stein*, and *R. M. W. Rickett*, J. Amer. chem. Soc. *80*, 4577 (1958).

[50] *R. Nietzki*, Ber. dtsch. chem. Ges. *10*, 2147 (1877); *20*, 2116 (1887).

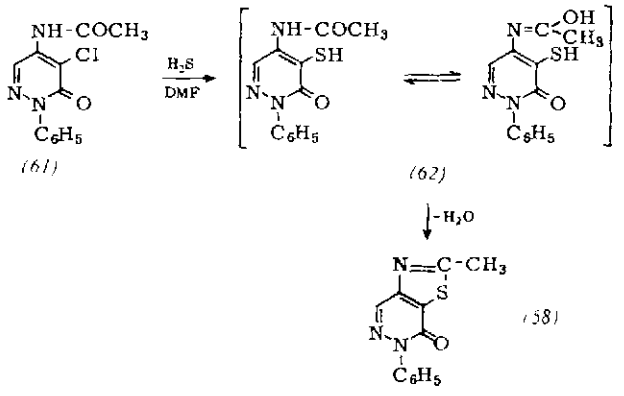
[51] German Published Patent Application 1168897 (May 4th, 1962), BASF, inventors: *H. Eilingsfeld* and *H. Weidinger*.

yields only the open-chain *N'*-thioformylhydrazino derivative *(60)*.



(59) *(60)*

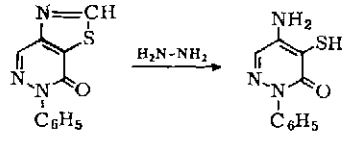
The thiazolo derivatives can also be obtained directly from the *N*-acylaminopyridazones, *e.g.* the *N*-acetyl derivative *(61)*, by treatment with hydrogen sulfide in dimethylformamide. The intermediate *(62)* immediately loses one molecule of water under the reaction conditions. This suggests that the halogen atom in the 4-amino-5-chloropyridazones, which is otherwise rather



(61) *(62)* *(58)*

inert, is activated by acylation. It is possible that, with the amidine derivatives, thiolysis is again preceded by replacement of the halogen atom by hydrogen sulfide.

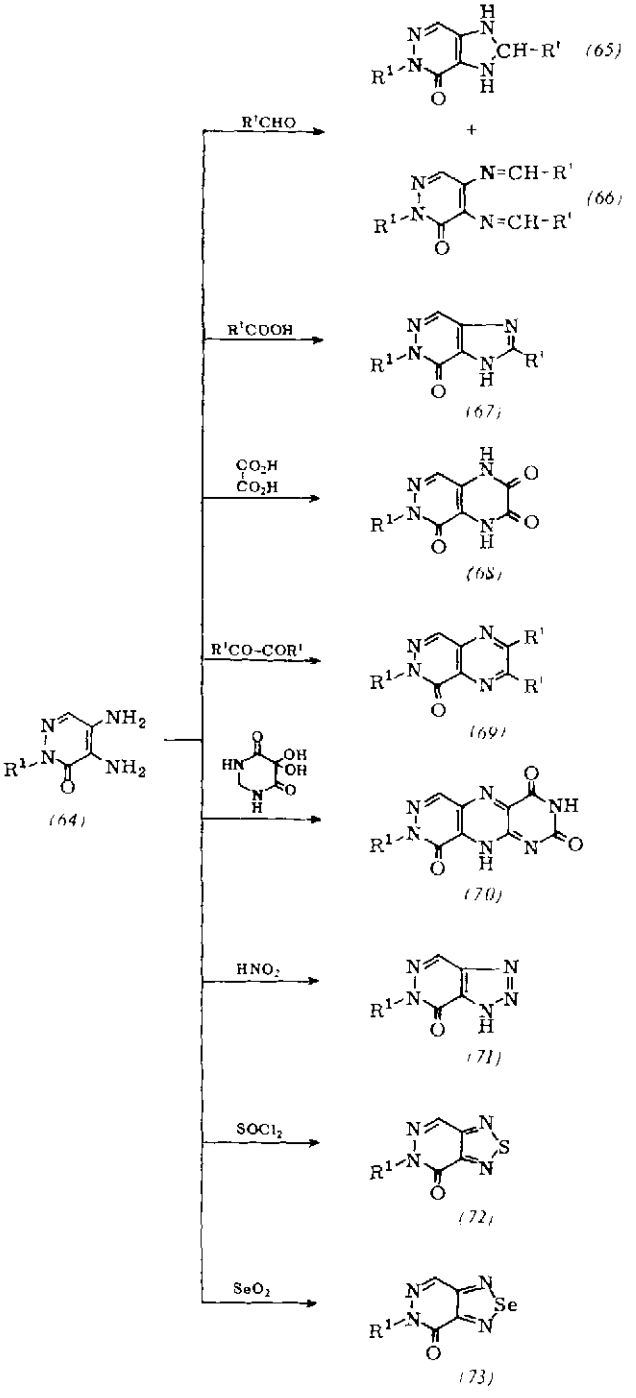
4-Amino-5-mercaptopyridazone *(63)* is formed by cleavage of the thiazole ring on hydrazinolysis of pyridazothiazoles such as *(58)*.



(58) *(63)*

Another convenient route to diheterocyclic systems of the pyridazone series has now been provided by the availability of 4-amino-5-hydroxypyridazones and 4,5-diaminopyridazones *(64)*, particularly the latter. Although aldehydes react with 4,5-diaminopyridazones *(64)* to form only the condensation products *(65)* and *(66)*, reaction of *(64)* with organic acids leads to pyridazo[4,5-*d*]imidazoles *(67)*, which are of interest on account of their relationship with naturally occuring purines.

Oxalic acid, α-diketones, and chloral (which is used in *F. Bergmann*'s method [52] for the preparation of 6-hydroxypteridines) yield pterin-like derivatives *(68)* and *(69)* from *(64)*. An "alloxazine" *(70)* is obtained from *(64)* and alloxan. The action of nitrous acid on *(64)* leads to a triazolo[*d*]pyridazone *(71)*, while thionyl chloride and selenium dioxide form a thiadiazolo *(72)* and a selenadiazolo derivative *(73)*, respectively.



(64) *(65)* *(66)* *(67)* *(68)* *(69)* *(70)* *(71)* *(72)* *(73)*

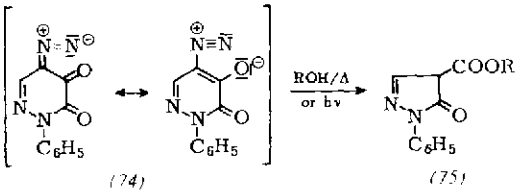
10. Ring Contraction

We shall conclude this paper with a description of some new transitions from the pyridazone series to the pyrazolone series. The 4-diazonium-5,6-dioxopyridazones *(74)* readily undergo a Wolff rearrangement of the type investigated by *Süs* [53] with hydrazonoquinones to form the corresponding pyrazolone-4-carboxylic acids *(75)*. The reactivity of the diazoniumpyridazones is higher than that of the purely aromatic hydrazonoquinones,

[52] *F. Bergmann, M. Tamari*, and *H. Ungar-Waron*, J. chem. Soc. (London) *1964*, 565.

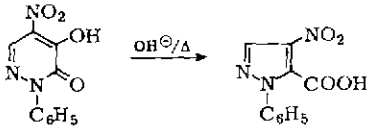
[53] References given in *H. Zollinger*: Chemie der Azofarbstoffe. Birkhäuser, Basel 1958, pp. 90ff.

as shown by the fact that this rearrangement takes place without photocatalysis on heating gently in a suitable medium, *e.g.* an alcohol [54].



(74) (75)

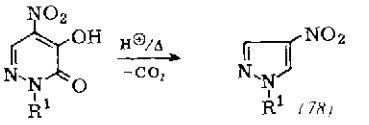
Another reaction leading from pyridazones to pyrazoles occurs when 5-hydroxy-4-nitropyridazones are warmed in an acidic or alkaline medium: the compounds undergo ring contraction to form derivatives of 4-nitropyrazole. This rearrangement can be effected with 1-aryl-5-hydroxy-4-nitropyridazone *(50)*, $R^1 = C_6H_5$, in alkaline medium; the reaction proceeds smoothly to yield 4-nitro-1-phenylpyrazole-5-carboxylic acid *(76)*.



(50) (76)

[54] Cf. *P. Yates* and *E. Robb*, J.Amer.chem.Soc. *79*, 5760 (1957).

5-Hydroxy-4-nitropyridazones which are unsubstituted or alkyl-substituted in the 1-position *(77)*, on the other hand, react only in acidic media, and the 4-nitropyrazole-5-carboxylic acid formed decarboxylates spontaneously to the correspondingly substituted 4-nitropyrazole *(78)*.



(77) (78)

R^1 = H, Alkyl

This ring concentration shows an interesting similarity to the rearrangement of 5-hydroxypyridazone described by *Ach* [55], and to the recently discovered rearrangement of 1-aryl-3,5-dihalogenopyridazones [56].

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German version: Angew. Chem. *77*, 282 (1965)
Translated by Express Translation Service, London

[55] *F. Ach*, Liebigs Ann. Chem. *253*, 44 (1889); cf. *A. Smith*, Liebigs Ann. Chem. *289*, 310 (1896).

[56] *K. Obata*, *H. Kizu*, and *A. Mabi*, J. pharm. Soc. Japan *83*, 725 (1963); *K. Obata* and *Y. Maki*, Chem. pharmac. Bull. (Tokyo) *12*, 176 (1964); cf. *J. Druey*, *K. Meier*, and *A. Staehelin*, Pharmac. Acta Helvetiae *38*, 498 (1963).

The Chemistry of Vinylsulfonic Acid [1]

BY DR. H. DISTLER

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Published on the occasion of the 100th anniversary of the establishment of Badische Anilin- & Soda-Fabrik AG., on April 6th, 1965

Vinylsulfonic acid and its derivatives can be prepared from β-chloroethanesulfonyl chloride or carbyl sulfate (β-hydroxysulfonyloxyethanesulfonic anhydride). The chemistry of vinylsulfonic acid has assumed industrial importance since the discovery of a simple synthesis of β-chloroethanesulfonyl chloride from chloroethane or ethane, sulfur dioxide, and chlorine by the Reed process. Carbyl sulfate is as important a starting material as β-chloroethanesulfonyl chloride, and surpasses the latter in some respects, e.g. on account of the low price of its components ethylene and sulfur trioxide. Vinylsulfonates undergo addition reactions with alcohols, phenols, thiols, sulfinic acids, carboxylic acids, amides, imides, and hydrazides, as well as with amines, ureas, diazonium salts, and nitroparaffins. Furthermore, they undergo halogenation, nitration, olefination, and the Diels-Adler reaction. — Methods for the preparation of the free vinylsulfonic acid are described. Alkyl vinylsulfonates are excellent alkylating agents. The derivatives of vinylsulfonic acid are used e.g. as plasticizers, emulsifiers, and fungicides.

I. Synthesis of Vinylsulfonates

A. Alkyl Vinylsulfonates

Alkyl vinylsulfonates are obtained by the reaction [3] of alkoxides with β-chloroethanesulfonyl chloride [2]:

$$ClCH_2\text{-}CH_2\text{-}SO_2Cl \xrightarrow[\text{in ROH}]{2\ RONa} CH_2{=}CH\text{-}SO_2\text{-}OR + 2\ NaCl \quad \text{(a)}$$

The reaction proceeds most smoothly and gives the highest yield when a 30% methanolic solution of sodium methoxide is added to the β-chloroethane-

[1] Delivered in part as a lecture at the 19th International Congress for Pure and Applied Chemistry in London, July 1963.

[2] The preparation of β-chloroethanesulfonyl chloride on a technical scale: unpublished work (1955–1956) of *K. Küspert*; see also *Ch. Walling* and *W. F. Pease*, J. org. Chemistry *23*, 478 (1958); German Pat. 1152687 (Oct. 28th, 1961) BASF, inventors: *H. Schlecht* and *H. Götz*.

sulfonyl chloride solution until the end-point is reached. An excess of the base is to be avoided, as otherwise the alcohol adds onto the double bond. Higher esters are prepared in a similar manner. The vinylsulfonates of aliphatic alcohols hydrolyse easily to yield vinylsulfonic acid and the alcohol, methyl vinylsulfonate being the easiest to cleave. When the hydrolysis is carried out with steam, using methanol as solvent, very pure vinylsulfonic acid is obtained even on a technical scale [4]:

$$CH_2=CH-SO_2-OCH_3 \xrightarrow{H_2O} CH_2=CH-SO_3H + CH_3OH \quad (b)$$

In a different preparation, β-chloroethanesulfonyl chloride is esterified with an alcohol in the presence of pyridine [5]. Vinylsulfonyl chloride can similarly be used for the synthesis of esters in the presence of alkali [6].

B. Aryl and Polyfluoroalkyl Vinylsulfonates

Unlike the alkyl vinylsulfonates, the aryl esters are remarkably stable towards hydrolysis, and can therefore be prepared by reacting a phenol with β-chloroethanesulfonyl chloride in an aqueous alkaline medium:

$$ClCH_2-CH_2-SO_2Cl + C_6H_5-OH + 2\ NaOH \quad (c)$$

$$\xrightarrow[-2\ NaCl]{H_2O} CH_2=CH-SO_2-OC_6H_5$$

It is advisable to carry out the acylation at pH 8–9 and a temperature of 0 to 5 °C. At higher temperatures and at pH > 9, the phenol adds onto the α,β-unsaturated sulfonate [7]. In the presence of a base acting as HCl-acceptor, acylation and dehydrochlorination take place with great ease. Aryl vinylsulfonates are formed with good, occasionally with quantitative yields, even under technical conditions.

Polyfluorinated alcohols can be similarly esterified [8]:

$$HCF_2-(CF_2)_2-CH_2OH + ClCH_2-CH_2-SO_2Cl \quad (d)$$

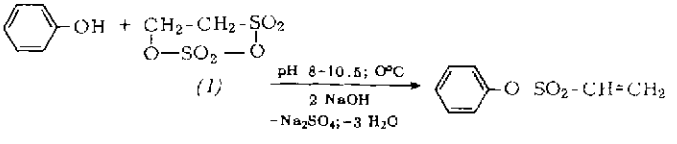
$$\xrightarrow[-H_2O;-2\ NaCl]{2\ NaOH} HCF_2-(CF_2)_2-CH_2-O-SO_2-CH=CH_2$$

Similar to aryl vinylsulfonates, the resulting esters are relatively stable to hydrolysis and have no alkylating effect. Fluorinated alcohols containing 5 to 11 carbon atoms give the highest yields, and it is immaterial whether they are fully or only partially fluorinated.

Table 1. Aryl vinylsulfonates $CH_2=CH-SO_2-OR$ prepared from β-chloroethanesulfonyl chloride and various phenols.

R	B.p. [°C/mm]	M.p. [°C]	Yield [%]
Phenyl	90–91/0.1	40–42	85
p-Tolyl	143–148/7		82
2,4-Dimethylphenyl	128–132/0.5		83
3,5-Dimethylphenyl	125–130/0.4		82
4-t-Butylphenyl	117–119/0.1		90
4-Chloro-2-methylphenyl	153–159/1	52–53	80
4-Chloro-3-methylphenyl	115–120/0.2		82
2-Chlorophenyl	110–115/0.2		96
3-Chlorophenyl	114–118/0.2		96
4-Chlorophenyl	105–110/0.1–0.2	44	96
2,4-Dichlorophenyl	130–136/0.2–0.4		85
2,5-Dichlorophenyl	122–128/0.2	37	70
2,4,6-Trichlorophenyl	131–133/0.1	46–47	82
2,4,5-Trichlorophenyl	123–128/0.2	65	76
Pentachlorophenyl	190/0.2	93	93
2-Bromophenoyl	102–105/0.2		88
2,4,6-Tribromophenyl		81.5–82.5	86
4-Thiocyanatophenyl		98–101	72
2-Formylphenyl	146–152/0.1–0.3		68
2-Methoxyphenyl	135–140/0.2		66
4-Methoxycarbonylphenyl	156–161/0.2		64
4-Ethoxycarbonylphenyl	142–148/0.2		64
2-Methoxycarbonylphenyl	133–138/0.2		62
2-Phenoxycarbonylphenyl	182–187/0.2		65
α-Naphthyl		51–53	84
o-Biphenylyl	132–136/0.2		82
2-Acetylphenyl	64–66/0.3		80
2-Fluorophenyl	118–121/0.3		86
4-Fluorophenyl	124–126/0.2		84
2,4,6-Triiodophenyl		112–114	45
1,3-Phenylene		54–56	92

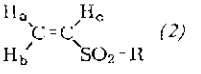
Aryl vinylsulfonates can also be prepared from phenols and carbyl sulfate *(1)* in an aqueous alkaline medium at about 0 °C [9].



(1)

The yields are sometimes lower than in the case of β-chloroethanesulfonyl chloride, possibly because of the easy conversion of carbyl sulfate into the sulfate of β-hydroxyethanesulfonic acid, *i.e.* ethionic acid, which no longer shows any acylating action.

Table 2. ^{1}H-NMR data (chemical shifts τ and coupling constants J) of vinylsulfonyl derivatives *(2)*.



(2)

R	τ_a [ppm]	τ_b [ppm]	τ_c [ppm]	J_{ab} [cps]	J_{ac} [cps]	J_{bc} [cps]
–OH	6.13	6.41	6.73	-1.1_6	10.2_0	16.7_5
–OCH_3	6.22	6.42	6.56	-0.6_0	10.1_7	16.9_4
–OC_4H_9	6.14	6.40	6.57	-0.5_5	10.2_9	16.8_6
–O–C_6H_5	6.08	6.29	6.61	-0.7_3	9.9_7	16.6_2
p-O–C_6H_4–$C(CH_3)_3$	6.13	6.35	6.67	-0.6_4	10.1_8	16.9_7
–O–2,4,6–Cl_3–C_6H_2	6.24	6.51	6.92	-0.5_0	10.1_5	16.7_4
–O–2,4,5–Cl_3–C_6H_2	6.23	6.41	6.76	-0.8_9	10.1_2	16.7_7
–$N(CH_3)$–C_6H_5	6.03	6.15	6.58	-0.1_9	9.9_3	16.6_2

The spectra were recorded in $CDCl_3$ at a concentration of 20 % by weight, and at a temperature of 38 °C, using a Varian A 60 spectrometer (60 Mc). The parameters of the lines belonging to the vinyl group were calculated by iteration as an ABC-problem. The values τ_a, τ_b, and τ_c of the chemical shifts are based on tetramethylsilane as an internal standard. Spectroscopic details are given in [10].

[3] German Pat. 1091104 (March 5th, 1960) BASF, inventors: *H. Distler* and *K. Küspert*.

[4] German Pat. 1171419 (May 8th, 1962) BASF, inventors: *H. Distler* and *A. Wegerich*.

[5] *W. F. Whitmore* and *E. F. Landau*, J. Amer. chem. Soc. *68*, 1797 (1946).

[6] U.S. Pat. 2348705 (1944) DuPont, inventors: *V. V. Aldermann* and *W. E. Hanford*; Chem. Abstr. *39*, 711 (1945).

[7] German Pat. 1135898 (Sept. 7th, 1960) BASF, inventors: *W. Müller*, *H. Distler*, and *A. Palm*.

[8] German Published Patent Application 1163797 (Febr. 27th, 1962) BASF, inventors: *H. Distler* and *W. Müller*.

[9] German Pat. 1119253 (June 18th, 1960) BASF, inventor: *H. Distler*.

[10] *W. Brügel*, *Th. Ankel*, and *F. Krückeberg*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *64*, 1121 (1960).

II. Reactions of Vinylsulfonates

A. Reactions with Compounds Containing Active Hydrogen

Most reactions with compounds (HA) containing active hydrogen proceed very smoothly, giving rise to β-substituted ethanesulfonates:

$$HA + H_2C{=}CH{-}SO_3R \rightarrow A{-}CH_2{-}CH_2{-}SO_3R \qquad (e)$$

Since vinylsulfones react in a similar manner, we propose to use the term "sulfonethylation", introduced by *Truce* and *Wellisch* [11], also to describe additions to vinylsulfonates.

1. Addition of Alcohols and Phenols [7]

In the presence of catalytic quantities of a base, primary, secondary, and tertiary alcohols add onto vinylsulfonates with great ease:

$$ROH + CH_2{=}CH{-}SO_2{-}OR' \xrightarrow[0\text{–}10^{\circ}C]{\text{Base}} \underset{(3)}{RO{-}CH_2{-}CH_2{-}SO_2{-}OR'} \qquad (f)$$

The hydroxides, carbonates, or alkoxides of the alkali metals and the alkaline earth metals are used as bases, in quantities of up to 2 % of the sulfonate. Quaternary ammonium hydroxides such as trimethylbenzylammonium hydroxide (Triton B®) are also suitable.

Adducts formed from long-chain primary alcohols and aryl vinylsulfonates are very good plasticizers for PVC [7]: they are distinguished by their compatibility, low volatility, and low solidification point.

The addition of long-chain alcohols to alkyl vinylsulfonates at a low temperature leads to alkyl β-alkoxyethanesulfonates *(3)*, which can be saponified to metal β-alkoxyethanesulfonates. These are suitable as emulsifiers in the preparation of stable polymer dispersions [12].

$$(3) \xrightarrow{NaOH} RO{-}CH_2{-}CH_2{-}SO_3Na + R'OH$$

The reaction of alkyl β-alkoxyethanesulfonates *(3)* with tertiary amines results in ammonium salts, which are useful in the production of low-foaming polymer dispersions [13].

$$\underset{(3)}{RO{-}CH_2{-}CH_2{-}SO_3R'} + NR_3 \rightarrow RO{-}CH_2{-}CH_2{-}SO_3^{\ominus} + R_3R'N^{\oplus}$$

Phenols can also add onto vinylsulfonates, giving very stable alkyl β-aroxyethanesulfonates which crystallize easily in most cases. Esters with more than one vinylsulfonic acid group, *e.g.* resorcinyl divinylsulfonate, are cross-linking agents used in the chemistry of paints [14].

2. Addition of Sulfur Compounds

In the presence of tertiary amines, vinylsulfonates give symmetrical thioethers *(4)* with H_2S.

$$H_2S + CH_2{=}CH{-}SO_2{-}OR \xrightarrow{\text{Base}} \underset{(4)}{S(CH_2{-}CH_2{-}SO_2{-}OR)_2}$$

Unsymmetrical thioethers *(5)* are formed with thiols or thiophenols.

$$R{-}SH + CH_2{=}CH{-}SO_2{-}OR' \xrightarrow{\text{Base}} \underset{(5)}{RS{-}CH_2{-}CH_2{-}SO_2{-}OR'}$$

Thus the addition of long-chain alkanethiols to alkyl vinylsulfonates leads to alkyl β-alkylthioethanesulfonates. The reactions proceed smoothly, and the yields are quantitative. The products [15] can be saponified to metal sulfonates which crystallize easily.

$$\underset{(6)}{RS{-}CH_2{-}CH_2{-}SO_2{-}OR'} \xrightarrow{NaOH} RS{-}CH_2{-}CH_2{-}SO_3Na + R'OH$$

These metal sulfonates *(6)* serve, *inter alia*, as emulsifiers in the production of stable polymer dispersions [12]. The easy addition of thiols is utilized for the quantitative determination of vinylsulfonates (cf. Section "Experimental"). The thiophenol adducts crystallize very easily. They can be converted into the β-sulfonylethanesulfonate derivatives by oxidation with potassium permanganate or H_2O_2.

3. Addition of Sulfinic Acids [16]

Sulfinic acids *(7)* react almost quantitatively with α,β-unsaturated sulfonates. The immiscible components can be reacted in an aqueous medium at 50–80 °C, an acid being added to adjust the pH to 4–6. The resulting sulfones *(8)* are obtained in high purity and crystallize with remarkable ease. Sulfones such as *(10)* and formaldehyde are formed on the addition of hydroxymethanesulfinic acid *(9)* (formaldehyde sulfoxylate).

$$\underset{(7)}{R'{-}SO_2H} + CH_2{=}CH{-}SO_2{-}OR \xrightarrow[\text{pH 4–6}]{} \underset{(8)}{R'{-}SO_2{-}CH_2{\cdot}CH_2{-}SO_2{-}OR}$$

$$2\,CH_2{=}CH{-}SO_2{-}OR + HO{-}CH_2{-}SO_2H \xrightarrow[\text{pH 4–6}]{} \underset{(10)}{O_2S(CH_2{-}CH_2{-}SO_2{-}OR)_2} + HCHO$$

$$(9)$$

If *(9)* is reacted with a bifunctional compound, such as *e.g.* resorcinyl divinylsulfonate, a linear high-melting polymer is obtained [17].

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[11] *W. E. Truce* and *E. Wellisch*, J. Amer. chem. Soc. *74*, 2881 (1952).

[12] German Pat. 1127590 (May 3rd, 1960) BASF, inventors: *H. Fikentscher, H. Willersinn, E. Penning*, and *H. Distler*.

[13] German Pat. applied for.

[14] French Pat. 1321629 (1961) BASF, inventors: *D. Ludsteck, G. Lützel, W. Rohland*, and *H. Distler*.

[15] German Published Patent Application 1108210 (Jan. 2nd, 1960) BASF, inventor: *H. Distler*.

[16] German Pat. applied for.

[17] The K-value [as defined by *H. Fikentscher*, Cellulosechemie *13*, 58 (1932)] is 20–25.

4. Addition of Sodium Hydrogen Sulfite [18]

The addition of sodium hydrogen sulfite to vinylsulfonates is similar to its addition to derivatives of maleic and acrylic acids and results in practically quantitative yields of sodium β-(alkoxysulfonyl)ethanesulfonates:

$$NaHSO_3 + CH_2{=}CH{-}SO_2{-}OR \longrightarrow NaSO_3{-}CH_2{-}CH_2{-}SO_2{-}OR \qquad (g)$$

The immiscible components are reacted in an aqueous medium either at or slightly above room temperature. The sulfonates formed are generally crystalline and water-soluble. When R is sufficiently long, the sulfonates will exhibit good surface-active properties.

5. Addition of Amines

Nucleophilic agents such as primary and secondary amines react vigorously and quantitatively with vinylsulfonates to give substituted taurine esters *(11a)* and *(11b)*, which are characterized by very good fungicidal activities [19].

$$2\ CH_2{=}CH{-}SO_2{-}OR + R'{-}NH_2 \longrightarrow R'{-}N(CH_2{-}CH_2{-}SO_2{-}OR)_2 \qquad (11a)$$

$$CH_2{=}CH{-}SO_2{-}OR + R'_2NH \longrightarrow R'_2N{-}CH_2{-}CH_2{-}SO_2{-}OR \qquad (11b)$$

The "sulfonethylation" of long-chain amines with methyl vinylsulfonate leads to methyl β-alkylaminoethanesulfonates, which give surface-active metal sulfonates on alkaline hydrolysis [20]. Polyadducts are formed when polyamines are reacted with di- or polyfunctional vinylsulfonates [21].

Taurine esters can be quaternized with the usual alkylating agents to give water-soluble products, *e.g. (12)*, which have a strong microcidal action and are used in combating algal growth [22]. They undergo a Hofmann elimination [Reaction (h)] under very mild conditions. Since the low concentration of OH^- ions in water is sufficient for this elimination to occur, the vinylsulfonate separates out when an aqueous solution of the taurine ester is simply allowed to stand for a fairly long time. Heating increases the OH^- concentration, and therefore promotes the elimination, which occurs instantaneously in the presence of NaOH or sodium carbonate.

$$[C_6H_5{-}O{-}SO_2{-}CH_2{-}CH_2{-}N^{\oplus}R^1R^2R^3]\ X^{\ominus} \qquad (12) \qquad (h)$$

$$\longrightarrow C_6H_5{-}O{-}SO_2{-}CH{=}CH_2 + [HNR^1R^2R^3]^{\oplus}X^{\ominus}$$

This easy elimination can be utilized in the synthesis of tertiary amines which are otherwise difficult to prepare. The vinylsulfonate is recovered quantitatively, and the tertiary amine can be isolated from the aqueous solution.

6. Addition of Nitroparaffins [23]

Nitroparaffins can be "sulfonethylated" using NaOH, KOH, quaternary ammonium hydroxides, or tertiary amines as catalysts, the use of *N,N*-dimethylcyclohexylamine at 70 to 90 °C being particularly convenient.

$$3\ CH_2{=}CH{-}SO_2{-}OR + O_2N{-}CH_3 \xrightarrow{Base} O_2N{-}C(CH_2{-}CH_2{-}SO_2{-}OR)_3 \qquad (i)$$

$$CH_2{=}CH{-}SO_2{-}OR + \text{C}_6\text{H}_4(NO_2)H \xrightarrow{Base} \text{C}_6\text{H}_4(NO_2)(CH_2{-}CH_2{-}SO_2{-}OR) \qquad (k)$$

Higbly satisfactory results are obtained when the reaction is carried out with primary and secondary nitroparaffins.

Nitrocycloalkanes, *e.g.* nitrocyclooctane or nitrocyclododecane, also give good yields. The resulting nitroalkanesulfonates crystallize very easily, and exhibit remarkable fungistatic actions.

7. Addition of Phosphorus Compounds

Derivatives of thiophosphoric acid are easily "sulfonethylated" in the presence of a catalysing base.

$$(R'O)_2P(S)(O){-}SH + CH_2{=}CH{-}SO_2{-}OR \xrightarrow{Base} (R'O)_2P(S)(O){-}S{-}CH_2{-}CH_2{-}SO_2{-}OR \qquad (13)$$

The products *(13)* do not however show the expected insecticidal action.

8. Addition of Compounds Containing Dichloromethyl Groups

Compounds containing active hydrogen atoms, for example the derivatives of dichloroacetic acid, can be "sulfonethylated" in the presence of a base catalyst [24].

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[18] German Pat. 1124032 (June 25th, 1960) BASF, inventors: *H. Distler* and *H. J. Krause*.

[19] German Pat. 1151149 (May 20th, 1961) BASF, inventors: *H. Distler, G. Leibner, K. J. Fust, E. Pommer*, and *H. Stummeyer*.

[20] German Pat. 1129284 (May 4th, 1960) BASF, inventors: *H. Fikentscher, H. Willersinn, E. Penning*, and *H. Distler*.

[21] German Pat. 1116405 (Jan. 29th, 1960) BASF, inventors: *K. Demmler, H. Distler, F. F. Miller*, and *L. Würtele*.

[22] German Published Patent Application 1174454 (Sept. 5th, 1961) BASF, inventors: *H. Distler, W. Müller, H. Stummeyer*, and *E. Pommer*.

[23] German Pat. 1157217 (March 24th, 1961) BASF, inventor: *H. Distler*.

[24] German Published Patent Application 1134070 (Dec. 23rd, 1960) Farbenfabriken Bayer, inventors: *H. Timmler* and *R. Wegler*.

Aryl esters are cleaved less easily when the reaction is catalysed by alkoxides.

$$Cl_2CH\text{-}COOR' + CH_2{=}CH\text{-}SO_2\text{-}OR \quad (CN) \quad (l)$$
$$\xrightarrow{Base} Cl_2C(COOR')(CN)\text{-}CH_2\text{-}CH_2\text{-}SO_2\text{-}OR$$

9. Michael Condensation

Similarly to the nitroalkanes and dichloroacetic acid derivatives, other compounds containing active methylene groups, *e.g.* esters, nitriles, and ketones, can also be "sulfonethylated". Ethyl acetoacetate, derivatives of malonic acid, ethyl cyanoacetate, and benzyl cyanide undergo the reaction with good yields.

$$CH_2{=}CH\text{-}SO_2\text{-}OR + CH_3\text{-}CO\text{-}CH_2\text{-}CO\text{-}OC_2H_5 \quad (m)$$
$$\xrightarrow{Base} RO\text{-}SO_2\text{-}CH_2\text{-}CH_2\text{-}CH(CO\text{-}OC_2H_5)\text{-}CO\text{-}CH_3$$

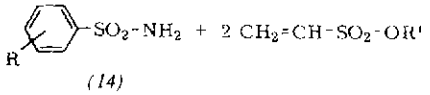
Double addition [25] may sometimes occur, provided that an excess of vinylsulfonate is employed, in which case both active hydrogens participate in the reaction.

$$CH_2{=}CH\text{-}SO_2\text{-}OR + H_2C(COOR')_2 \quad (n)$$
$$\xrightarrow{Base} CH(COOR')_2\text{-}CH_2\text{-}CH_2\text{-}SO_2\text{-}OR$$

The catalyst, generally *N,N*-dimethylcyclohexylamine, is always added in such a quantity that a spot-test just gives an alkaline reaction.

10. Addition of Sulfonamides, Amides, Imides, and Hydrazides of Carboxylic Acids, and of Ureas, Thioureas, and Oximes

Sulfonamides possessing replaceable hydrogen can be "sulfonethylated" at higher temperatures, the reaction being catalysed by the hydroxides of the alkali and alkaline earth metals [26]. Sulfonamides with unsubstituted nitrogen atoms *(14)* undergo double addition:



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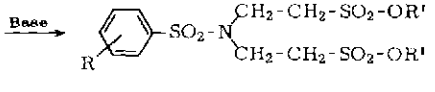


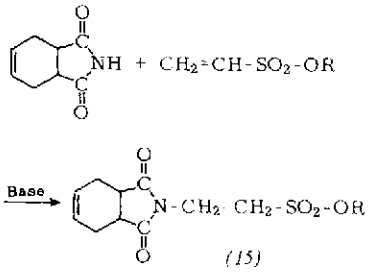
Carboxamides react less readily than sulfonamides, undergoing only monosubstitution:

$$R\text{-}CO\text{-}NH_2 + CH_2{=}CH\text{-}SO_2\text{-}OR' \quad (o)$$
$$\xrightarrow{Base} R\text{-}CO\text{-}NH\text{-}CH_2\text{-}CH_2\text{-}SO_2\text{-}OR'$$

[25] Unpublished work together with *W. Müller*.

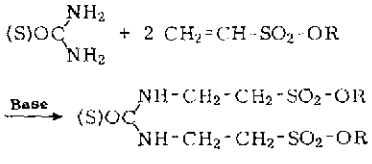
[26] German Published Patent Application 1155118 (Dec. 30th, 1961) BASF, inventor: *H. Distler*.

Carboxylic imides, on the other hand, are very reactive, giving crystalline products in high yields, *e.g. (15)*. *N,N*-Dimethylcyclohexylamine is generally used as the catalyst.



(15)

Urea and thiourea give the disubstituted products *(16)* in moderate yields.

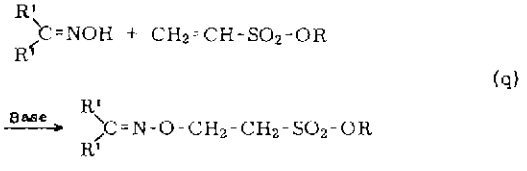


(16)

By comparison, carboxylic hydrazides react much more readily to give monosubstituted products:

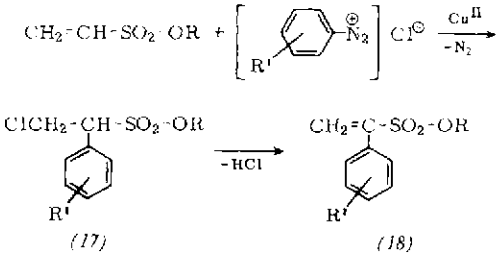
$$R'\text{-}CO\text{-}NH\text{-}NH_2 + CH_2{=}CH\text{-}SO_2\text{-}OR \quad (p)$$
$$\xrightarrow{Base} R'\text{-}CO\text{-}NH\text{-}NH\text{-}CH_2\text{-}CH_2\text{-}SO_2\text{-}OR$$

Oximes react at higher temperatures in the presence of bases, the reaction being sometimes very vigorous.



11. Addition of Diazonium Salts

In the presence of Cu(II) salts, diazonium chlorides react with vinylsulfonates at room temperature to give crystalline products *(17)*.



(17) *(18)*

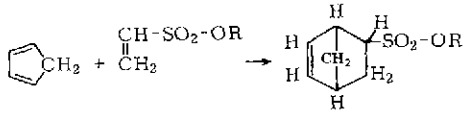
The synthesis is a form of the Meerwein reaction [27]. The easy elimination of HCl in the presence of a base leads to substituted vinylsulfonates *(18)*. Vinylsulfones react in a similar manner [28].

[27] *H. Meerwein, E. Buchner,* and *K. v. Emster,* J. prakt. Chem. *152,* 237 (1939).

[28] *E. Siegel* and *S. Petersen,* Angew. Chem. *74,* 873 (1962); Angew. Chem. internat. Edit. *1,* 593 (1962).

1. Diels-Alder Reaction

Heating of a vinylsulfonate with a diene, such as cyclopentadiene or hexachlorocyclopentadiene results in a substituted sulfonate, *e.g. (19)*, in very good yields.



(19)

2. Reaction with Olefins [29]

Olefins, *e.g.* propylene, butylene, propylene oligomers, and higher α-olefins, react with α,β-unsaturated sulfonates giving highly satisfactory yields of terminally unsaturated alkenesulfonates:

$$(CH_3)_2C{=}CH_2 + H_2C{=}CH{-}SO_3R \rightarrow H_2C{=}C(CH_3){-}(CH_2)_3{-}SO_3R \quad (r)$$

The reactants are heated at 100 °C or above, using a sealed tube for the low-boiling olefins. The products are suitable as plasticizers for PVC.

3. Reaction with Halogens

Cl_2, Br_2, and I_2 are practically inert toward vinylsulfonates, even in the warm. On irradiation or addition of compounds (*e.g.* azodiisobutyronitrile) capable of forming free radicals, however, rapid bromination or chlorination will occur. The addition of bromine is almost quantitative under these conditions:

$$CH_2{=}CH{-}SO_2{-}OR + Br_2 \rightarrow Br{-}CH_2{-}CHBr{-}SO_2{-}OR \xrightarrow{-HBr} CH_2{=}CBr{-}SO_2{-}OR \xrightarrow{Br_2} Br{-}CH_2{-}CBr_2{-}SO_2{-}OR \quad (s)$$

The α,β-dibromo derivatives lose HBr on treatment with a dilute solution of sodium carbonate or aqueous NaOH. The resulting α-bromovinylsulfonates can be rebrominated to give tribromo derivatives. The mono-, di-, and tribromo derivatives are distinguished by their unusually strong microcidal action, which is comparable to that of the organic compounds of mercury [30].

4. Nitration [31]

Below 30 °C, nitrating acid or sodium nitrate in conc. sulfuric acid react with aryl vinylsulfonates to give exclusively mononitrated products. Above 30 °C, however, hydrolysis occurs to form nitrophenols. Owing to ester cleavage, attempts aimed at the preparation of more highly nitrated derivatives under more vigorous conditions, were unsuccessful. It may be noted that the analogous phenyl acrylate and phenyl crotonate are split immediately under the same conditions, and cannot be nitrated.

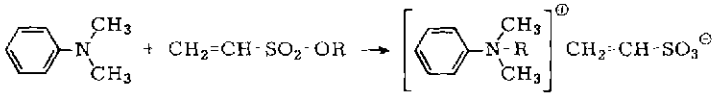
[29] German Pat. 1126860 (Dec. 9th, 1960) BASF, inventors: *W. Friedrichsen* and *H. Distler*.

[30] German Pat. applied for.

[31] German Pat. applied for.

5. Alkylation [32]

Alkyl vinylsulfonates are among the most effective alkylating agents. Unlike dimethyl sulfate or methyl *p*-toluenesulfonate, they are capable of converting *e.g.* phenol into anisole in a smooth reaction at room temperature. The reactions proceed under very mild conditions, and are usually quantitative. Primary, secondary, and tertiary alcohols undergo similar reactions. Sulfhydryl and primary or secondary amino groups linked to aromatic residues can be alkylated as well. Tertiary amines are converted into the quaternary ammonium salts *(20)* under very mild conditions.



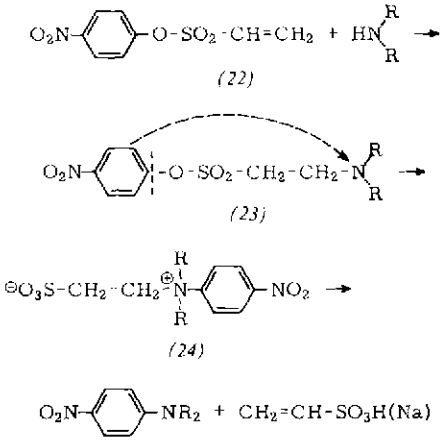
(20)

These products *(20)* are particularly useful as catalysts in emulsion polymerizations without emulsifiers [33].

Liquid methyl vinylsulfonate and ammonium chloride react vigorously in the absence of water, giving ammonium vinylsulfonate *(21)* and gaseous methyl chloride.

$$NH_4Cl + H_2C{=}CH{-}SO_3CH_3 \rightarrow ClCH_3 + H_2C{=}CH{-}SO_3^{\ominus}\ NH_4^{\oplus} \quad (21)$$

All attempts to use aryl vinylsulfonates for the arylation of amines in a similar way have been unsuccessful. If the aryl vinylsulfonate carries one or more electron-attracting substituents, *e.g.* nitro groups, on the nucleus, intramolecular arylation takes place to a small extent. For example, dimethylamine adds onto 4-nitrophenyl vinylsulfonate *(22)* in the cold, to give an unstable taurine ester *(23)*. The electrophilic character of the nitro group clearly weakens the ester bond,



(22)

(23)

(24)

and thereby favors intramolecular alkylation. An internal salt *(24)* is finally obtained, which in an aqueous alkaline medium undergoes a Hofmann degradation resulting in *N,N*-dialkylnitroaniline and a metal vinylsulfonate.

[32] German Pat. 1122064 (Jan. 9th, 1960) BASF, inventors: *H. Distler, W. Müller*, and *H. Werner*.

[33] German Pat. 1114320 (April 28th, 1960) BASF, inventors: *E. Penning, H. Reinhard*, and *H. Distler*.

6. Polymerization

Alkyl and aryl vinylsulfonates polymerize very sluggishly. On the other hand, the copolymerization with other vinyl monomers proceeds easily [34], and a number of such copolymers have been described [35,36]. Aryl vinylsulfonates can moreover be incorporated into polyester resins [37].

III. Synthesis of Other Derivatives of Vinylsulfonic Acid

A. Vinylsulfonamides

1. Syntheses

The synthesis of vinylsulfonamide has frequently been attempted, but only *Matlack* [38] succeeded in giving the first unambiguous description of this compound: m.p. 24 °C; $n_D^{20} = 1.4880$ [39]; b.p.143 °C/2 mm. He prepared vinylsulfonamide by the thermal degradation of β-alkylaminosulfonamide or β-methoxyethanesulfonamide, using alumina, calcium oxide, or phosphoric acid as catalyst.

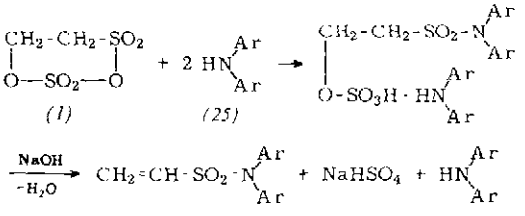
Vinylsulfonamide can also be prepared by the dehydration of ammonium vinylsulfonate between −40 and +40 °C with phosphorus pentoxide or magnesium perchlorate in the presence of small amounts of sulfur or phenols [40], as well as by the thermal cleavage of 2-aminoethanesulfonic anhydride (taurine anhydride) at 300 to 500 °C under reduced pressure [41]. The method suggested in another patent [42], whereby an aqueous solution (pH 6.5 to 7.5) of vinylsulfonyl chloride is treated with ammonium chloride at 15 to 30 °C in the presence of an alkaline buffer, does not seem to give vinylsulfonamide, as the product is not identical with the material described by *Matlack*.

A simple and elegant route to vinylsulfonamide [43] is provided by the reaction of vinylsulfonyl chloride or β-chloroethanesulfonyl chloride with ammonia in an inert solvent. Side reactions, such as the addition of ammonia to the vinylsulfonamide already formed, and the formation of tris-(2-sulfamoylethyl)amine, $N(CH_2-CH_2-SO_2-NH_2)_3$, are extensively suppressed under these conditions. If β-chloroethanesulfonyl chloride is used, 3 moles of ammonia are required for the reaction to take place.

$$ClH_2C-CH_2-SO_2Cl + 3\ NH_3 \rightarrow H_2C=CH-SO_2NH_2 + 2\ NH_4Cl \quad (t)$$
$$40\text{–}50\,\%$$

The use of vinylsulfonyl chloride instead of β-chloroethanesulfonyl chloride offers no advantage as far as the yield of vinylsulfonamide is concerned. The yield can however be considerably improved by using a primary or secondary aliphatic amine instead of ammonia [42,44]. With diethylamine for example, under otherwise identical conditions, *N,N*-diethylvinylsulfonamide (b.p. 80–84 °C/1 mm Hg; 78 °C/0.5 mm Hg [*]; m.p. −1.3 to −0.4 °C; $n_D^{25} = 1.4602$; $n_D^{20} = 1.4622$ [*]) can be prepared in a yield of about 70 % [45]. Addition reactions take place if an excess of the aliphatic dialkylamine is used [46].

Vinylsulfonamides derived from aromatic amines are prepared by an older method [47,58], *e.g.* by the reaction of aniline with ethane-1,2-disulfonyl chloride giving vinylsulfanilide (m.p. 68 °C), or by *Ebel*'s method [48] of treating primary or secondary *(25)* aromatic amines with carbyl sulfate *(1)* followed by treatment with alkali:



(u)

Carbyl sulfate *(1)* is prepared by treating 1 mole of ethylene with 2 moles of SO_3. Aromatic amines react with carbyl sulfate at room temperature without complications, but it is advisable to dilute the reaction mixture with an inert solvent. The sulfuric ester is cleaved by aqueous NaOH even at room temperature or slightly above. The yields obtained with this method are usually 80 % or more.

N-Arylvinylsulfonamides are soluble in strong alkalis, as are all compounds of this type, the dissolution being accompanied by the formation of salts. They are noted for their action as herbicides and are used in weed control [49].

Unfortunately, Reaction (u) is inapplicable to aliphatic amines, which form amides of ethionic acid with carbyl sulfate [50]. The potassium salts *(26)* of these products crystallize with particular ease. Vinylsulfonamides are said to be formed on the hydrolysis of the amide *(26)*, possibly as in Equation (v).

$$R_2N-SO_2-CH_2-CH_2-OSO_3K + KOH \xrightarrow[-K_2SO_4]{-H_2O} R_2N-SO_2-CH=CH_2 \quad (v)$$
(26)

[34] *W. Kern* and *R. C. Schulz* in Houben-Weyl: Methoden der organischen Chemie. 4th Edit., Thieme Verlag, Stuttgart 1961, Vol. 14/1, p. 1103.

[35] *C. S. Marvel* et al., J. Polymer Sci. *10*, 39 (1953); *C. G. Overberger, D. E. Baldwin*, and *H. P. Gregor*, J. Amer. chem. Soc. *72*, 4864 (1950).

[36] Japanese Published Patent Application 4195 (1958), inventors: *Kanneyoshi* et al.

[37] German Pat. 1118452 (May 13th, 1960) BASF, inventors: *H. Willersinn, G. Becht, H. Wurzler*, and *H. Distler*.

[38] *A. S. Matlack*, J. org. Chemistry *23*, 729 (1958).

[39] Present author's measurement.

[40] U.S. Pat. 2700055 (March 1st, 1953) Monsanto, inventor: *H. F. Park*.

[41] U.S. Pat. 2709707 (Oct. 26th, 1953) Monsanto, inventor: *H. F. Park*.

[42] U.S. Pat. 2710882 (July 20th, 1953) Monsanto, inventor: *H. F. Park*.

[43] German Published Patent Application 1168891 (March 15th, 1961) BASF, inventors: *D. Ludsteck* and *H. Distler*.

[44] Belg. Pat. 591410 (May 31st, 1960) Farbenfabriken Bayer, inventors: *G. Schrader* and *H. Schlör*.

[45] Unpublished work by the author.

[*] Present author's measurement.

[46] *K. A. Petrov* and *A. A. Neymyševa*, Zh. obshch. Khim. *29*, 1494 (1959).

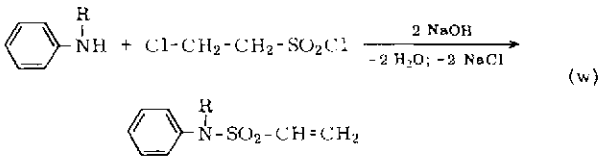
[47] *W. Autenrieth* and *P. Rudolph*, Ber. dtsch. chem. Ges. *34*, 3474 (1901); *P. W. Clutterbuck* and *J. B. Cohen*, J. chem. Soc. (London) *1922*, 121.

[48] German Pat. 832149 (March 16th, 1950) BASF, inventor: *F. Ebel*.

[49] German Published Patent Application 1107999 (April 11th, 1959) Schering AG., inventors: *M. Ehlers, G. Liedtke*, and *H. Hilgert*.

[50] German Published Patent Application 1175226 (July 19th, 1961) Farbwerke Hoechst, inventors: *R. Kühne, H. Diery*, and *M. Großmann*.

The vinylsulfonamides of primary or secondary aromatic amines may also be prepared very simply by Reaction (w).

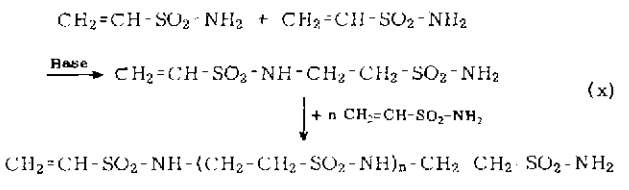


(w)

The amine is treated with β-chloroethanesulfonyl chloride in an aqueous alkaline medium (pH 9 to 10) at 0 to 5 °C. The addition of dichloroethane is advantageous, since it results in a better distribution and therefore in higher conversions. The yields are over 70 %, especially when secondary aromatic amines such as *N*-methylaniline or *N*-methyltoluidine are used. Surprisingly, the aromatic amine does not add onto the double bond of the vinylsulfonamide under these conditions, as do primary and secondary aliphatic amines. A similar but very complicated method also leads to *N*-arylvinylsulfonamides in the absence of water. Owing to the presence of by-products, however, the isolation is very difficult [51].

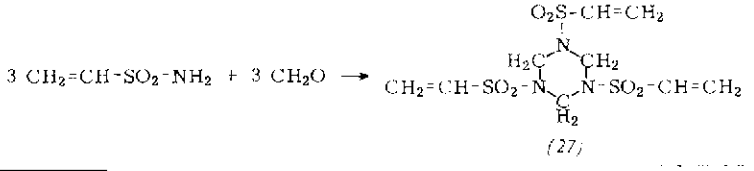
2. Chemical Properties

The reactions described for vinylsulfonates (cf. Section II) can be easily applied to vinylsulfonamides. The strong tendency of vinylsulfonamide to undergo polymerization at the C–C double bond is particularly interesting [52]. Both *N*-alkyl- and *N*-aryl-vinylsulfonamides are less susceptible to polymerization. However, they can copolymerize with other vinyl monomers [53, 54]. Furthermore, unsubstituted vinylsulfonamide tends to polymerize in the presence of basic catalysts and at elevated temperatures, presumably by head-to-tail addition:



(x)

With formaldehyde in the presence of catalytic amounts of conc. sulfuric acid, vinylsulfonamide undergoes cyclization to give a triazine derivative *(27)* [55]. This is used as a cross-linking agent in the paint industry [56].



(27)

B. Vinylsulfonyl Halides

1. Vinylsulfonyl Chloride

Sodium vinylsulfonate reacts with phosphorus pentachloride between 30 and 40 °C to give vinylsulfonyl chloride [57], which is a colorless, lachrimatory liquid (b.p. 42–44 °C/5 mm Hg; n_D^{20} = 1.4686; d_4^{20} = 1.393). A simpler method, giving a higher yield, is the dehydrochlorination of β-chloroethanesulfonyl chloride with lutidine at −50 °C [58].

Lutidine may be replaced by other tertiary amines, *e.g.* dimethylaniline or diethylaniline, the latter being particularly convenient because it forms an easily crystallizable hydrochloride. Side reactions will occur unless very low temperatures are used, and above +50 °C β-chloroethanesulfonyl chloride will decompose completely into 1,2-dichloroethane and SO_2.

Attempts have failed to dehydrochlorinate β-chloroethanesulfonyl chloride with catalysts such as active carbon, $Al_2O_3/ZnCl_2$, silica gel/$ZnCl_2$, or silica gel/$MgCl_2$. 1,2-Dichloroethane and SO_2 were formed instead at temperatures above 180 °C. This result is in good agreement with that of *Rieche*'s pyrolytic experiments [59] showing that alkanesulfonyl chlorides liberate SO_2 and form alkyl chlorides.

2. Vinylsulfonyl Fluoride

β-Chloroethanesulfonyl chloride can be converted with potassium fluoride into vinylsulfonyl fluoride [60]:

$$ClH_2C{-}CH_2{-}SO_2Cl + 3\ KF \rightarrow H_2C{=}CH{-}SO_2F + KHF_2 + 2\ KCl \qquad (y)$$

On dehydrochlorination with weak bases, such as $NaHCO_3$, MgO, or $CaCO_3$, β-chloroethanesulfonyl fluoride leads to vinylsulfonyl fluoride, a colorless liquid which strongly irritates the mucous membranes (b.p. 119 °C; n_D^{25} = 1.3797 [61]). It is very suitable as starting material for the preparation of vinylsulfonamides. The vinyl group generally behaves as described for vinylsulfonates.

The polymerization of vinylsulfonyl fluoride and its copolymerization with other vinyl monomers, *e.g.* vinyl acetate and styrene, were described by *Kern* and *Schulz* [62].

[51] *W. V. Farrar*, J. chem. Soc. (London) *1960*, 3058.

[52] *R. H. Wiley* and *D. E. Gensheimer*, J. Polymer Sci. *42*, 119 (1960).

[53] *W. Kern*, *R. C. Schulz*, and *H. Schlesmann*, Makromolekulare Chem. *39*, 1 (1960).

[54] German Pat. 758682 (Jan. 28th, 1940) Casella Farbwerke, inventors: *W. Zerweck* and *W. Kunze*; U.S. Pat. 2760955 (May 1st, 1953) Monsanto, inventors: *H. F. Park* and *R. M. Dickey*.

[55] German Published Patent Application 1178071 (Febr. 16th, 1961) BASF, inventors: *D. Ludsteck*, *W. Rahland*, and *G. Lützel*; French Pat. 1315384 (Febr. 16th, 1961) BASF, inventors: *D. Ludsteck*, *W. Rohland*, and *G. Lützel*.

[56] German Published Patent Application 1147191 (Febr. 23rd, 1961) BASF, inventors: *D. Ludsteck*, *W. Rohland*, and *G. Lützel*.

[57] *E. F. Landau*, J. Amer. chem. Soc. *69*, 1219 (1947).

[58] *C. S. Rondestvedt jr.*, J. Amer. chem. Soc. *76*, 1926 (1954).

[59] *A. Rieche* and *E. Naumann*, J. prakt. Chem. [4] *9*, 108 (1959).

[60] German Pats. 952803 (Sept. 21st, 1952), 1002323, 1007318 (Dec. 16th, 1952) Farbwerke Hoechst, inventors: *O. Scherer* and *F. Schächer*; Chem. Zbl. *1957*, 5426.

[61] *W. Kern*, *R. C. Schulz*, and *H. Schlesmann*, Makromolekulare Chem. *39*, 1 (1960).

[62] German Published Patent Application 1006157 (April 16th, 1953) Farbwerke Hoechst, inventors: *H. Scherer* and *K. H. Kahrs*; Chem. Zbl. *1958*, 12835; *W. Kern* and *R. C. Schulz* in *Houben-Weyl*: Methoden der organischen Chemie. 4th Edit. Thieme Verlag, Stuttgart 1961, Vol. 14/1, p. 1105.

3. Reduction of Sulfonyl Halides – a New Olefin Synthesis

According to *Otto* [63], and *Pauly* and *Bazlen* [64], sulfonyl chlorides can be reduced to sulfinic acids with zinc and HCl. Simpler and more elegant is *Bredereck*'s method [65], which uses sodium hydrogen sulfite and leads directly to the sodium sulfinates. The application of this method to β-chloroethanesulfonyl chloride and to vinylsulfonyl chloride slightly above room temperature results in a vigorous reaction yielding ethylene instead of β-chloroethanesulfinic acid and vinylsulfinic acid, respectively [66].

This smooth formation of olefins is not restricted to β-chloroethanesulfonyl chloride and vinylsulfonyl chloride but proceeds with all β-halogenoalkylsulfonyl chlorides. When 2-chloropropane-1-sulfonyl chloride is used, propylene is eliminated quantitatively even at 10 to 20 °C. Temperatures of 50 to 60 °C are required in other cases. The reduction can also be carried out with sodium dithionite or with zinc dust and HCl, in which case the pH is adjusted to 5–6. The unstable intermediate, *e.g.* vinylsulfinic acid *(28)*, loses SO_2 to give ethylene.

$$\begin{matrix} Cl\text{-}CH_2\text{-}CH_2\text{-}SO_2Cl \xrightarrow{pH\ 5\text{-}6} \\ CH_2{=}CH\text{-}SO_2Cl \xrightarrow{H_2} \end{matrix} [CH_2{=}CH\text{-}SO_2H] \longrightarrow \underset{+\ SO_2}{CH_2{=}CH_2}$$

(28)

The rate of formation of the olefin increases with increasing alkalinity of the reaction medium and with the temperature. If a temperature of about 10 °C is used, the sulfinic acid, *e.g.* chloroethanesulfinic acid, can be extracted with ether after acidification with H_2SO_4. We obtained free chloroethanesulfinic acid containing about 20 % water in the form of a yellowish oily liquid which decomposed slowly at 0 °C. Attempts to increase the stability by salt formation with bases had an adverse effect: ethylene was formed as soon as NaOH was introduced. It appears that free β-chloroethanesulfinic acid and vinylsulfinic acid can exist only for a short time. Nevertheless, they undergo all reactions characteristic for sulfinic acids, *e.g.* precipitation with iron(III) chloride, addition to acrylamide, acrylic esters, vinylsulfonamide, vinylsulfonates, and other α,β-unsaturated systems.

C. New Synthesis of Vinyl Sulfones [67]

The reactions between β-halogenoalkanesulfonyl chlorides and sodium hydrogen sulfite, dithionite, or zinc dust at low temperatures result in the formation of unstable β-chloroalkanesulfinic acids, which can be stabilized by adding them onto the following conjugated systems: acrylic acid, acrylamide, acrylic esters, acrylonitrile, methacrylic acid, crotonic acid, maleic acid, acrolein, methacrolein, methyl vinyl ketone, vinylsulfonic acid and its derivatives, vinyl sulfones, *etc.* The reaction is assumed to take the following course:

$$\begin{matrix} ClCH_2\text{-}CH_2\text{-}SO_2Cl \xrightarrow[0\text{-}10^{\circ}C]{H_2} [ClCH_2\text{-}CH_2\text{-}SO_2H] \\ \xrightarrow{+\ CH_2{=}CHY} ClCH_2\text{-}CH_2\text{-}SO_2\text{-}CH_2\text{-}CH_2\ Y \\ \text{(29)} \\ \xrightarrow{-\ HCl} CH_2{=}CH\text{-}SO_2\text{-}CH_2\text{-}CH_2\text{-}Y \\ \text{(30)} \end{matrix} \qquad (\gamma)$$

Y = COOH, CHO, COR, $SO_3H(R)$, SO_2R, $CH{=}CH_2$

Since the β-chloroalkanesulfinic acids are very unstable at room temperature, the addition must be carried out at 0 to 10 °C. Furthermore, the reaction is advantageously carried out in a strongly acid medium since the sulfinic acids must be present in the free form and not as salts. The β-chloroalkylsulfones *(29)*, produced in a very pure form, can generally be converted to vinyl sulfones *(30)* under very mild conditions, using the alkali metal or alkaline earth carbonates or hydroxides as dehydrochlorinating agents.

Vinyl sulfones *(30)* are sometimes very sensitive to aqueous alkalis since the latter catalyse the hydration of the vinylsulfonyl group. It is therefore advisable not to exceed the stoichiometric amount of the base. The pH must not be over 6.5 in the dehydrochlorination of the particularly sensitive 3-(β-chloroethanesulfonyl)propionamide. Boiling with water, possibly in the presence of catalytic amounts of a base, promotes the hydration of the vinylsulfonyl group.

D. Preparation of Vinylsulfonic Acid and Its Salts

Several methods have been suggested for the preparation of vinylsulfonic acid and its salts, but only a few are really applicable. Irrespective of this fact, all practicable methods will be discussed in this Section.

1. Metal Vinylsulfonates

a) The removal of hydrogen chloride from sodium β-chloroethanesulfonate with aqueous alkali [68] has long been carried out on a technical scale. This method has recently become of interest after it was found possible to add sodium hydrogen sulfite onto vinyl chloride [69] in the presence of ultraviolet light or radical-formers

$$ClCH_2\text{-}CH_2\text{-}SO_3Na \xrightarrow[-\ NaCl]{NaOH} CH_2{=}CH\text{-}SO_3Na \qquad (\alpha)$$

such as azodiisobutyronitrile, thus making sodium β-chloroethanesulfonate accessible *via* a simple route. It is equally advantageous to prepare this compound from an NaCl melt with carbyl sulfate [70].

[63] *Otto* and *Schiller*, Ber. dtsch. chem. Ges. *9*, 1584 (1876); *Otto* and *Lüders*, ibid. *13*, 1283 (1880).

[64] *C. Pauly*, Ber. dtsch. chem. Ges. *10*, 941 (1877); *M. Bazlen*, ibid. *60*, 1470, 1479 (1927).

[65] *H. Bredereck*, Chem. Ber. *87*, 136 (1954).

[66] Belg. Pat. 595105 (Sept. 15th, 1960) BASF, inventors: *H. Distler* and *H. A. Brauns*.

[67] Belg. Pat. 635013 (July 17th, 1963) and French Pat. 1363046 (July 16th, 1963) BASF, inventors: *H. Distler* and *H. A. Brauns*.

[68] German Pat. 836491 (May 20th, 1941) Farbwerke Hoechst, inventor: *W. Schmidt*; Chem. Zbl. *1952*, 5975; German Pat. 678730 (Febr. 23rd, 1936) IG.-Farbenindustrie, inventors: *O. Nicodemus* and *W. Schmidt*; *W. Kern*, *V. V. Kale*, and *B. Scherhag*, Makromolekulare Chem. *32*, 37, 43 (1959).

[69] Belg. Pat. 593513 (July 28th, 1960) Colgate Palmolive Co.

[70] German Pat. 1059443 (Dec. 20th, 1957) DuPont, inventors: *W. E. Catlin* and *A. M. Jenkins*.

Sodium β-bromoethanesulfonate loses hydrogen bromide with even greater ease [71], forming vinylsulfonate in very good yields [72]. Sodium vinylsulfonate can be separated from NaBr or NaCl by recrystallization from 96 % ethanol.

b) The hydrolysis of ethane-1,2-disulfonyl chloride in an aqueous ammoniacal solution leads to ammonium vinylsulfonate [5, 73]:

$$ClSO_2\text{-}CH_2\text{-}CH_2\text{-}SO_2Cl \xrightarrow[NH_3]{H_2O} CH_2{=}CH\text{-}SO_3^{\ominus}\overset{\oplus}{N}H_4 \qquad (\beta)$$

c) An elegant route to vinylsulfonate is *via* the hydrolysis of the easily available carbyl sulfate *(I)* [74], which first undergoes ring-cleavage with aqueous alkali to give the salt of ethionic acid *(Ia)*, followed by cleavage of the ester bond leading to vinylsulfonate.

$$\begin{matrix} CH_2\text{-}CH_2\text{-}SO_2 \\ | \quad\quad | \\ O\text{—}SO_2\text{—}O \end{matrix} \xrightarrow[-2\,H_2O,\,Na_2SO_4]{3\,NaOH} CH_2{=}CH\text{-}SO_3Na$$

(I)

The formation of a small amount of the sodium salt of isethionic acid (β-hydroxyethanesulfonic acid) is a disadvantage in the alkaline hydrolysis. Sodium sulfate, an interfering substance in several cases, *e.g.* in the polymerization, can be removed almost entirely at 0 °C as the decahydrate.

Similarly to carbyl sulfate, ethionic acid [75] can be hydrolysed to give vinylsulfonate [76]:

$$\underset{(Ia)}{HO_3S\text{-}O\text{-}CH_2\text{-}CH_2\text{-}SO_3H} \xrightarrow[-Na_2SO_4]{3\,NaOH} CH_2{=}CH\text{-}SO_3Na \qquad (\gamma)$$

d) β-Chloroethanesulfonyl chloride, easily obtainable by the chlorosulfonation of chloroethane [2], can be hydrolysed to form a very pure vinylsulfonate containing only NaCl [77]:

$$ClCH_2\text{-}CH_2\text{-}SO_2Cl \xrightarrow[-2\,H_2O]{3\,NaOH} CH_2{=}CH\text{-}SO_3Na + 2\,NaCl \qquad (\delta)$$

Sodium hydroxide can be replaced by hydroxides or carbonates of the alkali or the alkaline earth metals. The use of tertiary amines or ammonia leads to ammonium salts on hydrolysis. Oxides of heavy metals such as Cu, Hg, Zn, Sn, or Pb react with β-chloroethanesulfonyl chloride in an aqueous suspension, and form very soluble, colorless metal vinylsulfonates.

The common feature of all these methods is that the vinylsulfonate is coprecipitated with a neutral salt such as sodium sulfate. After removal of the inorganic salt, the vinylsulfonate can be directly polymerized. To avoid spontaneous polymerization (which is particularly probable at about pH 7), stabilizers known in the chemistry of acrylates are used. These are hydroquinone, sodium nitrite, or nitroso compounds. Vinylsulfonate solutions above pH 9, on the other hand, are usually stable.

2. Free Vinylsulfonic Acid

a) In order to prepare free vinylsulfonic acid, a concentrated aqueous solution of the metal vinylsulfonate is saturated with HCl at about 0 °C [78]. An aqueous solution of vinylsulfonic acid is obtained from a dilute solution of vinylsulfonate with the aid of strongly acidic ion exchangers. The hydrolysis of ethane-1,2-disulfonyl chloride [5, 6, 79] also leads to vinylsulfonic acid.

b) A very simple preparation of vinylsulfonic acid, and one that is also practicable on the technical scale, utilizes the fact that methyl vinylsulfonate can be easily saponified. The latter is obtained in practically quantitative yield from β-chloroethanesulfonyl chloride and sodium methoxide in a methanolic solution [3], and is hydrolysed by a countercurrent of steam in a column packed with Raschig rings [4]. The methanol simultaneously distills off:

$$CH_2{=}CH\text{-}SO_2\text{-}OCH_3 \xrightarrow[100°C]{H_2O} CH_2{=}CH\text{-}SO_3H + CH_3OH \qquad (\varepsilon)$$

The resulting 40 to 45 % aqueous solution of vinylsulfonic acid is free from foreign salts, and can be concentrated to 55 % in a thin-layer evaporator made of Hastelloy®. Vinylsulfonic acid can be isolated in small quantities from its aqueous solution by distillation under a high vacuum. The product is a colorless, oily liquid, soluble in water and most organic solvents.

Potassium permanganate is reduced instantaneously to the Mn(II) state by vinylsulfonic acid, which resembles conc. H_2SO_4 in its dehydrating action: a pine shaving dipped into vinylsulfonic acid turns dark immediately. Vinylsulfonic acid remains unchanged for a fairly long time when stored in a closed container at about 0 °C. The polymerization of vinylsulfonic acid and its salts is the subject of numerous patents and publications [80].

IV. Experimental

A. Detection of Vinylsulfonates

1. Determination of Aryl Vinylsulfonates (Thiol Addition)

Aryl vinylsulfonates (also vinylsulfonamides and vinyl sulfones) can be determined by a method used for acrylic compounds, *i.e.* by the addition of thiols to the vinyl group:

$$RSH + CH_2{=}CH\text{-}SO_2\text{-}OC_6H_5 \xrightarrow{Base} RS\,CH_2\text{-}CH_2\text{-}SO_2\text{-}OC_6H_5$$

[71] *C. S. Marvel* and *M. S. Sparberg*, Org. Syntheses, Coll. Vol. II, 558 (1943).

[72] *A. Ulinska* and *D. Stazevska*, Roczniki Chem. *35*, 1495 (1961).

[73] *S. M. McElvain, A. Jelinek*, and *K. Rorig*, J. Amer. chem. Soc. *67*, 1578 (1945).

[74] *D. S. Breslow* and *R. R. Hough*, J. Amer. chem. Soc. *79*, 5000 (1957).

[75] For the preparation of ethionic acid, see *Houben-Weyl*: Methoden der organischen Chemie. 4th Edit., Thieme Verlag, Stuttgart 1955, Vol. 9, p. 353.

[76] German Pat. 677843 (March 1st, 1936) Kalle, inventors: *W. Neugebauer* and *H. Mengel*; Chem. Zbl. *1939* II, 2162; *D. S. Breslow, R. R. Hough*, and *I. T. Fairclough*, J. Amer. chem. Soc. *76*, 5361 (1954).

[77] German Pat. 1090656 (Jan. 7th, 1959) BASF, inventors: *H. Distler* and *K. Küspert*; German Pat. 1110628 (April 23rd, 1960) BASF, inventors: *K. Küspert and H. Distler*.

[78] *D. S. Breslow* and *G. E. Hulse*, J. Amer. chem. Soc. *76*, 6399 (1954).

[79] *S. M. McElvain, A. Jelinek*, and *K. Rorig*, J. Amer. chem. Soc. *67*, 1578, 1580 (1945).

[80] *W. Kern* and *R. C. Schulz* in *Houben-Weyl*: Methoden der organischen Chemie. 4th Edit., Thieme Verlag, Stuttgart 1961, Vol. 14/1, p. 1099.

About 0.3 to 0.7 g of a sample (quantity E) are dissolved in 100 ml of 95% alcohol (or alcohol/toluene, acetone, or methanol). A 5% alcoholic solution of n-dodecanethiol (20 ml) and 1 ml of a 5% solution of KOH in ethanol are then added at 20 to 25 °C. The mixture is allowed to stand for 2 to 3 minutes, is shaken a few times, and acidified with glacial acetic acid. The sample is then titrated against 0.1 *N* iodine to a yellow end-point (the yellow color should persist for at least 2 minutes). Titer: a ml of 0.1 *N* iodine solution. The blank test is carried out under the same conditions. Titer: b ml of 0.1 *N* iodine solution.

$$\text{Iodine value} = \frac{(b-a) \times 2.538}{E}$$

The method fails with vinylsulfonic acid and its salts.

2. Determination of Alkyl Vinylsulfonates

The method of thiol addition cannot be applied to metal and alkyl vinylsulfonates, since these convert the thiols into thioethers. Hydrogenation on Pd is therefore recommended. The analytical results obtained in this way are fairly satisfactory. Owing to the fact that substitution takes place, conventional methods of determining iodine values lead to erroneous results.

3. Physiological Effects

All alkyl vinylsulfonates are very toxic, methyl vinylsulfonate being particularly so; being a powerful alkylating agent, its toxicity resembles that of dimethyl sulfate. It also has a strong lachrimatory action, and causes inflammation of the skin leaving behind deep, slow-healing ulcers. Esters with fluorinated alcohols (with 3 to 6 carbon atoms) are chemical warfare agents. Aryl vinylsulfonates are less toxic, but can sometimes irritate the skin. Their strong fungicidal action, comparable to that of the organomercury derivatives, is particularly striking. Aryl vinylsulfonates are used as microcides and in combating the South American leaf-cutting ant [81].

B. Syntheses

1. Methyl Vinylsulfonate

β-Chloroethanesulfonyl chloride (326 g, 2 moles) is placed in a container fitted with a stirrer, and cooled to 0 °C. An approximately 30% methanolic solution of 710 g of sodium methoxide is then added dropwise over a period of 2 hours, the mixture being maintained at about 0 °C. The addition is stopped when the pH reaches a value of 5. (The solution must not under any circumstances be allowed to become alkaline.) After warming for 1 hour to about 30 °C, NaCl is filtered off and the solvent is distilled off *in vacuo*. The gel-like residue is washed with about 100 ml of ice-cold water. After drying, the methyl vinylsulfonate is distilled under vacuum (< 1 mm), giving 210 g of a colorless liquid, b.p. 54–60 °C/0.2–0.4 mm; $n_D^{20} = 1.4310$; 86% yield.

Warning: Care should be taken in all work with methyl vinylsulfonate. Contact with skin must be avoided, and the operator should wear rubber gloves, and work in a fume-cupboard!

2. Pentachlorophenyl Vinylsulfonate

Pentachlorophenol (800 g, 3 moles) and 1500 ml of cyclohexanone are suspended in 500 ml of water. β-Chloroethanesulfonyl chloride (570 g, 3.5 moles) and about 1150 g of 25% NaOH are then added, simultaneously and dropwise, over a period of about 1.5 hours, the mixture (pH 7 to 8) being stirred and cooled to 0–5 °C. Stirring is continued for another 30 minutes, and the reaction mixture is then adjusted to pH 4–5 with about 5 g of conc. HCl. Cyclohexanone is distilled off by steam, the ester is separated from the warm solution and added immediately to 750 ml of alcohol with constant stirring. Pentachlorophenyl vinylsulfonate crystallizes out on cooling to 15 °C. The crystals are filtered with suction and washed with a little alcohol. After drying, 1000 g of the ester are obtained in the form of colorless crystals, m.p. 82 to 86 °C (yield 93%, calculated on pentachlorophenol). After recrystallization from alcohol the substance melts at 93 °C.

3. 2-Chlorophenyl Vinylsulfonate

2-Chlorophenol (257 g, 2 moles), 500 ml of 1,2-dichloroethane, and 1000 ml of water are placed in a vessel fitted with a stirrer. Crude (ca. 85%) carbyl sulfate (704 g, 3.2 moles) is then added in several portions, with vigorous stirring, over a period of about 2 hours at 0 to 5 °C, the mixture being adjusted to pH 10–10.5 by the simultaneous dropwise introduction of 1370 g of 25% NaOH. Stirring is continued for another ½ hour and the reaction mixture is then made weakly acidic by the addition of 5 g of conc. HCl and separated in a separating funnel. This last operation is facilitated by warming to 30–35 °C. The organic phase is steam-distilled, removing the solvent and unaltered 2-chlorophenol. Separation of the product from water in the warm yields 430 g (96.5% calculated on 2-chlorophenol) of ca. 98% pure 2-chlorophenyl vinylsulfonate. The ester is distilled under vacuum; b.p. 110–115 °C/0.2 mm; $n_D^{20} = 1.5212$.

4. Phenyl Vinylsulfonate

Phenol (188 g, 2 moles), 400 ml of water, and 400 ml of 1,2-dichloroethane are placed in a 4 l three-necked flask. β-Chloroethanesulfonyl chloride (375 g, 2.3 moles) and about 700 g of 25% NaOH are then added, simultaneously and dropwise, from two inlet tubes, over a period of 2 to 3 hours, the mixture (pH 8.5–9.5) being stirred and cooled to 0–5 °C. Stirring is continued for another hour, and the reaction mixture is then made weakly acidic with conc. HCl. The organic mixture is then separated (separation being facilitated by warming to 30–40 °C), dried over sodium sulfate, filtered, and distilled under vacuum. Phenyl vinylsulfonate distills over at 90 to 91 °C/0.1 mm. It is a colorless, oily liquid solidifying at 40 to 42 °C; $n_D^{40} = 1.5171$; yield: 313 g (85% calculated on phenol).

5. Cresyl β-Allyloxyethanesulfonate

A suspension of 2.5 g of dry finely powdered NaOH in 500 g of allyl alcohol is treated with 198 g of cresyl vinylsulfonate over a period of 3 hours. The reaction mixture is maintained at 40 °C for 4 hours and then at 50 °C for 1 hour. The solution is filtered and the filtrate distilled under vacuum, giving 214 g (84%) of cresyl β-allyloxyethanesulfonate, b.p. 135 to 142 °C/0.1 mm.

6. β,β′-Sulfonyl-bis-(2-chlorophenyl ethanesulfonate)

Sodium hydroxymethanesulfinate dihydrate (85 g) is added to 218.5 g of 2-chlorophenyl vinylsulfonate and 500 ml of water. The reaction mixture is heated to 80–85 °C, with constant stirring. The pH of the solution is adjusted to 4.5 to 6.5 by the slow addition of 25 g of 50% H_2SO_4. The reaction reaches completion in about 1 hour, after which the product is filtered off with suction and dried. Sulfonylbis-(2-chlorophenyl ethanesulfonate) is thus obtained as white crystals, m.p. 150 °C (from alcohol). The yield is 210 g (83.5 %).

[81] German Published Patent Application 1173720 (March 24th 1961) BASF, inventors: *H. Distler* and *E. Pommer*.

7. Monophenyl Ethane-1,2-disulfonate

Phenyl vinylsulfonate (92 g), 100 ml of ethanol, 250 ml of water, and 150 g of a 40% solution of sodium hydrogen sulfite are placed in a flask fitted with a stirrer. The reaction is allowed to proceed at about 50 to 60 °C until a clear solution is obtained. The mixture is then cooled to about 5 °C, reduced to $^2/_3$ of the original volume under vacuum, and the product is filtered off with suction. A yield of 135 g (about 93%) of sodium phenyl ethane-1,2-disulfonate is thus obtained.

8. Phenyl β-(1-Nitrocyclohexyl)ethanesulfonate

N,N-Dimethylcyclohexylamine (26 g) is added dropwise over a period of about 2 hours to 200 g of nitrocyclohexane and 184 g of phenyl vinylsulfonate at 70 to 90 °C. The reaction mixture is kept slightly alkaline at all times. After stirring for a further 2–3 hours, the excess nitrocyclohexane is removed with steam. The organic phase of the residue is separated and diluted with 200 ml of ethanol, yielding 244 g (78%) of phenyl β-(1-nitrocyclohexyl)ethanesulfonate, m.p. 72–73 °C.

9. *N,N*-Bis-(1-phenoxysulfonyl-2-ethyl)-*p*-toluenesulfonamide

Phenyl vinylsulfonate (92 g, 0.5 mole) and 43 g (0.25 mole) of *p*-toluenesulfonamide are heated to 110 °C for 3–4 hours with constant stirring, in the presence of 2 g of powdered NaOH, and the mixture is then boiled with water. The water-insoluble residue is recrystallized from about 300 ml of alcohol giving 108 g of *N,N*-bis-(1-phenoxysulfonyl-2-ethyl)-*p*-toluenesulfonamide in the form of white crystals, m.p. 117 °C.

10. 2,4,6-Trichloro-3-nitrophenyl Vinylsulfonate

2,4,6-Trichlorophenyl vinylsulfonate (720 g) is dissolved in 3000 g of conc. sulfuric acid in a flask fitted with a stirrer, the reactants being cooled to about 10 °C. At this temperature, 171 g of 98% HNO_3 are added, dropwise, over a period of 1 hour. After stirring for a further hour at the same temperature, the reaction mixture is poured into about 10 l of ice-cold water, precipitating the 2,4,6-trichloro-3-nitrophenyl vinylsulfonate as yellow crystals. After filtration and drying, 786 g of the product are obtained (94.3% yield). After recrystallization from alcohol, the m.p. is 108–109 °C.

11. 3-(β-Chloroethanesulfonyl)propionamide

β-Chloroethanesulfonyl chloride (489 g, 3 moles) is added dropwise, over a period of 1.5 hours, to a solution of 312 g (3 moles) of $NaHSO_3$ in 1500 ml of water, with stirring and cooling to 5–10 °C. The pH is adjusted to 5–5.5 by the simultaneous addition of 1326 g of about 25% NaOH. After stirring for a further 15 minutes, 300 g of a 49% solution of H_2SO_4 (1.5 moles) are added dropwise, at the same temperature. The mixture is then stirred for another hour and cooled to 0–5 °C. Sodium sulfate decahydrate is filtered off with suction and washed with about 1000 ml of ice-cold water. The filtrate is treated with 1200 g of a 15% aqueous solution of acrylamide (3 moles) at 5 to 10 °C, with constant stirring. Crystals begin to separate in about 20 minutes. The stirring is continued for about another hour and the solution is allowed to stand for 2 to 3 days at 5 to 10 °C to complete the crystallization. The crystalline product is filtered with suction, washed free from acid with ice-cold water, and dried in an air cupboard, yielding 391 g (65.6%) of β-chlorocthanesulfonylpropionamide as a white powder, m.p. 138–140 °C.

12. 3-Vinylsulfonylpropionamide

To a suspension of 200 g (1 mole) of 3-(β-chloroethanesulfonyl)-propionamide in 600 ml of water, stirred and maintained at 20 to 25 °C, 156 g of a 25% solution of NaOH is added dropwise over a period of 2 hours, with constant stirring, in such a manner that the pH does not exceed 7. A clear, colorless solution is obtained. Pure vinylsulfonylpropionamide is isolated by extraction with four portions (200 ml each) of ethyl acetate. The product is a white crystalline solid, m.p. 74 °C (from alcohol/benzene).

13. Preparation of Ethylene

Water (500 ml) and 260 g of an approximately 40% aqueous solution of $NaHSO_3$ are mixed in a flask fitted with a stirrer, the solution is adjusted to pH 5–6 and maintained at 50 to 60 °C. β-Chloroethanesulfonyl chloride (163 g, 1 mole) and 630 g of a 25% aqueous solution of NaOH are then added, dropwise and simultaneously, from two inlet tubes. This procedure yielded 21.8 l (N.T.P.) of ethylene in a vigorous reaction.

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New Cotton Dyes

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Published on the occasion of the 100th anniversary of the establishment of Badische Anilin- & Soda-Fabrik AG., on April 6th, 1965.

The present paper deals with new cotton dyes, approaching the subject from two directions. In the first section the synthesis of a new type of reactive dye from products of Reppe acetylene chemistry is reported. The second part describes a dyeing process which does not start with reactive dyes. Instead, the homopolar bonding between dye and cotton is formed by linking the dye to the substrate via polyfunctional bridges. These two programs have led to the development of the ®Primazin P and ®Basazol dyes.

In his review of the century which had passed since the discovery of the first synthetic dye, *Zollinger* [1] referred to the reactive dyes as "the most important technical discovery of the last two decades in the field of dye chemistry". After decades of dyeing cotton with vat dyes and direct dyes, reactive dyes now presented the possibility of using brilliant dyes with relatively simple structures. Stimulated by this new development, fashion turned to brighter hues. The problems solved by the dye manufacturers in this connection are reflected in the many types of reactive dyes which have since been produced.

I. Reactive Dyes Containing Dichloropyridazone Residues [*]

The reactive dyes which have become commercially available can be grouped into a few types. They contain either activated vinyl [*(a)* and *(b)*] or alkyl hydrogen sulfate groups *(c)*, or they are imide chlorides containing the characteristic grouping *(d)*, with a halogen atom attached to the imide carbon atom. This last structural unit in particular has been frequently varied as part of heterocyclic rings. The first reactive dyes were members of the triazine series. These were followed by dyes based on chlorinated pyrimidines, quinoxalines [2], and phthalazines. The ®Remazol dyes [3] are vinyl sulfones *(a)* or compounds which are converted to vinyl sulfones when

$-SO_2-CH=CH_2$ *(a)* $-NH-CO-CH=CH_2$ *(b)*

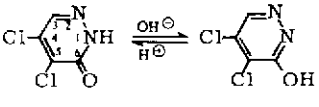
$-SO_2-NH-CH_2-CH_2-O-SO_3H$ *(c)* $-N=\underset{|}{C}-Cl$ *(d)*

fixed to the fiber by treatment with alkali. The dyes containing acrylamide groups *(b)* have similar structures.

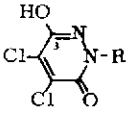
The reactive dyes described below are 1-substituted 4,5-dichloro-6-pyridazones. The negative leaving group (on reaction with the fiber) is again a halogen atom, and the reactive group forms part of a heterocycle; however, these compounds are not imide chlorides.

1. The 4,5-Dichloro-6-pyridazone System

The reactivity of halogen atoms on the pyridazone ring depends on several factors. 4,5-Dichloro-6-pyridazone, which is prepared from hydrazine and mucochloric acid (α,β-dichloro-β-formylacrylic acid) can be heated in strong sodium hydroxide solution and recovered unchanged on acidification. Provided that the nitrogen



(1a) *(1b)*



(2)

atom 1 is unsubstituted, the equilibrium between the "lactam form" *(1a)* and the "lactim form" *(1b)* in NaOH solution lies in favor of the aromatic "lactim form". In the 4,5-dichloro-3-hydroxypyridazones *(2)*, which are prepared from dichloromaleic acid and hydrazine derivatives, the two halogen atoms again lack the reactivity required of reactive dye components.

Only the 1-substituted 4,5-dichloro-6-pyridazones *(3a)* show sufficient activation of the 4-chlorine atom. The fact that it is the 4-halogen atom which is particularly readily replaced by nucleophilic reagents was first recognized by *Sonn* [4] who studied 4,5-dibromo-1-

[1] *H. Zollinger*, Angew. Chem. *73*, 125 (1961).

[*] By *H. R. Hensel*.

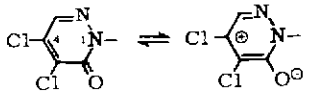
[2] *K. G. Kleb, E. Siegel*, and *K. Sasse*, Angew. Chem. *76*, 423 (1964); Angew. Chem. internat. Edit. *3*, 408 (1964).

[3] *J. Heyna*, Angew. Chem. *74*, 966 (1962); Angew. Chem. internat. Edit. *2*, 20 (1964).

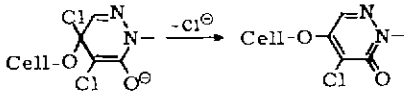
[4] *A. Sonn*, Liebigs Ann. Chem. *518*, 290 (1935).

phenyl-6-pyridazone [5]. Swiss workers [6] later investigated the substitution with primary amines, and *Dury* [7], in a comprehensive study of the chemistry of pyridazones, synthesized a large number of 4,5-disubstituted derivatives.

Owing to the presence of the 1-substituent in *(3a)*, enolization of the carbonyl group is no longer possible. However, its polarization *(3b)* leads to an electron deficiency at C–4, which is required for a nucleophilic reaction. Attack by the cellulose anion Cell–$O^{\ominus}$ results



(3a) *(3b)*



(4a) *(4b)*

in the formation of the intermediate *(4a)* with a tetrahedral C–4. This loses the chlorine atom with reformation of the carbonyl group *(4b)*. Thus the oxygen atom serves as an electron acceptor. If the system is regarded as a vinylogous acyl chloride, it becomes clear why only the β-chlorine atom (*i.e.* that on C–4) is activated.

2. Synthesis of Dyestuff Intermediates

Druey [8] has attempted to use 3,4,5-trichloropyridazine, which can be obtained from the "lactim" *(1b)*, in the same way as substituted s-triazines. However, stepwise substitution of the chlorine atoms does not proceed as smoothly here as in the case of the technically important cyanuric chloride. The hopes which had initially been aroused by these products were thus partly disappointed.

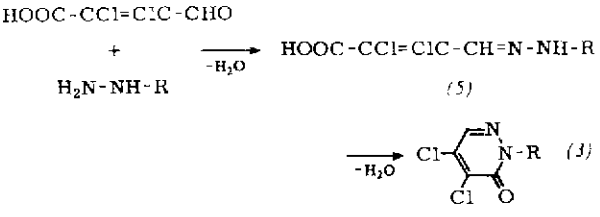
Instead of selectively removing one of the chlorine atoms from 3,4,5-trichloropyridazines, we synthesized 4,5-dichloro-6-pyridazones from mucochloric acid and hydrazine derivatives. The pyridazone ring can often be closed simply by heating the components in aqueous solution [9].

Mucochloric acid itself is technically readily available by a new process developed by *Dury* and *Reicheneder*, involving oxidative chlorination of 2-butyne-1,4-diol, which can be obtained from acetylene [10, 11]. Thus our first aim was to prepare unsymmetrically substituted hydrazine derivatives and to investigate their ring closure to form the corresponding pyridazones.

a) The Hydrazone-Pyridazone Ring Closure

Whereas aliphatic hydrazine derivatives can generally be smoothly cyclized with mucohalic acids, the tendency of aromatic hydrazine derivatives to close the ring strongly depends on the substituents on the aryl group (cf. Table 1). Phenylhydrazine combines with mucochloric acid in aqueous solution at 50–60 °C to form 4,5-dichloro-1-phenyl-6-pyridazone, passing rapidly through the hydrazone stage, which can be recognized by its deep yellow color. *p*-Nitrophenylhydrazine and 2,4-dinitrophenylhydrazine, on the other hand, initially form only the open-chain hydrazones *(5)*, even if the reaction is carried out in glacial acetic acid containing acetic anhydride [12]. In order to complete the ring closure, it is necessary to heat at 50–60 °C in concentrated sulfuric acid. 4,5-Dichloro-1-(*p*-nitrophenyl)-6-pyridazone, which is colorless in the pure form, can also be obtained by nitration of 4,5-dichloro-1-phenyl-6-pyridazone.

Table 1. Reaction of arylhydrazines with mucochloric acid.



(5) *(3)*

R	Method [*]	Product	Yield [%]	M.p. [°C]
C_6H_5	A, B, C	*(3)*	92	164
4-CH_3–C_6H_4	A, B, C	*(3)*	90	146–147
4-CO_2H–C_6H_4	A, B, C	*(5)* *(3)*	85 75	304 304
4-SO_3H–C_6H_4	A, C	*(3)*	88	>340
2,6-$(CH_3)_2C_6H_3$	B, C	*(3)*	75	131
2-SO_3H-5-NH_2–C_6H_3	C	*(3)*	80	>340
4-NO_2–C_6H_4	A, B C, D	*(5)* *(3)*	90 95	210 231–232
2-CH_3O-4-NO_2–C_6H_3	A, B	*(5)*	85	187
2-NO_2-4-CH_3–C_6H_3	A, B	*(5)*	90	195 (decomp.)
2-NH_2-4-CH_3–C_6H_3	E	*(3)*	85	166
2,4-$(NO_2)_2$–C_6H_3	B	*(5)*	95	206
3-NO_2–C_6H_4	A B, C	*(5)* *(3)*	92 85	206 216
4-NH_2–C_6H_4	E	*(3)*	78	153
3-NH_2–C_6H_4	E	*(3)*	82	145

[*] A: in 10 % hydrochloric acid, 30 min, 90 °C.
B: in glacial acetic acid/acetic anhydride (5:1), 2 h, 90–100 °C.
C: in H_2SO_4 (96 %), 2 h, 80 °C.
D: by nitration in H_2SO_4 with HNO_3 (65 %), 20–40 °C.
E: from the corresponding nitro compound by Béchamp reduction.

[5] *A. Bistrzycki* and *H. Simonis*, Ber. dtsch. chem. Ges. *32*, 535 (1899).

[6] *K. Meier, B. H. Ringier*, and *J. Druey*, Helv. chim. Acta *37*, 523 (1954).

[7] *K. Dury*, Angew. Chem. *77*, 282 (1965); Angew. Chem. internat. Edit. *4*, 292 (1965).

[8] *J. Druey*, Angew. Chem. *70*, 5 (1958).

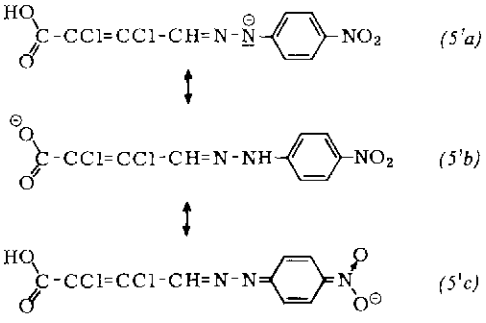
[9] *H. R. Hensel* and *H. Baumann*, U.S. Pat. 3045014 (June 20th, 1960), BASF; Chem. Zbl. *1964*, 32–2063.

[10] *F. Reicheneder* and *K. Dury*, German Pat. 1119850 (April 24th, 1959), BASF; Chem. Zbl. *1962*, 15765; German Pat. 1125421 (May 28th, 1960), BASF; Chem. Zbl. *1963*, 10643.

[11] *K. Dury*, Angew. Chem. *72*, 864 (1960).

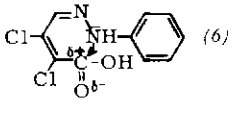
[12] According to our results, the 2,4-dinitrophenyl derivative, m.p. 221 °C, described by *A. N. Kosst, A. A. Shumakova, J. I. Koslova*, and *I. I. Grandberg*, Vestnik Moskovskogo Univ., Ser. Mat., Mech., Astr., Fiz., Khim. *14*, 205 (1959); Chem. Zbl. *1961*, 13597, is the open-chain hydrazone.

The open-chain *p*-nitrophenylhydrazone *(5')* [*i.e. (5)* with R = *p*-NO_2–C_6H_4] can be esterified and is characterized by the deep red-violet color which develops on reaction with aqueous alkali. The color is due to the anion, which may be represented by the three resonance structures *(5'a)*, *(5'b)*, and *(5'c)*.



When ether/diazomethane vapors are passed over the yellow solution of the nitrophenylhydrazone *(5')* in dimethylformamide, the surface of the solution turns deep violet, which is again the color of the anion *(5'a)* ↔ *(5'c)*. The color disappears on shaking, or when the diazomethane solution is run in. Only then is nitrogen evolved, and the methyl ester is obtained by working up the resulting yellow solution. The color reaction impressively demonstrates the high proton affinity of diazomethane and the enhanced mobility of the proton in *(5')*. It also confirms the mechanism suggested by *E. Müller* [12a] for methylation with diazomethane, in which the first step is the uptake of a proton to form a methyldiazonium cation.

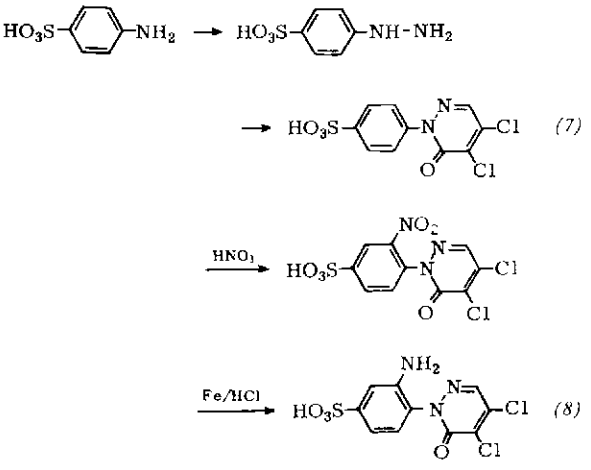
2,6-Dimethylphenylhydrazine, which is obtained from *vic*-xylidine, reacts with mucochloric acid to form the pale yellow 4,5-dichloro-1-(2',6'-dimethylphenyl)-6-pyridazone on short heating in glacial acetic acid. Even a sulfo group in the *o*-position with respect to the hydrazine group does not prevent formation of the pyridazone. This shows that *steric factors* do not have a decisive influence on the ring closure reaction. It can be seen from Stuart models of 4,5-dichloro-1-(*p*-tolyl)-6-pyridazone and its 2'-nitro derivative that an *ortho*-substituted aryl residue is compatible with pyridazone formation. It is not necessary for the two rings to be coplanar. Instead, they are probably rotated out of the common plane to a certain extent, depending on the nature and position of the substituents on the aryl ring; this phenomenon is also found in the pyrazolone series [13]. Thus the principal factors governing the ring closure are *substituent effects*. They increase or decrease the electron density at N–1 and effect the attack of this center on the carboxyl carbon atom C–6 which carries a partial positive charge [cf. *(6)*].



(6)

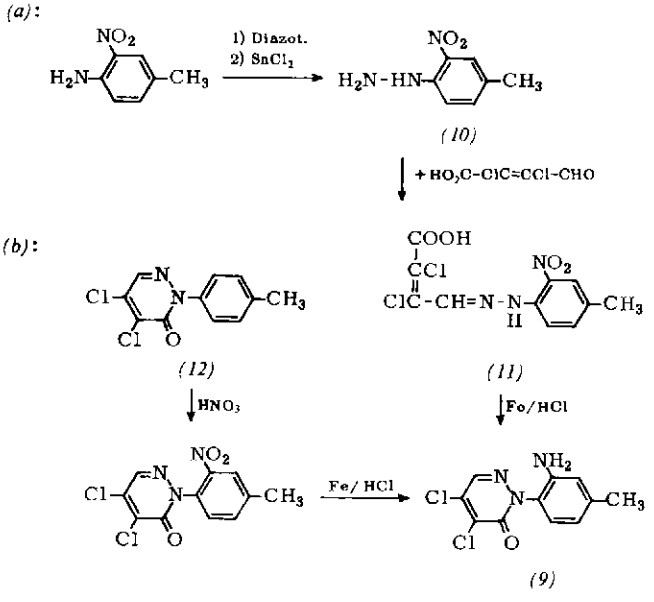
b) 1-Aryl-4,5-dichloro-6-pyridazones in Diazo and Coupling Components

1-Phenylpyridazones containing amino groups can be obtained *via* the corresponding nitro or acetamino compounds. Another route starts from sulfanilic acid, which is diazotized and reduced with sodium sulfite to form 4-sulfophenylhydrazine; this is not isolated, but is reacted directly with mucochloric acid. In this way, the intermediate *(7)* can be obtained in 88% yield by a single pass in an acidic aqueous solution. The amine *(8)* is obtained by nitration and subsequent Béchamp reduction.



(7) *(8)*

It was found that the 4,5-dichloro-6-pyridazonyl group is a first-order substituent, *i.e.* it is *ortho*- and *para*-directing with respect to the 1-phenyl residue. Thus 1-(2'-amino-4'-tolyl)-4,5-dichloro-6-pyridazone *(9)* can be prepared by two routes: (a) 3-Nitro-*p*-toluidine is converted to the hydrazine derivative *(10)*, which is then reacted with mucochloric acid. The hydrazone *(11)* is

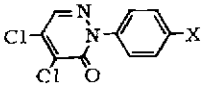


unaffected by boiling glacial acetic acid, and undergoes ring closure to form the pyridazone only after the nitro group has been reduced to the amino group. The same amine *(9)* (identified by melting point and infrared spectrum) can be obtained [Route (b)] from the *p*-tolylpyridazone *(12)* by nitration and reduction. Thus the nitro group enters the *o*-position with respect to the dichloropyridazonyl residue.

Components which contain reactive dichloropyridazonyl residues and are suitable for azo coupling have been prepared by acylation with acyl chlorides. 4,5-Dichloro-

[12a] *E. Müller*: Neuere Anschauungen der organischen Chemie. 2nd Edit., Springer, Berlin-Göttingen-Heidelberg 1957, p. 444.
[13] *H. Hopff*, Chimia *15*, 193 (1961).

1-phenyl-6-pyridazone reacts with chlorosulfonic acid to form the sulfochloride *(13)* (m.p. 141 °C), and with phosgene in molten urea/$AlCl_3$ [14] to form the carboxylic acid corresponding to *(14)*; this acid can also be obtained from *p*-aminobenzoic acid *via p*-hydrazinobenzoic acid by reaction with mucochloric acid.

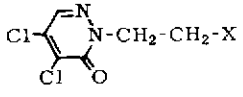


(13): X = SO_2Cl

(14): X = COCl

Dyes or dye intermediates containing amino groups can be acylated in the usual manner with the acyl chlorides *(13)* and *(14)* [m.p. of *(14)*: 153 °C]. However, the resulting dyes are only moderately soluble. We therefore turned our attention to the synthesis of intermediates containing aliphatic bridges.

β-Hydrazinopropionitrile is readily obtainable from hydrazine and acrylonitrile. It reacts with mucochloric acid to give the pyridazone derivative *(15)* (yield > 90%),



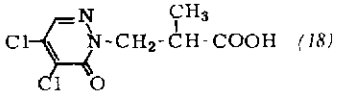
(15): X = CN

(16): X = COOH

(17): X = COCl

which forms the β-substituted propionic acid *(16)* on hydrolysis with sulfuric acid (70%) or hydrochloric acid. Intermediates obtained by reaction with the acyl chloride *(17)* can be converted to azo dyes which are completely satisfactory with regard to solubility and affinity.

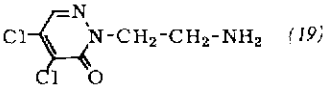
The bridge between the reactive 4,5-dichloro-6-pyridazonyl residue and the chromophore system has some effect on the affinity of the dye. For this reason, intermediates with a branched aliphatic chain were also prepared. The isobutyric acid dervative *(18)*, m.p. 135 °C, is obtained from hydrazine and methacrylonitrile by reaction with mucochloric acid and subsequent hydrolysis.



(18)

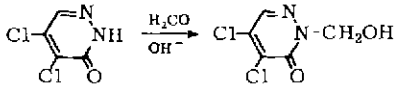
c) Aminoalkyl and Hydroxymethyl Derivatives of 4,5-Dichloro-6-pyridazone

β-Aminoethylhydrazine, which is prepared from hydrazine and ethylene imine, can be reacted with mucochloric acid to form the pyridazone derivative *(19)*, which is isolated from its solution in hydrochloric acid as the hydrochloride (m.p. 265 °C). The corresponding γ-aminopropyl derivative is obtained by catalytic hydrogenation of the nitrile [15]. Aliphatic amines of this type are particularly suitable for reaction with anthraquinone- and phthalocyanine dyes which contain acyl chloride groups.

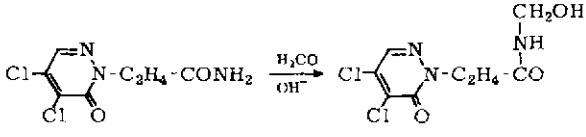


(19)

4,5-Dichloro-6-pyridazone *(1a)*, m.p. 205 °C, reacts with formaldehyde in alkaline solution to form the 1-hydroxymethyl compound *(20)*, m.p. 104 °C. In a similar reaction the hydroxymethylamide *(22)*, m.p. 136 °C, is obtained from the propionamide *(21)*, m.p. 173 °C, and formaldehyde. Hydroxymethyl compounds of this type can be combined with dyes or dye intermediates containing activated methylene groups by condensation in concentrated sulfuric acid [15,16].



(1a) *(20)*



(21) *(22)*

3. Dyes

a) Synthesis of Dyes

The high stability of the dichloropyridazonyl group is of advantage in the synthesis of dyes. This group remains intact below pH 8.5 even at 100 °C. It survives sulfonations, nitrations, and reductions. The preparation of metal complexes, chroming and cobalting at 100 °C, and oxidative coppering or coupling down to pH 10 are also possible without special precautions.

The reader is referred to the patent literature [17–24] for details of the preparation of the azo-, anthraquinone-, and phthalocyanine dyes.

Mucochloric acid is used as a starting material in all the syntheses mentioned so far. Mucobromic acid has been used

[14] *W. Braun*, German Pat. 726227 (Febr. 16th, 1938), I.G.-Farbenindustrie; Chem. Zbl. *1943* I, 2757.

[15] *J. Tscherniac*, German Pat. 134979, 134980 (1901); Friedländer *6*, 143, 145 (1904).

[16] *A. Einhorn*, Liebigs Ann. Chem. *343*, 207 (1905); *361*, 113 (1908). See also *Houben-Weyl*: Methoden der Organischen Chemie. 4th Edit., Thieme, Stuttgart 1957, Vol. XI/1, p. 795.

[17] *H. R. Hensel, H. Baumann, K. Dury*, and *W. Federkiel*, German Pat. 1135115 (June 25th, 1959), BASF; Chem. Abstr. *58*, 2526a (1963).

[18] *A. Tartter* and *H. R. Hensel*, German Pat. 1123065 (Aug. 17th, 1959), BASF; Chem. Zbl. *1963*, 3770.

[19] *H. R. Hensel, H. Baumann, A. Tartter*, and *H. Weißauer*, Brit. Pat. 946471 (Jan. 26th, 1961), BASF.

[20] *A. Tartter, H. R. Hensel*, and *H. Baumann*, German Pat. 1130096 (April 29th, 1960), BASF; Chem. Abstr. *57*, 9998e (1962).

[21] *A. Tartter, H. Baumann*, and *H. R. Hensel*, German Pat. 1150478 (May 4th, 1960), BASF; Chem. Zbl. *1964*, 6/7-2509.

[22] *H. Baumann, H. R. Hensel*, and *A. Tartter*, German Pat. 1154213 (May 18th, 1960), BASF; Chem. Zbl. *1964*, 16–2395.

[23] *A. Tartter, H. R. Hensel*, and *F. Graser*, Belg. Pat. 613990 (Febr. 15th, 1962), BASF; Chem. Abstr. *58*, 8068d (1963).

[24] *H. R. Hensel* and *H. Baumann*, Belg. Pat. 636895 (Sept. 2nd, 1963), BASF.

in a similar manner. Although dyes containing the 4,5-dibromo-6-pyridazonyl group can be combined with the fibers under milder conditions (lower temperature), the advantages do not compensate for the higher costs.

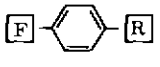
b) Affinity of Dyes

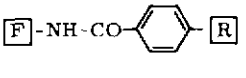
The dyeing of cellulose fibers always begins with the penetration of the dye molecule, which is dissolved in water, into the cellulose micelles, where they can become fixed in various ways. In the case of substantive dyes, the latest views [25] are in favor of an aggregation of the dye molecules, with no true adhesion between the dye and the cellulose. The situation is different in the case of reactive dyes. Here the dye is finally attached to the substrate by a covalent bond, and this step is preceded by a phase in which the dye molecules are adsorbed on the surface of the fibers. The fact that they react preferentially with the cellulose anions is explained by an increase in the concentration of the dye at the cellulose surface, just as is assumed to be the case in reactions on catalyst surfaces [25a].

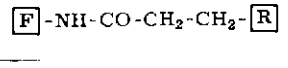
The adsorption process, in which the distribution equilibrium between the dye bath and the fiber is displaced in favor of the fiber, is affected by two factors: molecular structure and solubility. Of these, the solubility can be varied only within narrow limits. It is normally determined by the number of sulfo groups in the dye molecule; in addition there is a solvation effect in the case of metal complexes.

The molecular structure, on the other hand, offers many possibilities of modification. Assuming that the chromogenic portion [F] of the dye molecule is given, the structure can be modified not only by altering the reactive residue [R], but also by altering the bridge between [F] and [R]. In the case of the reactive dyes of the triazine and pyrimidine series, which are synthesized from imide chlorides, the bridge is an imino group. It affects the resistance to hydrolysis and the reactivity of the dye through the reactivity of its hydrogen atom [26]. Aliphatic bridges, on the other hand, favor the adsorption on the surface of the substrate owing to their flexibility [26a].

The reactive dyes of the 4,5-dichloro-6-pyridazone series can be classified according to the nature of the bridges. In the azo dyes of Type I, which are prepared from the amines in Table 1, the chromophore [F] is linked to the 4,5-dichloro-6-pyridazonyl ring by a phenylene group. The dyes obtained by acylation with the acyl chlorides

I: 

II: 

III: 

(13), *(14)*, and *(17)*, on the other hand, contain a carboxamide or sulfonamide bridge linked to the pyridazone ring [R] by an aromatic (Type II) or aliphatic (Type III) group.

Thus these dyes are similar to the dichloroquinoxaline dyes of the ®Levafix-E series, which also contain a carboxamide bridge. However, *Rattee*'s view [25a] that the high color yield [*] of the dichloroquinoxaline dyes is partly due to their pronounced planar-angular structure, is not applicable to the 4,5-dichloro-6-pyridazone dyes. Here, the best coloristic properties are shown by the dyes of Type III, in which the residue [R] can move freely. This favors the adsorption process and the subsequent nucleophilic substitution of the reactive chlorine atom. The number of collisions appears to be higher for this type than for the more rigid dye molecules of Types I and II. Another advantage is that the conjugation is interrupted by the non-planarity of the molecule; consequently the chromogenic part and the reactive part of the dye do not affect each other, so that the dye exhibits good light-fastness.

c) Stability and Fixation of the Dyes

It was explained in Section I that the chlorine atom on C-4 of the pyridazone residue is responsible for the reactivity of the dyes discussed here.

The kinetics of the nucleophilic substitution are directly related to a number of questions concerning the application and synthesis of these dyes. Using the propionic acid derivative *(16)* as a model, the elimination of chloride ions was measured in 4% aqueous solution (*i.e.* roughly under the conditions prevailing in the dye bath) at various reaction times, temperatures, and pH values.

It can he seen from Figure 1 that, at pH 9, hydrolysis is observed only at elevated temperatures. In similar experiments with sodium hydrogen phosphate as a buffer (pH 8.5), no chloride ions were detected even after boiling (100 °C) for 20 hours. The same result is obtained on keeping the compound for 20 hours at 20–40 °C in Na_2CO_3 solution; under these conditions, chloride ions are formed only in the presence of stronger bases (above pH 10). Thus compound *(16)* is stable at 35 °C in sodium carbonate solution, but half of the chlorine is removed from C-4 after 3.5 hours in NaOH solution at 35 °C, and after 5 minutes at 60–65 °C.

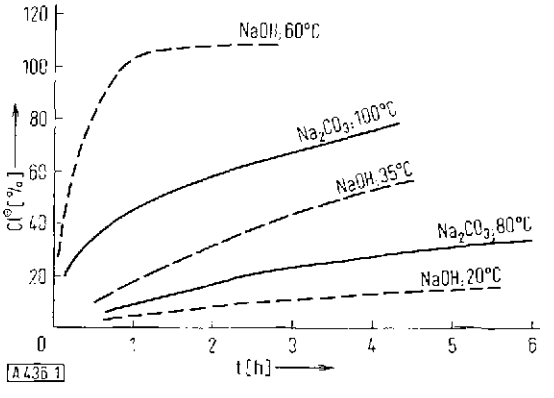


Fig. 1. Elimination of chloride ions from 4,5-dichloro-6-pyridazonyl-propionic acid *(16)* in 4% aqueous solution (total quantity of Cl = 200 %).
——— in sodium carbonate solution (pH 9.9)
- - - - - - - in sodium hydroxide solution (pH 11).

[25] *H. Bach, E. Pfeil, W. Philippar,* and *M. Reich,* Angew. Chem. *75*, 407 (1963).

[25a] *I. D. Rattee,* Chimia *18*, 293 (1964).

[26] *S. Horrobin,* J. chem. Soc. (London) *1963*, 4130.

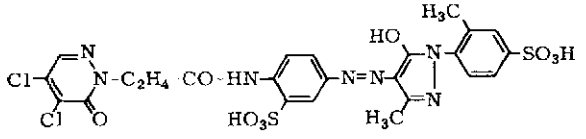
[26a] *H. Zollinger,* Chimia *15*, 186 (1961).

[*] The term color yield, or more accurately dyeing yield, denotes the proportion of a dye which remains on the fiber and cannot be washed off. In the case of the dyes discussed in the present paper, the dyeing yield is identical with the degree of fixation, *i.e.* the proportion of the dye which is attached to the fiber by homopolar bonds.

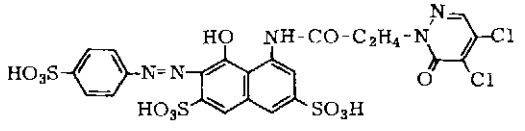
The half-reaction times for the hydrolysis of dyes (*i.e.* the time in which 50 % of the dye is hydrolysed) in various pH ranges have been determined by *Baumgarte* and *Feichtmayr* [27]. They concluded that the reaction proceeds by an S_N2 mechanism.

The fact that 4,5-dichloro-6-pyridazone dyes become attached to cotton and artificial wool very rapidly from alkaline printing pastes without special additives is of importance for their technical use.

Baumgarte and *Meyer* [27a] carried out a colorimetric determination of the color yield for a series of dichloropyridazone dyes, including the yellow dye *(23)* and the red dye *(24)*. The maximum yield was generally obtained after steaming for 3 minutes at 100 °C, or after 1 minute at 110 °C. Hot-air fixing at 150 °C gave yields of 50–60 % after 30 sec, and up to 75 % after 1 minute.



(23)



(24)

The storage life of the printing pastes is practically unlimited. Since the substantivity of the dyes is low, no difficulties are encountered in washing out unfixed dye.

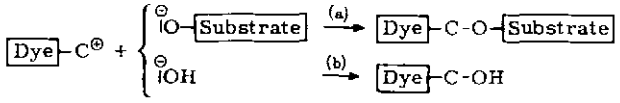
The dichloropyridazone dyes can also be used for dyeing cellulose fibers in a dye bath. However, their fixing power is not always sufficient for a number of new dyeing processes, in which reactive dyes are used under strongly alkaline conditions at room temperature.

These new reactive dyes are marketed as ®Primazin-P dyes. The letter "P" indicates that the dyes are pyridazone derivatives. They can be combined with all other reactive dyes.

II. Bonding of Dyes to Cellulose via Polyfunctional Bridges [*]

In order to produce homopolar bonds between dyes and high molecular-weight substrates (cellulose in particular) attempts were made to provide dyes with reactive groups which could assume a positive charge, *i.e.* form a carbonium ion, and which would thus be accessible to nucleophilic attack by the substrate. The reactive dye systems mentioned on page 312 have found wide application [1,2].

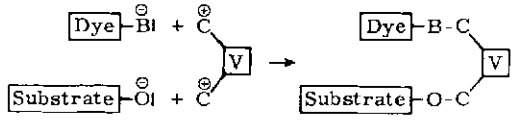
Besides the substrate, however, nucleophilic $OH^{\ominus}$ ions are also present during the dyeing process (Reaction a). Consequently, part of the reactive dye is always lost in hydrolytic side reactions (b) (see Scheme 1).



Scheme 1. Dyeing process (a) and hydrolytic side reaction (b) of the dye.

The color yield is therefore generally only 60–85 % [1]. Where hydrolysis of the reactive dye leads to water-insoluble products [2], the color yield is increased by the hydrolysis product deposited on the substrate. Reactive dyes which have been deactivated by hydrolysis are often substantively incorporated into the substrate, *i.e.* in the form of high molecular-weight aggregates [25]. This portion of the dye which is not fixed to the substrate by homopolar bonds reduces the fastness to wet processing and must be removed by thorough washing [1].

We therefore looked for reactions whereby dyes not containing reactive groups of this type could be attached by homopolar bonds to nucleophilic substrates in high yields. We found that even under the conditions used for dyeing and printing, color yields of up to about 90 % could be obtained by linking the dyes to the substrates *via* multifunctional, non-coloring bridges [V] (Scheme 2) [28]. In this process, dyes containing a *nucleophilic* group $-B:^{\ominus}$ and nucleophilic substrates such as the cellulose anion are reacted with bridge molecules containing several positively charged carbon atoms, to form mixed adducts. As can be seen from Scheme 2, the positively charged carbon atom is

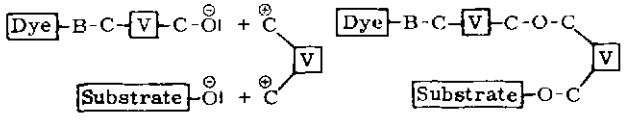


Scheme 2. Homopolar bonding between dye and substrate produced by a polyfunctional bridge molecule.

no longer supplied by the dye, but by the bridge. Consequently, any material lost by hydrolysis will be the bridge compound, and not the dye.

Since the dye and the component containing the positively charged carbon atoms can be used separately and in various proportions, the reaction of Scheme 2 can be made to yield higher degrees of fixation (cf. footnote on page 316 and Figure 2).

Even if some of the reactive groups of the polyfunctional bridge molecules have been deactivated by hydrolysis, the molecules can still take part in the reaction provided that two or more reactive groups are still available. Furthermore, hydrolysis of the bridge material yields compounds containing nucleophilic groups, which can themselves react with bridge molecules. One of the many conceivable combinations is shown in Scheme 3.



Scheme 3. Possible combinations of dye, substrate and bridge molecules.

[27] *U. Baumgarte* and *F. Feichtmayr*, Melliand Textilber. *44*, 163, 267, 600, 716 (1963); *45*, 775 (1964).

[27a] *U. Baumgarte* and *G. Meyer*, BASF, personal communication.

[*] By *G. Lützel.*

[28] *G. Lützel, W. Rohland, A. Tartter, G. Barts, W. Dietrich, R. Müller*, and *W. Federkiel*, German Published Patent Application 1155088 (Nov. 2nd, 1960), BASF.

Imide chlorides such as cyanuric chloride and its reaction products with amines or phenols [29–31], as well as a number of compounds containing epoxide [32,33], sulfate, or halogenoalkyl groups [33] have previously been described as bridging compounds. However, yields were unsatisfactory with compounds of these types.

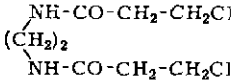
Several experimental results support the assumption that new homopolar bonds are formed in reactions according to Schemes 2 or 3. Thus the cotton dyes obtained with 1,3,5-tris-(β-chloropropionyl)hexahydro-s-triazine *(34c)*, 2,4,6-trisethylenimino-s-triazine *(29)* (triethylenemelmine), or bis(acryloylamino)methane *(25)* (methylenebisacrylamide) as the bridge compound are extremely fast to wet processing; the dye cannot be removed even by boiling dimethylformamide. Cellulose which has been treated in this way, in contrast to the untreated fabric, is extremely difficult to dissolve in cuprammonium solution. On the other hand, non-substantive dyes, which were applied to cotton under similar conditions but do not form bridges, can be completely removed by washing with water. Moreover, we were able to detect homopolar linkages between water-soluble cellulose models (β-dextrins) and dyes by chromatography [34].

1. Bridge Compounds

Compounds suitable as bridges must be able to form at least two positively charged carbon atoms which are accessible to nucleophilic attack. Multifunctional compounds of this type [*(25)–(33)*, *(34a)–(34m)*] contain, for example, polarized C=C double bonds, three-membered heterocyclic rings which are capable of undergoing addition, or reactive halogen atoms. We have synthesized such compounds [*(26)*, *(30)–(33)*, *(34e)*, *(34h)*] and compared their reactivities using the color yields on cotton as a basis.

$H_2C(NH\text{-}CO\text{-}CH{=}CH_2)_2$

(25) [28, 35–38, 48]



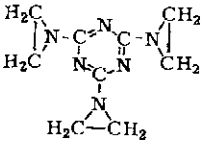
(27) [28, 35–38]

$H_2C(NH\text{-}CO\text{-}CH_2\text{-}CH_2\text{-}SO_2\text{-}C_6H_5)_2$

(26) [28, 35–38]

$O_2S(CH_2\text{-}CH_2OH)_2$

(28) [39]

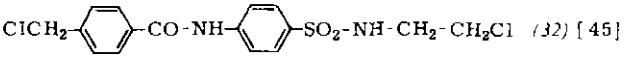


(29) [40, 41]

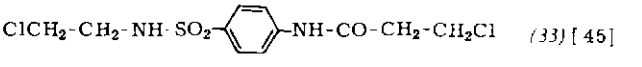
$O{=}C(NH\text{-}CH_2\text{-}C{\equiv}C\text{-}CH_2Cl)_2$

(30) [44]

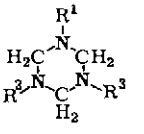
(31) [42, 43]



(32) [45]



(33) [45]



(34)

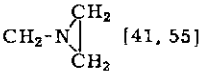
(a) $R^1 = R^2 = R^3 = -CO\text{-}CH{=}CH_2$ [28, 35–38, 46–48]

(b) $R^1 = R^2 = R^3 = -CO\text{-}CCl{=}CH_2$ [49, 50]

(c) $R^1 = R^2 = R^3 = -CO\text{-}CH_2\text{-}CH_2Cl$ [28, 35–38, 52]

(d) $R^1 = R^2 = R^3 = -CO\text{-}CHCl\text{-}CH_2Cl$ [49, 50]

(e) $R^1 = R^2 = R^3 = -SO_2\text{-}CH{=}CH_2$ [53, 54]

(f) $R^1 = R^2 = R^3 =$  [41, 55]

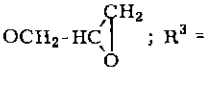
(g) $R^1 = R^2 = R^3 = -CO\text{-}CH_2Cl$ [57, 58]

(h) $R^1 = R^2 = R^3 = -CO\text{-}CH{=}CH\text{-}CH_2Cl$ [44]

(i) $R^1 = R^2 = R^3 = p\text{-}CO\text{-}C_6H_4\text{-}CH_2Cl$ [48, 58]

(k) $R^1 = R^2 = -CO\text{-}CH{=}CH_2$; $R^3 = -CO\text{-}CH_2\text{-}CH_2\text{-}SO_3Na$ [28, 35–38, 49]

(l) $R^1 = R^2 = -CO\text{-}CH{=}CH_2$; $R^3 = -CO\text{-}CH_2\text{-}CH_2\text{-}N(C_2H_5)_2$ [28, 35–38, 49, 51]

(m) $R^1 = R^2 =$  ; $R^3 = -CO\text{-}CH{=}CH_2$ [56]

[29] *W. F. Beech, D. A. Garrett, H. R. Hadfield,* and *R. L. Denyer*, German Pat. 1058016 (Nov. 21st, 1957), ICI; Chem. Zbl. *1960*, 3047.

[30] *R. L. Denyer* and *H. R. Hadfield*, German Pat. 1059398 (Nov. 21st, 1957), ICI; Chem. Zbl. *1960*, 5651.

[31] *W. F. Beech, D. A. Garrett, H. R. Hadfield,* and *R. L. Denyer*, German Pat. 1059399 (Nov. 21st, 1957), ICI; Chem. Zbl. *1960*, 3047.

[32] *P. Jäger, E. Koller, J. Wegmann,* and *H. Zollinger*, German Pat. 1091980 (Aug. 26th, 1958), Ciba; Chem. Zbl. *1961*, 8480.

[33] *K. Wedemayer, K. G. Kleb, H. A. Dortmann,* and *D. Delfs*, Belg. Pat. 574366 (Dec. 31st, 1958), Farbenfabriken Bayer.

[34] *U. Baumgarte* and *G. Lützel*, unpublished work.

[35] *J. Dehnert, W. Grosch, G. Lützel,* and *W. Rohland*, Belg. Pat. 627761 (Jan. 30th, 1963), BASF.

[36] *G. Lützel, W. Rohland, G. Meyer,* and *H. Wirth*, Belg. Pat. 630085 (March 26th, 1963), BASF.

[37] *W. Rohland* and *G. Lützel*, Brit. Pat. 932080 (Jan. 16th, 1962) BASF.

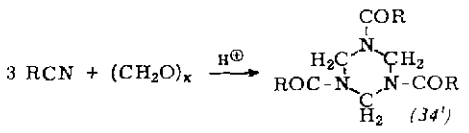
[38] *G. Lützel* and *W. Rohland*, Belg. Pat. 631235 (Apr. 18th, 1963), BASF.

[39] *J. Eisele, G. Lützel,* and *W. Rohland*, Belg. Pat. 622341 (Sept. 11th, 1962), BASF.

[40] *H. Bestian*, Liebigs Ann. Chem. *566*, 210 (1950).

a) Preparation

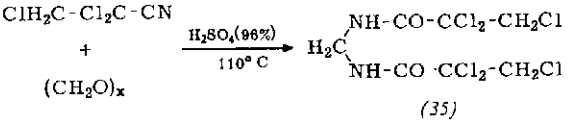
The 1,3,5-triacylhexahydro-s-triazines *(34)* were prepared by the method decribed by *Wegler* and *Ballauf* [46–48], from nitriles and paraformaldehyde or trioxane in anhydrous media and in the presence of strongly



(34')

acidic condensing agents, or [*e.g. (34f)* and *(34l)*] by nucleophilic addition to *(34a)*. The sulfur analogue *(34e)* is formed by the proton-catalysed condensation of vinylsulfonamide with paraformaldehyde [53].

The reaction of nitriles with paraformaldehyde in the presence of water leads to bis(acylamino)methanes [48]. However, some of these compounds can also be obtained in yields of up to 85% from nitriles in anhydrous media. For example, the cyclization of α,β-dichloropropionitrile leads to 1,3,5-tris-(α,β-dichloropropionyl)-hexahydro-s-triazine *(34d)*, which had previously been obtainable only by addition of halogen onto the α,β-unsaturated precursor *(34a)* [49], while the same reaction of α,α,β-trichloropropionitrile [61] yields bis-(α,α,β-trichloropropionylamino)methane *(35)*, m.p. 161 °C; NH bands at 1520 and 3340 cm^{-1}.



(35)

b) Reactions

In general compounds such as *(25)–(34')* react with groups which can be cyanoethylated. These include NH, SH, OH, or activated CH_2 groups. However, only a limited comparison can be drawn between cyanoethylation and the formation of homopolar bonds during the dyeing process, owing to the presence of water in the latter.

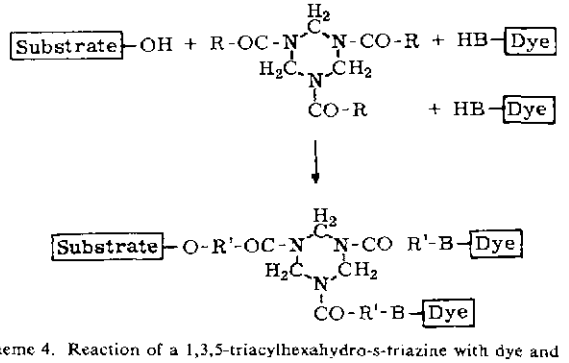
The best color yields were obtained with 1,3,5-triacylhexahydro-s-triazines *(34)*. These compounds are particularly effective as bridging groups for the following reasons:

1. The three substituents are very mobile, as can be seen from Stuart models.

2. The carbonyl groups have a strong polarizing effect.

3. If a halogen atom of the aromatic 2,4,6-trichloro-s-triazine is replaced by another substituent, the reactivities of the remaining halogen atoms decreases. On the other hand, the reactivity of the substituents on the non-aromatic hexahydro-s-triazine skeleton is not appreciably altered when some of these substituents react with other groups [62].

The reaction of a 1,3,5-triacylhexahydro-s-triazine *(34')* with nucleophilic dyes and substrates is shown in a simplified form in Scheme 4.



Scheme 4. Reaction of a 1,3,5-triacylhexahydro-s-triazine with dye and substrate molecules.

If we assume that each of the three reactive groups can react with equal probability with each of three partners (substrate, dye, water), then there are $3^3 = 27$ possible adducts, only 12 (= 44.5%) of which correspond to a dye-substrate compound. However, the color yields [27a] as found by spectrophotometry of dye cellulose compounds in concentrated phosphoric acid [63] are much higher than would be expected from this figure, values of about 90% being obtained with many dyes under optimum conditions. Thus hydrolysis is largely suppressed.

[41] *G. Lützel, W. Rohland,* and *D. Ludsteck,* German Pat. 1159899 (Febr. 4th, 1961), BASF.

[42] *H. Distler,* German Pat. 1094735 (July 18th, 1959), BASF; Chem. Zbl. *1962,* 8419.

[43] *D. Ludsteck, G. Lützel, W. Rohland,* and *H. Distler,* French Pat. 1321629 (Febr. 23rd, 1962), BASF.

[44] *W. Grosch, D. Ludsteck, G. Lützel,* and *W. Rohland,* Belg. Pat. 631290 (Apr. 19th, 1963), BASF.

[45] *G. Lützel* and *W. Rohland,* Belg. Pat. 631294 (Apr. 19th, 1963), BASF.

[46] *A. Ballauf* and *R. Wegler,* German Pat. 859170 (March 22nd, 1942), Farbenfabriken Bayer; Chem. Zbl. *1953,* 3150.

[47] *R. Wegler* and *A. Ballauf,* Ber. dtsch. chem. Ges. *81,* 527 (1948).

[48] *R. Wegler* and *H. Herlinger* in *Houben-Weyl:* Methoden der organischen Chemie. 4th Edit., Thieme, Stuttgart 1963, Vol. XIV/2, p. 392.

[49] *E. Zerner, M. Gradsten,* and *F. W. West,* U.S. Pat. 2559694 (June 10th, 1948), Sun Chemical Corporation; Chem. Abstr. *45,* 9914f (1951).

[50] *G. Lützel* and *W. Rohland,* Belg. Pat. 631257 (Apr. 18th, 1963), BASF.

[51] *G. Lützel* and *W. Rohland,* Belg. Pat. 624513 (Nov. 7th, 1962), BASF.

[52] *J. M. Gradsten* and *M. Pollock,* J. Amer. chem. Soc. *70,* 3079 (1948).

[53] *D. Ludsteck, W. Rohland,* and *G. Lützel,* German Pat. 1178071 (Febr. 16th, 1961), BASF.

[54] *D. Ludsteck, G. Lützel,* and *W. Rohland,* German Published Patent Application 1147191 (Febr. 23rd, 1961), BASF.

[55] *E. Zerner* and *M. W. Pollock,* U.S. Pat. 2651631 (Oct. 16th, 1951), Sun Chemical Corp.; Chem. Abstr. *48,* 10788 (1954).

[56] *W. Grosch, G. Lützel,* and *W. Rohland,* Belg. Pat. 629382 (March 8th, 1963), BASF.

[57] *H. A. Levine,* U.S. Pat. 2976152 (Dec. 19th, 1958), General Aniline and Film Corporation; Chem. Abstr. *55,* 14139 (1961).

[58] *W. Rohland* and *G. Lützel,* French Pat. 1354040 (Apr. 26th, 1963), BASF.

[59] *I. A. Lundberg,* U.S. Pat. 2475846 (Oct. 31st, 1946), American Cyanamid Co.; Chem. Abstr. *44,* 873 (1950).

[60] *C. Price* and *L. Krishnamurti,* J. Amer. chem. Soc. *72,* 5334 (1950).

[61] *J. G. Lichty,* U.S. Pat. 2231838 (March 15th, 1940), Wingfoot Corp.; Chem. Abstr. *35,* 3268^3 (1941).

[62] *F. Feichtmayr, G. Lützel* and *F. Würstlin,* BASF, unpublished work.

[63] *E. Rexroth,* BASF, personal communication.

Bifunctional bis(acylamino)alkanes such as *(25)–(27)* generally give lower color yields than the 1,3,5-triacylhexahydro-s-triazines *(34a)–(34d)*. α-Methyl-substituted analogues such as bis(methacryloylamino)methane [59] or 1,3,5-tris(methacryloyl)hexahydro-s-triazine, in contrast to *e.g.* the α-halogen compound *(34b)*, form practically no covalent bonds with dyes containing nucleophilic groups under the conditions used in dyeing (cf. Section II.4).

The color yield is also much lower in the case of 1,3,5-tris-(vinylacetyl)hexahydro-s-triazine [60], where the conjugation between the carbonyl group and the double bond is interrupted by a methylene group, than with the α,β-unsaturated or β-halogenated 1,3,5-triacylhexahydro-s-triazines, *e.g.(34a)* and *(34c)*.

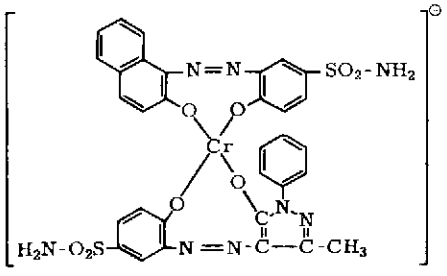
The color yield obtained with halogenomethylbenzoyl derivatives falls off rapidly with increasing halogenation. 1,3,5-Tris-(*p*-trichloromethylbenzoyl)hexahydro-s-triazine, m.p. 220–221 °C, unlike the *p*-chloromethylbenzoyl compound *(34i)*, gave practically no dyeing effect. Similar behavior is observed with bis-(α,α,β-trichloropropionylamino)methane *(35)*, as compared with *(25)*.

2. Dyes

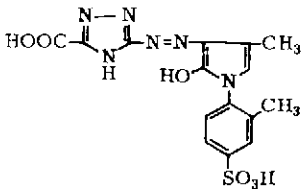
Dyes or substances which are to be reacted in accordance with Scheme 4 must contain nucleophilic groups, such as primary or secondary amino groups, sulfonamido or *N*-monosubstituted sulfonamido groups, hydroxy or mercapto groups, acetoacetyl groups, or heterocyclic systems with NH groups in the ring.

However, it is impossible to predict the color yield. The nucleophilic character of the groups containing active protons cannot be used as a basis for estimations, since the yield also depends on the number and position of the nucleophilic groups in the dye and substrate, on adjacent substituents, the diffusibility of the dye, and the spatial orientation of the dye with respect to the substrate (cf. also Section II 4). Dyes containing sulfonamido [*(36)*, brown] [64,65], aminoalkylsulfonamido [66], acetoacetyl [*(37)*, red] [67], or OH groups [*(38)*, red], heterocyclic compounds with NH groups [*(39a)*, yellow] [35], as well as dyes which are derivatives of triazole, pyrazole [*(39b)*, red] [35], indole, or imidazole, generally give good color yields.

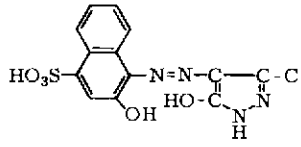
To obtain homopolar bonding of the dyes *(36)–(39)* with cellulose, cotton fabrics are impregnated with an aqueous solution containing *e.g.* 20 g/l of dye, 10–20 g/l of bis(acryloylamino)methane *(25)*, and 10 g/l of sodium carbonate or 10 g/l of a 32 % sodium hydroxide solution; the impregnated fiber is then dried, steamed for 5 min, and washed in boiling soap solution.



(36) [64]

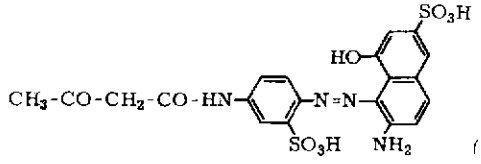


(39a) [35]

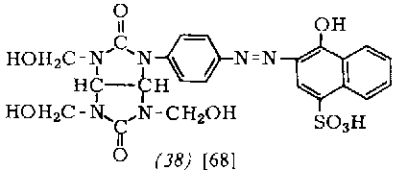


(1:2 Cr-complex)

(39b) [35]



(37) [67]



(38) [68]

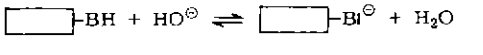
3. Substrates

The substrates must also contain or form groupings capable of nucleophilic attack at the positively charged carbon atoms of the bridge molecule. Examples are the hydroxy groups of polysaccharides and the amino or mercapto groups of natural polyamides, as well as their ions.

We have used the reaction (Scheme 4) mainly for the dyeing of cellulose. However, the results are applicable to other substrates containing hydroxy groups, such as paper, ®Cellophane film, wheat starch, or β-dextrin [34] (a cyclic compound consisting of seven glucose units). High molecular-weight polyamides such as wool or silk often give somewhat lower color yields than cellulose.

4. Dyeing of Cellulose

Hexahydro-s-triazine derivatives possess no appreciable substantivity. For this reason, bridges of this type are mainly used in impregnating processes (printing, pad dyeing), in which substantivity is undesirable. The substrate is impregnated with aqueous solutions or printing pastes containing the dye, the bridge compound, and an alkaline catalyst. In the first step the catalyst removes protons from the dye and the substrate, thus forming the nucleophilic centers:



[64] *H. Pfitzner*, German Pat. 742939 (Dec. 28th, 1938), BASF; Chem. Zbl. *44*, I, 1331.

[65] *F. Graser, D. Weiser, G. Lützel*, and *W. Rohland*, Belg. Pat. 631584 (Apr. 26th, 1963), BASF.

[66] *A. Tartter, G. Lützel*, and *W. Rohland*, French Pat. 1336945 (Aug. 30th, 1962), BASF.

[67] *H. Baumann* and *G. Lützel*, BASF, unpublished work.

Basic compounds which are themselves strongly nucleophilic, *e.g.* ethylenediamine or hexamethylenediamine, displace other reactants (*e.g.* cellulose) from the reaction. Consequently, the most suitable catalysts are those which do not form groupings more nucleophilic than hydroxide ions under the reaction conditions. The most important of such compounds are inorganic bases and their alkaline salts such as Na_2CO_3, $NaHCO_3$ *etc.*, as well as pyridine or ®Triton B (benzyltrimethylammonium hydroxide).

If one of the components is insoluble in water, it is used in a water-miscible solvent, *e.g.* dimethylformamide. In the case of moderately soluble compounds, it is often sufficient to deposit these on the substrate in a finely divided form; they dissolve on steaming for a few minutes.

The dye and the bridge component can also be applied in succession from different solvents. After drying, the reaction is started by raising the temperature. This is followed by washing in order to remove additives, alkalis, and unbonded dye from the substrate.

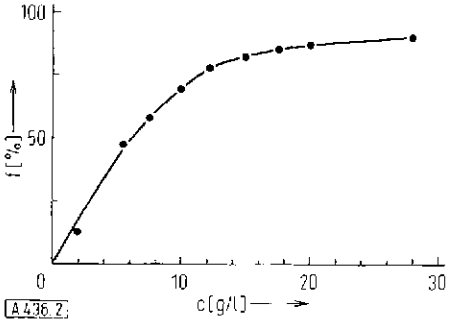


Fig. 2. Color yield (f) for printing of cotton with the 1:2 chromium complex of dye *(39b)* and the bridge component *(34a)* [27a]. (Dye concentration: 30 g/kg of printing paste.)

Abscissa: Concentration of bridge component *(34a)* [g/l].

Ordinate: Color yield f [%].

The color yield for a given dye depends on the nature and quantity of the bridge component used. 1,3,5-Triacylhexahydro-s-triazines *(34)* with the dyes *(36)–(39)* give maximum yields at dye/bridge component ratios as low as about 2:1 to 3:2 (cf. Figure 2). It is therefore possible in practice to work with a constant dye/bridge component ratio of about 2:1.

In the case of very dilute dye solutions (less than about 10 g/l), the concentration of bridge component should not be less than 6–10 g/l, to compensate for hydrolysis. The color yields then are unusually high.

The reaction time required for maximum yield depends, as with reactive dyes, on the application method (printing, dyeing), the nature of the heat supply (steaming, dry heat, contact heating [*]), the temperature, and the presence of additives (*e.g.* urea) (cf. Table 2). Many dyes

Table 2. Approximate reaction times for the linkage of bridge component, substrate, and dye.

Steaming at:		Dry heat at:	
102 °C	110 °C	150 °C	190 °C
3 min	45 sec	3 min	1 min

and bridge components give high color yields after steaming at 100 to 110 °C for only 30 to 60 sec. Such dyes can be applied by the technically important shortfixing process, in which the textile is passed through special steaming equipment (*e.g.* arch steamers) with residence times of only about 60 sec.

The reaction can even be carried out at room temperature, *e.g.* with the dye *(39a)*, by impregnating the substrate (*e.g.* cotton) with an alkaline solution of the dye, bridge component, and neutral salts, and by storing it in the wet state for 15 hours.

Thus it is possible, with the aid of the bridge components described, to form very fast homopolar bonds between cellulose and dyes containing nucleophilic groups. Good results have already been obtained using the new series of ®Basazol dyes [69]. The separate handling of the dye and the bridge component offers advantages over the use of reactive dyes, particularly in printing and impregnating processes.

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Translated by Express Translation Service, London

[68] *G. Lange, G. Krehbiel, F. Kohler*, and *H. J. Grasshoff*, German Published Patent Application 1153839 (June 11th, 1959), BASF.

[*] In "dry heating", the cellulose is heated in an air bath, while in "contact heating" it is passed over hot metal drums.

[69] *G. Meyer*, Textil-Praxis *18*, 767 (1963).

Metal Chelates as Polymerization Initiators

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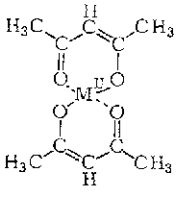
Metal chelates can be used as initiators in the polymerization of vinyl compounds. Their action, as shown here for the polymerization of styrene, is determined by both the central atom and the ligand. Chelates of manganese(III) and cobalt(III) with 1,3-dicarbonyl compounds are most effective. The metal chelate initiators can be activated by γ- or ultraviolet irradiation, or else by combination with cocatalysts such as organic halogen compounds or unsaturated hydrocarbons which are typical π-complex formers. There is some evidence indicating that the polymerization takes place via a free-radical mechanism. The central metal atom affects the steric configuration of the polymer chain.

Metal chelates have long been known and are relatively easy to prepare [1]. As far as polymers are concerned, some metal chelates, *e.g.* those of cobalt, manganese, and copper, have been known to promote the air-hardening of lacquers and varnish resins (siccatives). When combined with metal alkyls, the acetylacetonates of titanium, vanadium, or cobalt form Ziegler-Natta catalysts for the polymerization of olefins. Moreover, metal chelates promote the polyaddition of organic isocyanates [2]. Their solubility in organic liquids makes them particularly useful.

Polyethylene was unexpectedly obtained by using acetylacetonates *(1)* of Group VIII metals as catalysts in the cyclooligomerization of ethylene. This result gave the impetus for an investigation of the initiation of vinyl



(1)

polymerization by metal chelates. Since both the central atom and the ligand may be varied, the number of metal chelates available is almost unlimited.

1. Efficiency of Metal Chelates as Polymerization Initiators

The initiating efficiency as a function of the central atom and of the ligand was investigated in the case of the polymerization of styrene. Unstabilized styrene was heated for 1 hour with 0.5 % by weight of the metal chelate in an atmosphere of nitrogen, and the conversion into polystyrene was determined.

a) Effect of the Central Atom

As shown by Fig. 1 and Table 1, of all the metal acetylacetonates examined, those containing metals of Groups VII and VIII gave the highest yields of polystyrene, the complexes of manganese(III) and cobalt(III) being particularly effective. The rate of polymerization with manganese(III) acetylacetonate is comparable to that obtained by using di-t-butyl peroxide as an initiator (cf. Fig. 1). In the case of metals which can exist in more than one valence state, the chelate containing the metal in the higher valence state is always more active. Among the less active metal acetylacetonates, which are listed in

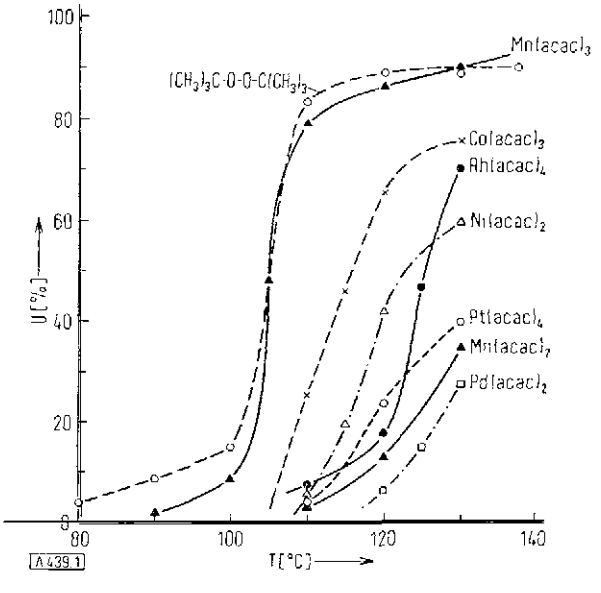


Fig. 1. Polymerization of styrene using metal acetylacetonates as initiators. The percentage of conversion U as a function of the temperature T. acac = Acetylacetonyl. (Duration of polymerization 1 hour, initiator concentration 0.5 % by weight.)

[1] *F. Gach*, Mh. Chem. *21*, 89 (1900).

[2] Brit. Pat. 886636 (Sept. 2nd, 1959), inventors: *D. M. O'Mant* and *H. J. Twitcheff*, Imperial Chemical Industries.

Table 1, only those containing ruthenium(III) and iron(III) still exhibit considerable catalytic activity. The conversions effected by the other metal acetylacetonates lie within the limits of error of the thermally initiated polymerization of styrene.

Table 1. Polymerization of styrene using metal acetylacetonates. (Duration of polymerization 1 hour, initiator concentration 0.5 % by weight.)

Polymerization with	Conversion [%]	
	at 120 °C	at 130 °C
$Ru(acac)_3$ [*]	19	30.5
$Fe(acac)_3$	16	27.2
$Co(acac)_2$	5.2	21.0
$U(acac)_4$	6.1	16
$Pb(acac)_4$	6.3	15.6
$Zr(acac)_4$	3	17
$Ce(acac)_4$	9	11.5
$Th(acac)_4$	8	11
$Zn(acac)_2$	5.8	14.8
thermal initiation alone	8.1	15.2

[*] acac = Acetylacetonyl.

b) Effect of the Ligands

Figure 2 shows that the chelates of manganese(III) with 1,3-dicarbonyl and aminocarboxylic compounds are the most effective. Even the manganese(III) complexes that are not chelates have a slight initiating effect. Under the same conditions, the polymerization of styrene by thermal initiation alone proceeds at a rate several times slower (cf. the last line in Table 1).

The initiator activity of the metal chelates of 1,3-dicarbonyl compounds steadily increases from the dibenzoylmethane complex to the ethyl acetoacetate complex

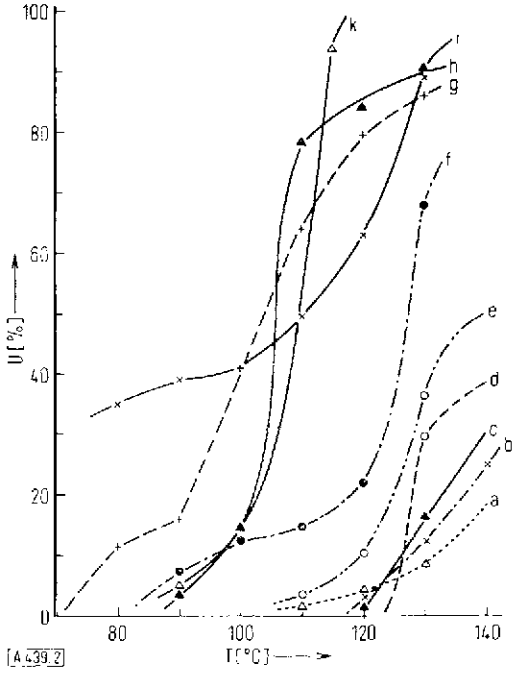


Fig. 2. Polymerization of styrene using manganese chelates as initiators. The percentage of conversion U as a function of the temperature T. (Duration of polymerization 1 hour, initiator concentration 0.5 % by weight.)

a: K_2MnCl_5; b: $K_3Mn(CN)_6$; c: Mn(III) oxalate; d: Mn(II) oxinate; e: Mn(II) acetylacetonate; f: Mn(III) *N*-hydroxymethylcaprolactam; g: Mn(III) anthranilate; h: Mn(III) acetylacetonate; i: Mn(III) 3-methylbut-1-en-3-yl acetoacetate enoxide; k: Mn(III) glycinate.

(Fig. 3). However, the stability constants of the complexes decrease in the same order, as shown by *Calvin* and *Wilson* [3,4] for copper(II) chelates. Obviously there is a connection between the stability of the complexes and their initiating action. A similar connection has been found in the case of the 1,3-dicarbonyl chelates of cobalt(III) and copper(II).

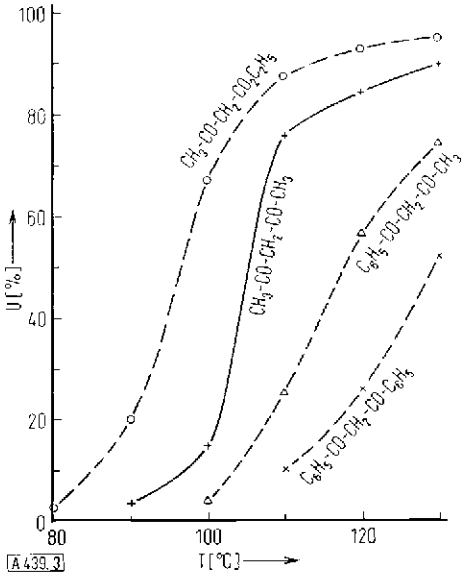


Fig. 3. Polymerization of styrene initiated by the manganese(III) chelates of various 1,3-dicarbonyl compounds. (Duration of polymerization 1 hour, initiator concentration 0.5 % by weight.)

Metal chelates of 3-methylbut-1-en-3-yl acetoacetate are even more active than those of ethyl acetoacetate; manganese(III) chelates of 3-methylbut-1-en-3-yl acetoacetate, for example, give a conversion of about 30% at 70–80 °C (Fig. 2).

When the ethyl residue in ethyl acetoacetate is replaced by the 3-methylbut-1-en-3-yl residue, the contribution of the carbonyl group to the resonance of the ester group increases, while the resonance in the chelate ring decreases. This leads to a further destabilization of these chelates, but stability constants are still unknown.

2. Activation of the Metal Chelate Initiators

A disadvantage of polymerization by metal chelates is that relatively high temperatures must be employed. We have therefore tried to activate the metal chelate initiators by irradiation and by additives.

a) Activation by Irradiation

The crystalline metal chelates were exposed to ultraviolet light or to γ-rays in the absence of air, and were then used immediately to initiate the polymerization of styrene. For the ultraviolet irradiation (60 minutes) a mercury vapor quartz lamp (Quarzlampen-Gesellschaft, Hanau, Model S 80) was used and for the γ-irradiation a ^{60}Co

[3] *M. Calvin* and *K. W. Wilson*, J. Amer. chem. Soc. *67*, 2003 (1945).

[4] *A. E. Martell* and *M. Calvin*: Die Chemie der Metallchelat-Verbindungen. Verlag Chemie, Weinheim/Bergstr. 1958, pp. 140, 150.

source (doses 10^2 to 10^6 r). On γ-irradiation the activity of the initiator increased as the doses were raised to about 10^3 r, after which it remained practically constant up to doses of 10^6 r. Figure 4 shows the activation obtained by irradiation of manganese(III) acetylacetonate. In the polymerization of styrene, the temperature at which the reaction begins is appreciably reduced (by about 20 °C) only by γ-irradiation of the initiator. Ultraviolet irradiation results in only very slight activation.

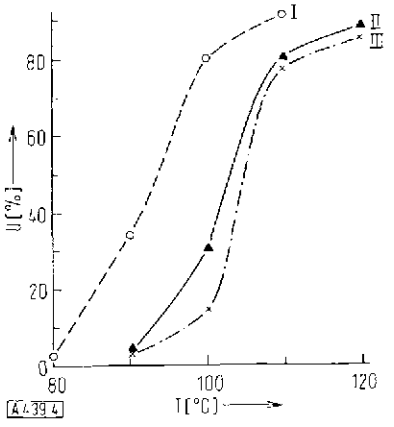


Fig. 4. Polymerization of styrene initiated by irradiated manganese(III) acetylacetonate. (Duration of polymerization 1 hour, initiator concentration 0.5 % by weight.)

Curve I: activation with γ-rays of 10^3 r.
Curve II: activation with ultraviolet light (Hg vapor lamp, 60 minutes).
Curve III: unirradiated reference sample.

b) Chemical Activation

The greatest increase in activity is reached by the addition of organic balogen compounds, such as hexachloroethane, carbon tetrachloride, chloroform, n-butyl chloride, or n-amyl chloride (see Tables 2 and 3), or of unsaturated hydrocarbons, *e.g.* 1,5-cyclooctadiene, 1,3-cyclooctadiene, 1,5,9-cyclododecatriene, or cycloheptatriene, which are typical π-complex formers [5]. *Teyssié* and *Dauby* [6] have recently shown that the emulsion polymerization of butadiene, initiated by rhodium(III) chloride, is also accelerated by the addition of 1,3-cyclobexadiene. A smaller increase in activity results from the use of the halides of aluminum, magnesium, and zinc, as well as from the addition of ketones, amines, phosphites, or carbon disulfide (see Table 3).

Table 2. Activation of manganese(III) acetylacetonate for the polymerization of styrene at 100 °C. (Duration of polymerization 1 hour, initiator concentration 0.5 % by weight, activator concentration 0.5 % by weight.)

Activator	Conversion [%]
Trichloroethylene	41
Chlorobenzene	42
Bromobenzene	51.5
Trichlorobenzene	52
2-Phenyl-4,6-dichlorotriazine	54
Dibromoethane	56.5
Cyanuric chloride	61
Bromoform	70.3
1,4-Di(chloromethyl)benzene	72.5
α-Bromo-ε-benzoylaminocaproic acid	74
Dibromomalonylguanidine	79
2-Amino-5-iodopyrimidine	80.5
Carbon tetrachloride	83
Chloroform	84.5
Hexachloroethane	85.5
n-Butyl chloride	87
n-Amyl chloride	92.5
Cyclopentadiene	49.5
Cycloheptatriene	58
Cyclohexadiene	56
1,3 Cyclooctadiene	63
Cyclooctatetraene	37.5
1,5,9-Cyclododecatriene	44
Zinc chloride	38.5
Magnesium chloride	46
No activator	9

Table 3. Increase in the initiator efficiency of manganese(III) acetylacetonate caused by activating additives. (Duration of polymerization 1 hour, initiator concentration 0.5 % by weight, activator concentration 0.5 % by weight.)

Activator	Conversion [%]
n-Amyl chloride	92.5
γ-Irradiation	80
1,3-Cyclooctadiene	63
Triphenylphosphine	60
Triphenylphosphite	40
Sodium hypophosphite	30
Benzil	20
No activator	9

The best activation is achieved with an approximately equimolar mixture of the metal chelate and the activator. The effects of various methods of activation on the rate of polymerization are compared in Table 3, the data being based on the polymerization of styrene with manganese(III) acetylacetonate.

Both in the presence and in the absence of an activator, the rate of polymerization is proportional to the square root of the initiator concentration (Fig. 5).

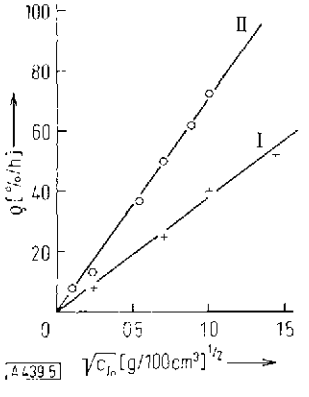


Fig. 5. Rate of the polymerization (ρ) of styrene at 110 °C as a function of the concentration of the metal chelate (c_{In}).

Curve I: non-activated cobalt(III) acetylacetonate as the initiator;
Curve II: cobalt(III) acetylacetonate activated by carbon tetrachloride, the ratio of initiator: activator being 1:1 by weight.

The polymerizations of acrylic esters, methacrylic esters, vinyl esters, ethylene, and butadiene can also be initiated by metal chelates, the results being similar to those obtained with styrene.

[5] German Pat. 1176864 (Oct. 9th, 1962), inventors: *H. Naarmann* and *E. G. Kastning*, BASF.

[6] *Ph. Teyssié* and *R. Dauby*, Polymer Letters *2*, 413 (1964).

3. Homo- and Copolymerization of Some Monomers

a) Homopolymerization of Olefins

Ethylene is converted into high-molecular weight polymers, when it is polymerized with metal chelates under a pressure of more than 300 atm and at temperatures above 80 °C. The results obtained with different chelates are reproduced in Table 4. The 1,3-dicarbonyl complexes of trivalent manganese and cobalt are again distinguished by high activity, which is further increased by activating additives. The number of CH_3 groups per 1000 carbon atoms of the polymer (Column 3 of Table 4) lies between 5 and 30, and the density varies between 0.928 and 0.958 g/cm³. Polyethylenes containing 10 to 20 methyl groups per 1000 carbon atoms and having densities between 0.94 and 0.95 g/cm³ can be prepared with particular ease.

Table 4. Polymerization of ethylene with metal chelates (duration 1 hour). The experiments at 1500 atm (upper part of the table) were carried out in a 300-ml autoclave at 145 °C with 0.1 g of initiator in 50 ml of n-hexane, and the experiments at 600 atm (lower part of the table) were carried out in a 50-l container at 125 °C with 4 g of initiator in 20 l petroleum ether.

Initiator	Yield [g of polymer/g of initiator]	CH_3/1000 C	Density [g/cm³]	K-value [7] (0.1 % in decalin)
Co(III)-acac [*]	220	12	0.950	92
Co(III)-benzac [**]	180	13	0.949	87.5
Co(II)-acac	175	12	0.950	90.5
Co(II)-benzac	150	12	0.950	86.5
Mo(III)-acac	280	10	0.952	94
V(III)-acac	275	11	0.953	82
Cr(III)-acac	20	28	0.928	97
Ni(II)-benzac	48	21	0.940	88
W(III)-acac	160	18	0.943	79.5
Co(III)-acac + CCl_4 (1:1)	1630	5	0.958	95
Co(III)-acac + $N(C_2H_5)_3$ (1:1)	400	8	0.956	94
Co(III)-acac + $P(C_6H_5)_3$ (1:1)	580	10	0.951	99.5
Co(III)-acac + Fe(III) butoxide (1:1)	630	6	0.956	89
Co(III)-acac + Co(II)-acac(1:1)	1140	6	0.956	96
Co(III)-acac	1125	15	0.943	85.5
Co(III)-acac + CCl_4 (1:1)	2060	11	0.951	90.5
Mn(III)-acac	1340	20	0.940	88
Mn(III)-acac + CCl_4 (1:1)	1850	18	0.942	92.5

[*] acac = Acetylacetonyl.
[**] benzac = Benzoylacetonyl.

b) Homopolymerization of Diolefins

The polymerizations of butadiene and isoprene initiated by metal chelates lead to particularly interesting polymers. Soluble, high-molecular polybutadiene is obtained by solution polymerization of butadiene. Depending on the central atom of the chelate, the product has up to 60 % of 1,4-*cis* and about 10 % of 1,2-vinyl configuration. The highest *cis* yield is reached with manganese(III) chelates, while cobalt(III) chelates and copper(II) chelates result in about 50 % and about 30 % of 1,4-*cis* yield, respectively. These polybutadienes differ substantially from those obtained with rhodium(III) salts [8,9], the latter leading to over 90 % of the 1,4-*trans* configuration.

The emulsion polymerization of butadiene proceeds at a considerably higher rate, at a lower temperature, and gives a higher conversion than the solution polymerization. The resulting high-molecular weight polymers are free from gels, and their steric compositition is similar to that of the polymers obtained in solution. In contrast to the solution polymerization which requires a temperature of 80 to 100 °C, the emulsion polymerization is carried out between 30 and 60 °C and in the presence of the usual emulsifiers. Chelates activated by halogen compounds are particularly suitable initiators. Butadiene is polymerized, as in the well-known SBR process [*], with a conversion of about 60 %. The K-values [7] of the products lie between 80 and 100. They increase with the conversion, reaching their final values at a conversion of about 60 %. The use of peroxide initiators in the emulsion polymerization of butadien under similar conditions leads to a polybutadiene with an appreciable gel fraction [9a], the product being sterically completely different (cf. Table 5) and unsuitable for use as raw material in the manufacture of rubber.

Table 5. Emulsion polymerization of butadiene at 50 °C, activated by carbon tetrachloride. The configuration was determined by infrared spectroscopy [9b].

Initiator	K-value (1 % in benzene)	Yield of 1,4-*cis* product [%]	Yield of 1,4-*trans* product [%]	Yield of 1,2-vinyl product [%]
Mn(III) acetylacetonate	91	55	38	7
Co(III) acetylacetonate	89.5	45	41	14
Cu(II) acetylacetonate	80.5	32	52	16
Peroxide	insol.	13	65	22

The technological characteristics of rubber (Mooney plasticity, "defo" value) [9c] can be adjusted within wide limits by varying the conditions of the polymerization (initiator concentration, type and amount of activator, regulator, and the conversion of butadiene). As regards its mechanical properties, polybutadiene rubber prepared with metal chelates is similar to the commercial SBR copolymers made of about 75 % of butadiene and 25 % of styrene. The behavior of the homobutadienes at low temperatures is, however, far superior, because their glass temperature [9d] is lower by about 30 °C than those of the copolymers.

[7] The K-value equals 10^3 k, when k is defined by *Fikentscher*'s viscosity equation:
$\log z = c\,[k + 75\,k^2/(1 + 1.5\,kc)]$
where z = relative viscosity; c = concentration of polymer [g/100 cm³]; k = constant. – *H. Fikentscher*, Cellulosechemie *13*, 58 (1932).

[8] *R. E. Rinehart, H. P. Smith, H. S. Witt*, and *H. Romeyn*, J. Amer. chem. Soc. *83*, 4864 (1961); *84*, 4145 (1962).

[9] *A. J. Canale, W. A. Hewett, T. M. Shryne*, and *A. E. Youngman*, Chem. and Ind. *1962*, 1054.

[*] Styrene-butadiene rubber.

[9a] "Gel fraction" is the polymer fraction which does not dissolve in benzene at 25 °C.

[9b] *H. Günzler* and *G. Schnell*, BASF.

[9c] For an explanation of these parameters, see *S. Boström*: Kautschuk-Handbuch. Berliner Union, Stuttgart 1962, Vol. 5, pp. 84–86.

[9d] The glass temperature is the temperature of transition from the liquid or elastic state to the glass-like state of the polymer.

In conclusion it can be stated that the polybutadienes obtained with metal chelates differ from both the SBR products and the sterically uniform polybutadienes prepared with the aid of organometallic initiators.

c) Copolymerization

Some monomeric vinyl compounds can be copolymerized using metal chelates even when the conventional radical initiators fail or present difficulties. For example, heating (80 °C) of a mixture of equal parts by weight of styrene and vinyl acetate in the presence of manganese(III) acetylacetonate yields a styrene-vinyl acetate copolymer containing 28 % by weight of vinyl acetate. Ethylene and styrene can be copolymerized at a temperature of 100 to 150 °C and an ethylene pressure of 1000 to 1600 atm.

Homogeneous copolymers are obtained when the amount of styrene is between 1.5 and 15 % by weight, or over 90 % by weight. Mixtures of polymers are formed in the intermediate region. The crystallinity of the copolymers with a predominant ethylene fraction depends on their styrene content.

The products whose styrene content predominates are transparent, but have lower softening points than polystyrene. Both the transparency and the temperature dependence of the mechanical shear modulus and of the mechanical loss modulus derived from the former [10] indicate homogeneous copolymers (cf. Figures 6a and 6b).

The presence of ethylene reduces the damping maximum from about 105 to about 80 °C, and correspondingly, the decrease in the shear modulus begins at a temperature about 25 °C lower. Moreover, the maximum which can be attributed to the beginning of rotation of longer CH_2-sequences and which is known from polyethylene occurs at −150 °C.

Vinyl ether, which does not homopolymerize with metal chelates, can be copolymerized with ethylene up to about 30 % by weight (see Table 6).

Table 6. Data relating to the copolymerization of ethylene and vinyl ether. (Duration of polymerization 1 hour, initiator 0.3 % by weight of manganese(III) acetylacetonate + 0.3 % by weight of chloroform.)

	p [atm]	T [°C]	Yield [g of polymer/g of initiator]	Vinyl ether units [%]
15 g Vinyl methyl ether	1570	128	970	1.5
40 g Vinyl ethyl ether	1500	150	400	10
100 g Vinyl ethyl ether	1510	150	295	33
50 g Vinyl n-butyl ether	1480	150	392	12.5

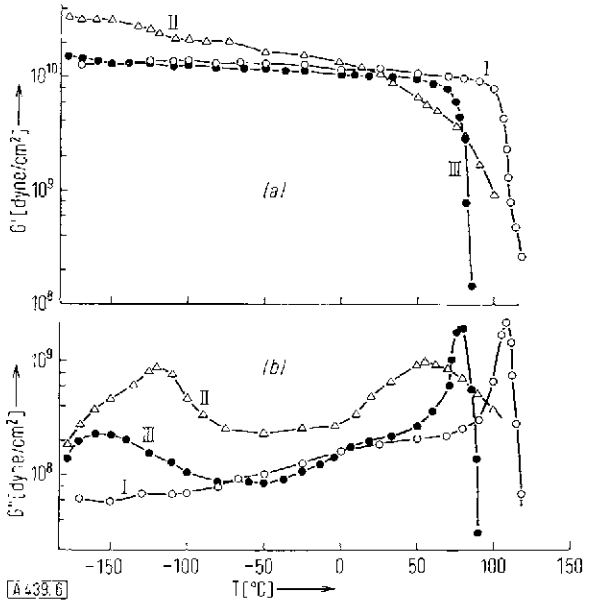


Fig. 6. Temperature dependence of the mechanical shear modulus G' (a) and the mechanical loss modulus G'' (b) obtained from torsional stress data using a frequency of 1 cps [**].

Curve I: polystyrene;
Curve II: polyethylene;
Curve III: copolymer made from 94 % by weight of styrene and 6 % by weight of ethylene.

[10] *K. H. Illers* and *H. Breuer*, Kolloid-Z. *176*, 110 (1961).

[**] Determined by *K. H. Illers*, BASF, Hauptlaboratorium.

4. Discussion

The mechanism of "vinyl polymerization" initiated by metal chelates has not yet been established beyond doubt. However, numerous observations point to a free-radical mechanism: for example, the copolymerization of equimolecular mixtures of styrene and methyl methacrylate results in copolymers whose composition is the same as that of the monomer mixture. *Walling* [11] believes that this indicates a free-radical mechanism and rules out an ionic one. A purely ionic mechanism is also disproved by the fact that the polymerization proceeds in an aqueous medium at a considerably higher rate, although the initiators dissolve preferentially in the organic phase.

Bamford [12] points out that polar vinyl compounds polymerize *via* a free-radical mechanism when mixed with metal carbonyl compounds containing formally zerovalent metals and with organic polyhalogen compounds. In the course of this polymerization, a halogen atom is cleaved off the halogen compound, accompanied by the oxidation of the metal atom, thus giving rise to an initiating halogenalkyl radical. The liberation of the halogen can also be effected by copper(I) acetylacetonate, or a finely divided metal. No change in the valence state of the central metal atom has however been established in the chelate-initiated vinyl polymerizations described here. Valence change occurs only when the polymerization temperature exceeds the decomposition temperature of the metal chelate, and a lower valence state is then formed, as for example in the case of cobalt(III) chelates at about 150 °C. After the valence state has changed, the rate of polymerization decreases to the value which would be obtained with the chelate containing the metal in the lower valence state.

It has been established by infrared spectroscopy and by labelling the ligands with ^{14}C that the ligand combines with the polymer. Although no statement can be inferred

[11] *C. Walling, E. R. Briggs, W. Cummings*, and *F. R. Mayo*, J. Amer. chem. Soc. *72*, 48 (1950).

[12] *C. H. Bamford, M. S. Blackie*, and *C. A. Finch*, Chem. and Ind. *1962*, 1763.

from this fact as to the mechanism, the observation is nevertheless compatible with the assumption that the polymerization might be initiated by free radicals originating from the ligands.

It must however be mentioned that the polymers prepared with the aid of metal chelates differ sterically in many respects from those obtained by the use of free-radical initiators, such as peroxides and azo compounds (cf. the steric differences in polybutadiene shown in Table 5). Poly(methyl methacrylate) polymerized with metal chelates is substantially isotactic and has a glass temperature of 78 °C. In contrast, poly(methyl methacrylate) prepared by peroxide-initiated polymerization has a predominantly syndiotactic structure and a glass temperature of 98 °C.

The steric structure of the polymers has been shown to be independent of both the ligands and the activating additives, which affect only the rate of the polymerization, *i.e.* the rate of initiation. Only the central metal atom of the chelate can therefore be responsible for the steric structure of the polymers [13]. Similar observations have been reported by *Bamford* [12]. Metal ions were also described by *H. P. Smith* [14] as influencing the steric structure of polybutadiene in peroxide-initiated free-radical polymerizations

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[13] German Published Patent Application 1180522 (Sept. 25th, 1962), inventors: *E. G. Kastning, H. Naarmann, C. Berding*, and *H. Reis*, BASF.

[14] German Published Patent Application 1164669 (Oct. 31st, 1962), inventor: *H. P. Smith*, U.S. Rubber Comp.

Recent Results in the Catalytic Oligomerization and Co-oligomerization of Butadiene

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A number of new catalyst systems based on transition-metal compounds have been developed for the oligomerization and co-oligomerization of butadiene. These catalysts promote dienylations and the formation of other C–C linkages, and make possible the synthesis of new open-chain and cyclic compounds from butadiene.

I. Introduction

As a result of investigations on the thermal oligomerization of butadiene, a number of cyclic hydrocarbons which are difficult to obtain by other methods, such as 1-vinyl-3-cyclohexene, 1,5-cyclooctadiene, and *trans*-1,2-divinylcyclobutane, can now be easily prepared [1]. These products are accompanied, according to *Reed*, by small quantities of n-1,3,7-octatriene, formed by open-chain linkage of two butadiene molecules. Although the cyclic hydrocarbons are formed from butadiene in a remarkably simple manner, the reaction conditions and the yields make the thermal oligomerization unsuitable for large-scale syntheses. However, various groups of workers have recently discovered catalysts which permit the highly selective oligomerization of butadiene under simpler conditions. Our work in this field is reported in the present paper.

II. The Dimerization of Butadiene

a) Cyclodimerization to 1,5-Cyclooctadiene

The dimerization of butadiene to cyclooctadiene in the presence of nickel catalysts was first described briefly by *Foster* [2]. Shortly afterwards, *Reed* [3] dimerized butadiene with the catalysts used by *Reppe* et al. [4] for the cyclization of acetylene. 1,5-Cyclooctadiene was obtained in 30–40 % yields when nickel carbonyl phosphines and nickel carbonyl phosphites were used. *Reed* also found that the activity of the catalysts was increased by addition of acetylene, and

[1] *S. Lebedev* and *S. Sergyenko*, Dokl. Akad. Nauk U.S.S.R. *1935*, No. III; Chem. Zbl. *1936*, II, 59; *K. Ziegler* and *H. Wilms*, Angew. Chem. *59*, 177 (1947); *K. Ziegler* and *H. Wilms*, Liebigs Ann. Chem. *567*, 1 (1950); *R. E. Foster* and *R. S. Schreiber*, J. Amer. chem. Soc. *70*, 2303 (1948); *H. W. B. Reed*, J. chem. Soc. (London) *1951*, 685.

[2] U.S.-Patent 2504016 (1947/50), Du Pont, inventor: *R. E. Foster*.

[3] *H. W. B. Reed*, J. chem. Soc. (London) *1954*, 1931.

[4] *W. Reppe* and *W. J. Schweckendick*, Liebigs Ann. Chem. *560*, 104 (1948).

that co-oligomers of butadiene and acetylene were formed as by-products. Investigations described in a series of patents [5] were primarily concerned with the activation of Reppe catalysts by unsaturated hydrocarbons. *Reed* had suspected that the true catalyst was formed by displacement of carbon monoxide from the nickel carbonyl complexes by olefins or acetylene, since his experiments had shown nickel carbonyl itself to be catalytically inactive. *Wilke* [6, 7] finally succeded in showing that nickel catalysts containing no carbonyl groups are indeed the most active, and that the catalysts are poisoned by carbon monoxide. He used complexes of nickel(0), which he obtained by reduction of nickel salts with metal alkyls in the presence of electron donors, and which enabled him to carry out selective syntheses of cyclooctadiene or cyclododecatriene [8].

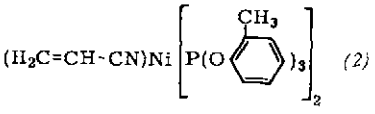
Despite previous failures and assumptions, we attempted to use nickel carbonyl as catalyst. If the displacement of carbon monoxide from nickel carbonyl by butadiene leads to an equilibrium, a sufficiently large excess of olefin and removal of the carbon monoxide formed should displace the equilibrium to such an extent as to lead ultimately to the formation of an active catalyst.

We found that nickel carbonyl dissolved in 1,5-cyclooctadiene rapidly loses up to two molecules of carbon monoxide at 100 °C, presumably with formation of cyclooctadienenickel(0) dicarbonyl. This complex is unstable and is catalytically inactive. Attempts to replace further carbonyl groups with 1,5-cyclooctadiene lead to rapid decomposition of the complex with separation of nickel. However, the complex can react in dilute solutions with excess butadiene if the carbon monoxide liberated is removed from the system. The product of this reaction is a catalyst solution which is suitable for oligomerization of butadiene [9].

During the synthesis of cyclic oligomers of butadiene by a continuous process with nickel carbonyl as catalyst, excess cyclooctadiene and butadiene are present in the reaction vessel. If nickel carbonyl is now introduced continuously, its carbonyl groups are displaced as described above, provided the carbon monoxide liberated is also removed continuously. If the process is discontinuous, it is necessary to generate the catalyst in a separate step. In a continuous synthesis in a pilot-plant, we have succeeded in oligomerizing about 800 kg of butadiene per mole of nickel carbonyl. Here 85–90% of the butadiene was cyclized to 1,5-cyclooctadiene and *trans*, *trans*,*trans*-1,5,9-cyclododecatriene. 1-Vinyl-3-cyclohexene and higher oligomers of butadiene are formed as by-products. The ratio of the two ring systems in the product depends on the conditions of the reaction. The formation of cyclododecatriene is favored by an increase in the butadiene concentration, the formation of cyclooctadiene by an increase in temperature. The product is exclusively the cyclodimer if phosphines or phosphites are introduced into the system as cocatalysts together with the nickel carbonyl [10]. The best results have been achieved with triaryl phosphites containing *o*-substituted rings [11]. These compounds give high reaction rates and result in extremely high selectivity. For example, with a butadiene pressure of 3.5 atm at 100 °C, a catalyst system containing nickel carbonyl and tri-*o*-tolyl phosphite as cocatalyst gives 90% 1,5-cyclooctadiene with a conversion of 1000 kg of butadiene per mole of nickel carbonyl. Another very active cyclodimerization catalyst containing no carbonyl groups can be prepared as follows: Nickel carbonyl is first treated with acrylonitrile to form bisacrylonitrilenickel(0) *(1)* as described by *Schrauzer* [12].

$$Ni(H_2C{=}CH{-}CN)_2 \quad (1)$$

The complex is then allowed to react further with tri-*o*-tolyl phosphite (or another phosphite or phosphine) to form acrylonitrilenickel(0) bis(tri-*o*-tolyl phosphite) *(2)*



(2)

It is immaterial to the dimerization whether the complex *(2)* is prepared in advance, or whether it is formed in a solvent, *e.g.* cyclooctadiene, by mixing the reagents. In pilot-plant experiments, 600 kg of butadiene per mole of the complex were converted into cyclooctadiene in 90% yield.

Catalysts for the synthesis of cyclooctadiene other than highly toxic nickel carbonyl and dangerous aluminum alkyls include complexes obtained by treating soluble nickel chelates with molten or finely divided metals of Groups I–III in the presence of phosphines or phosphites in cyclooctadiene as solvent [13]. This reaction is favored by the presence of tertiary alcohols and butadiene. Catalysts made with one mole of nickel acetylacetonate and containing tri-*o*-tolyl phosphite as complexing ligand converted 200 kg of butadiene per hour at 100–110 °C and a butadiene pressure of 3.5 atm. The yield of cyclooctadiene was 93%, based on the reacted butadiene.

b) Oligomerization to Open-Chain Dimers

As mentioned above, *Reed* believed that one of the fractions isolated from the products of thermal dimerization of butadiene contained 1,3,7-octatriene [14], *i.e.* a product formed by open-chain oligomerization of butadiene. *Wilke* then succeeded in carrying out the first open-chain oligomerization of dimethylbutadiene and isoprene using Ziegler catalysts containing titanium and

[5] For example, U.S.-Patent 2964575 (1959/60), Cities Service Research and Development Co., inventors: *A. A. Sekul* and *H. G. Sellers*.

[6] *G. Wilke*, Angew. Chem. *75*, 10 (1963); Angew. Chem. internat. Edit. *2*, 105 (1963).

[7] Austrian Patent 219580 (1959/61), Studiengesellschaft Kohle mbH., Mülheim/Ruhr.

[8] Belgian Patent 598363 (1959/60), Studiengesellschaft Kohle mbH., Mülheim/Ruhr.

[9] Belgian Patent 641663 (1962/63), BASF, inventors: *H. Muller*, *D. Wittenberg*, and *E. Scharf*.

[10] Patent applied for by BASF.

[11] German Published Patent Application 1144268 (1960), BASF, inventors: *N. von Kutepow*, *H. Seibt*, and *F. Meier*.

[12] *G. N. Schrauzer*, J. Amer. chem. Soc. *81*, 5310 (1959).

[13] German Published Patent Application 1126864 (1960), BASF, inventor: *H. Müller*.

[14] *H. W. B. Reed*, J. chem. Soc. (London) *1951*, 685.

chromium [15-17], and later dimerized butadiene to 3-methyl-1,4,6-heptatriene in the presence of cobalt or preferably iron catalysts. The yields obtained were still too low to make the process industrially attractive.

During our work on the dimerization of butadiene, we found two methods of linking two molecules of butadiene together to give good yields of open-chain products at high reaction rates. The principal products are n-octatrienes [18] or 3-methyl-1,4,6-heptatriene [19,19a], depending on the catalyst system used.

The n-octatrienes can be synthesized with the nickel catalysts used for the cyclodimerization, *i.e.* containing nickel(0) and electron donors as ligands. Surprisingly, in the presence of alcohols, these catalysts no longer bring about cyclization but effect open-chain linkage of two butadiene molecules. Examples of suitable dimerization initiators are the nickel carbonyl phosphites, nickel carbonyl phosphines, and above all the nickel complexes, *e.g. (2)*, prepared as described above from bisacrylonitrilenickel(0) and phosphites. For simplicity, the complexes are not used in pure form. Instead, the bisacrylonitrilenickel(0) and the phosphorus compound are introduced together into the alcohol which is to be used as the solvent.

The principal products are isomeric n-octatrienes; of these *trans*-n-1,3,7-octatriene, *cis,trans*-n-1,3,6-octatriene, and *trans,trans,trans*-n-2,4,6-octatriene have been isolated and identified. 3-Methyl-1,4,6-heptatriene and 1,5-cyclooctadiene are also formed in small amounts, together with more or less large quantities (depending on the reaction conditions) of branched and unbranched dodecatetraenes and higher oligomers of butadiene. Preparatively interesting quantities of a new five-membered cyclic dimer of butadiene have also been isolated. Chemical analysis and infrared and nuclear resonance spectra of this compound show that it is 1-vinyl-3-methylcyclopentane *(3)*.

(3)

In total, the yields of distillable oligomers were up to 90%.

Which of the hydrocarbons predominates, depends essentially on the complexing ligand of the catalyst. Thus, when the ligand is triethyl phosphite, tributylphosphine, or phosphorus trimorpholide, the principal products are 1,3,6-octatriene, 1,3,7-octatriene, and 2,4,6-octatriene, respectively.

A mixture of open-chain oligomers of butadiene was also obtained in high yield in a rapid reaction by the action of cobalt(0) catalysts on butadiene at 50–100 °C. Similar results have recently been reported by Japanese authors [20,21].

Our catalysts were obtained by reduction of cobalt salts in organic solvents in the presence of butadiene. Suitable reducing agents include organometallic compounds, metals, and metal hydrides. The reactions yield brown solutions which presumably contain cobalt(0) complexed with butadiene. The action of butadiene on these solutions gives rise to oligomers: dimers, trimers, and tetramers can be separated by fractional distillation. The new oligomers have the composition $(C_4H_6)_n$ and contain n + 1 double bonds. They are therefore open-chain compounds. Two of the double bonds are conjugated. The dimeric fraction consists of about 90% 3-methyl-1,4,6-heptatriene *(4)* and 10% 1,3,6-octatriene *(5)*, which are formed by 1,2- and 1,4-addition, respectively, of two butadiene molecules:

$$\begin{array}{l} H_2C{=}CH{-}CH{=}CH{-}\underset{\displaystyle CH_3}{CH}{-}CH{=}CH_2 \quad (4) \\ \uparrow \\ H_2C{=}CH{-}CH{=}CH_2 + H_2C{=}CH{-}CH{=}CH_2 \\ \downarrow \\ H_2C{=}CH{-}CH{=}CH{-}CH_2{-}CH{=}CH{-}CH_3 \quad (5) \end{array}$$

The dimers have a 1,3-diene structure. It is therefore not surprising that the reaction does not stop at this stage but proceeds further by the scheme indicated to yield trimers, tetramers, and higher oligomers. If a given amount of butadiene is allowed to react with a constant quantity of catalyst for various times, it can be demonstrated that the oligomers are built up in steps. As the conversion increases, the yield of dimers decreases, while the yield of higher oligomers increases (see Table 1).

Table 1. Yields at various conversions during the oligomerization of butadiene with cobalt catalysts.

Butadiene conversion [%]	30	50	60	90
Yield of dimers [%]	90	78	72	16
Yield of trimers and tetramers [%]	8	15	16	45
Yield of higher oligomers [%]	2	7	12	39

The character of the catalysts described above changes completely when phosphorus compounds such as tri-*o*-tolyl phosphite are added as cocatalysts. The principal products are then 1,5-cyclooctadiene and 1-vinyl-3-cyclohexene [22]; open-chain oligomers are formed only in traces.

III. Trimerization of Butadiene

In 1956 *Wilke* [23] discovered that certain Ziegler catalysts containing titanium bring about the ready cyclization of butadiene to give high yields of *trans,trans,*

[15] German Published Patent Application 1078108 (1958), Studiengesellschaft Kohle mbH., Mülheim/Ruhr, inventor: *G. Wilke*.

[16] *G. Wilke*, J. Polymer Sci. *38*, 45 (1959).

[17] *L. Y. Zacharkins*, Dokl. Akad. Nauk U.S.S.R. *131*, 1069 (1960).

[18] Belgian Patent 635483 (1962/63), BASF, inventors: *H. Seibt* and *N. von Kutepow*.

[19] Belgian Patent 618625 (1961/62), BASF, inventor: *D. Wittenberg*.

[19a] *D. Wittenberg*, Angew. Chem. *75*, 1124 (1963); Angew. Chem. internat. Edit. *3*, 153 (1964).

[20] *S. Otsuka* et al., J. Amer. chem. Soc. *85*, 3709 (1963); J. chem. Soc. Japan, ind. Chem. Sect. *66*, 1094 (1963).

[21] *T. Saito* et al., J. chem. Soc. Japan, ind. Chem. Sect. *66*, 1099 (1963); Bull. chem. Soc. Japan *1964*, 105.

[22] French Patent 1350644 (1961/63), BASF, inventors: *D. Wittenberg, H. Lautenschlager, N. von Kutepow, F. Meier*, and *H. Seibt*.

[23] German Patent 1050333 (1956/59), Studiengesellschaft Kohle mbH., Mülheim/Ruhr, inventor: *G. Wilke*.

cis-1,5,9-cyclododecatriene. This synthesis is of great theoretical and practical importance and was subsequently also carried out with catalysts based on chromium and nickel compounds [24]. The products then contained two other isomers of cyclododecatriene, namely the *trans,trans,trans*- and the *trans,cis,cis*-compounds.

Investigations by *Wilke* et al. [24] showed that, with catalysts containing titanium, the cyclotrimerization is effected by the trivalent central metal atom. It is surprising, therefore, that we found a system which apparently contains divalent titanium and which is a very effective catalyst for the cyclotrimerization of butadiene to *trans,trans,cis*-1,5,9-cyclododecatriene [*]. This catalyst is formed by the reaction of titanium halides, particularly titanium tetrachloride, with aluminum and aluminum chloride in aromatic solvents [25]. *Natta* et al. [26] discovered independently that a complex with the composition $TiCl_3 \cdot Cl_2AlC_6H_5 \cdot AlCl_3$ is apparently formed when this reaction is carried out in benzene. Later, *Martin* and *Vohwinkel* [27] produced conclusive proof that this was in fact an aromatic complex with the composition $TiCl_2 \cdot 2\ AlCl_3 \cdot C_6H_6$, in which the titanium is divalent. These authors found that the same complex results from the reaction of titanium(II) chloride with aluminum chloride in benzene. The compound obtained in this manner also catalyses the synthesis of cyclododecatriene [28]. The activity and selectivity of the catalyst are greatly improved when substances are present which form complexes with aluminum chloride [29]. The acidic character of aluminum chloride is then at least partially neutralized, with consequent suppression of side reactions. Examples of suitable complexing agents are ethers, thioethers, amines, and alkali metal halides.

The titanium catalysts are very selective and extremely active. Using the catalyst combination aluminum/aluminum chloride/titanium tetrachloride/sodium chloride/benzene, it was possible to produce 1000 kg of cyclododecatriene per mole of titanium tetrachloride in 90% yield, at a daily output of 10 kg of cyclododecatriene per liter of reaction space. The concentration of titanium in the reaction product is between 0.5×10^{-3} and 1×10^{-3} gram-atom/l. About 1% vinylcyclohexene and cyclooctadiene are formed as by-products. The remainder is a low molecular-weight, waxy polybutadiene with a molecular weight of 1500. Unlike the rubbery polybutadienes which frequently result from the oligomerization of butadiene, this does not hinder the manipulation of the reaction products.

If iron(III) chloride is used instead of the titanium compound, the reaction is less specific and yields a mixture of *trans,trans,trans*- and *trans,trans,cis*-1,5,9-cyclododecatrienes, together with other cyclic and open-chain oligomers of butadiene [30].

We were also able to develop nickel-containing catalysts for the industrial synthesis of *trans,trans,trans*-1,5,9-cyclododecatriene; previously *Reed* [3] had obtained cyclododecatriene as a by-product in the dimerization of butadiene with nickel-based catalysts.

In the simplest case, nickel carbonyl is used as catalyst. The procedure is fundamentally the same as for the synthesis of cyclooctadienes. It is essential to maintain a high concentration of butadiene and to ensure that the temperature is not too high. This catalyst system is particularly suitable for the industrial process, although lower rates of reaction result than with titanium catalysts. The process is technically simpler, however, and the only by-product formed in appreciable quantities is cyclooctadiene, which is not undesired.

Bisacrylonitrilenickel *(1)* reacts with pyridine, quinoline, or quinaldine to form complexes of the composition *(6)*, which are also suitable for the synthesis of cyclododecatriene.

$$Ni(CH_2{=}CH{-}CN)_2 \cdot \text{(pyridine)} \qquad (6)$$

IV. Co-oligomerization of Butadiene with Other Unsaturated Compounds

In the co-oligomerization of butadiene with other unsaturated compounds two types of reaction can be distinguished, according to the manner in which the molecules are linked together.

The first type includes ring-closure reactions in which C–C bonds are formed simply by electron shifts. A classical example is the uncatalyzed Diels-Adler reaction of butadiene. New examples have recently been added by *Wilke* et al. [6,31], *e.g.* the co-oligomerization of two molecules of butadiene with ethylene or dimethylacetylene to form 1,5-cyclodecadiene or 1,2-dimethyl-1,4,8-cyclodecatriene.

The second reaction type gives rise to open-chain co-oligomers, which are formed by C–C linkage and a hydrogen shift, the hydrogen moving either from the butadiene or from the other unsaturated compound. Only in the former case products with conjugated double bonds are obtained. *Wittenberg* has suggested the term "dienylation" for this reaction [19a].

$$H_2C{=}CH{-}CH{=}CH_2 + RCH{=}CHR' \rightarrow H_2C{=}CH{-}CH{=}CH{-}RCH{-}CH_2R'$$

Our investigations have shown that the formation of cyclic and open-chain co-oligomers without conjugated double bonds is favored by nickel(0) catalysts, while cobalt catalysts favor dienylation.

The simplest dienylation reaction is the oligomerization of butadiene with cobalt catalysts to form 3-methyl-1,4,6-heptatriene *(4)* and higher oligomers described above.

$$H_2C{=}CH{-}CH{=}CH_2 + H_2C{=}CH{-}CH{=}CH{-}\overset{CH_3}{\overset{|}{C}}H{-}CH{=}CH_2 \qquad (4)$$

$$\rightarrow H_2C{=}CH{-}CH{=}CH{-}\overset{CH_3}{\overset{|}{C}}H{-}CH{=}CH{-}\overset{CH_3}{\overset{|}{C}}H{-}CH{=}CH_2$$

[24] *H. Breil, P. Heimbach, M. Kröner, H. Müller*, and *G. Wilke*, Makromolekulare Chem. *69*, 18 (1963).

[*] Subsequent to these investigations our attention was drawn to the fact that similar results had already been reported by *F. Vohwinkel* (Max-Planck-Institut für Kohlenforschung) [28].

[25] German Patent 1097982 (1959/61), BASF, inventor: *H. Müller*.

[26] *G. Natta, G. Mazzanti*, and *G. Pregaglia*, Gazz. chim. ital. *89*, 2065 (1959); *G. Natta* and *G. Mazzanti*, Tetrahedron *1960*, 86.

[27] *H. Martin* and *F. Vohwinkel*, Chem. Ber. *94*, 2416 (1961).

[28] Belgian Patent 634893 (1962/63), BASF, inventors: *H. Müller* and *D. Wittenberg*.

[29] German Patent 1095819 (1959/61), BASF, inventor: *H. Müller*.

[30] German Patent 1106758 (1960/61), BASF, inventor: *H. Müller*.

[31] Austrian Patent 232495 (1962/64), Studiengesellschaft Kohle mbH., Mülheim/Ruhr.

Using cobalt catalysts at 80 °C, we have obtained very pure *trans*-1,3-hexadiene from ethylene and butadiene under pressure. A side reaction is the formation of 5-methyl-1,3,6-nonatriene *(8)* and 3-methyl-1,4,6-nonatriene *(9)* by reaction of the hexadiene *(7)* with a further molecule of butadiene.

$$H_2C{=}CH{-}CH{=}CH_2 + H_2C{=}CH_2 \rightarrow H_2C{=}CH{-}CH{=}CH{-}CH_2{-}CH_3 \quad (7)$$

$$H_2C{=}CH{-}CH{=}CH{-}\underset{\displaystyle CH_3}{CH}{-}CH{=}CH{-}CH_2{-}CH_3 \quad (8)$$

$$H_2C{=}CH{-}CH{=}CH_2 + H_2C{=}CH{-}CH{=}CH{-}CH_2{-}CH_3 \quad (7)$$

$$H_2C{=}CH{-}\underset{\displaystyle CH_3}{CH}{-}CH{=}CH{-}CH{=}CH{-}CH_2{-}CH_3 \quad (9)$$

Butadiene reacts very readily with acrylic esters, even at 40–60 °C and normal pressure, to form heptadienoic esters as the principal products.

$$H_2C{=}CH{-}CH{=}CH_2 + H_2C{=}CH{-}COOR \rightarrow CH_2{=}CH{-}CH{=}CH{-}CH_2{-}CH_2{-}COOR \quad (10)$$

Butadiene also reacts with phenyacetylene at room temperature. After the reaction has proceeded for a few minutes, yellow crystals of 1,8-diphenyl-1,3,5,7-octatetraene *(11)* formed by dienylation at both ends of the butadiene molecule separate out of the reaction mixture.

$$C_6H_5{-}C{\equiv}CH + H_2C{=}CH{-}CH{=}CH_2 + HC{\equiv}C{-}C_6H_5 \rightarrow C_6H_5{-}HC{=}CH{-}HC{=}CH{-}CH{=}CH{-}HC{=}CH{-}C_6H_5 \quad (11)$$

The dienylation is catalysed by the cobalt complexes described above for the synthesis of methylheptatriene. These are used in solution in ethers or hydrocarbons. Unlike the corresponding nickel complexes, they are relatively stable. Their activity and selectivity are scarcely affected by the addition of amines, ketones, esters, alcohols, or even small quantities of water. The simplest catalyst for the reaction is cobalt carbonyl.

Co-oligomers of butadiene and other unsaturated compounds, resulting from the addition of a C–H bond of the unsaturated compound onto butadiene, have been obtained by *Friedmann* [32], *Alderson* [33], and *Verbanc* [34] using cobalt oxide and rhodium chloride as catalysts. For example, butadiene and ethylene give 1,4-hexadiene:

$$H_2C{=}CH{-}CH{=}CH_2 + H_2C{=}CH_2 \rightarrow H_3C{-}CH{=}CH{-}CH_2{-}CH_2{=}CH_2$$

Wilke [6] used nickel(0) complexes to co-oligomerize butadiene and ethylene. In this reaction, the principal product is 1,5-cyclodecadiene, with n-1,4,9-decatriene as a by-product. We carried out experiments with catalysts formed from nickel chelates, alkali metals, and butadiene in organic solvents and succeeded in co-oligomerizing butadiene and ethylene to obtain a 50% yield of 1,5,9-decatriene. 1,3,8-Decatriene, 1,5,9-cyclodecatriene, 1,5-cyclooctadiene, and 1-vinyl-3-cyclohexene were also isolated from the reaction products.

On studying the behavior of styrenes in this reaction, we found that these react very readily with butadiene [35]. Here the main reaction is the linkage of two molecules of butadiene with one molecule of the styrene to form aryl-n-decatrienes *(12)*.

$$Ar{-}CH{=}CH_2 + 2\ H_2C{=}CH{-}CH{=}CH_2 \rightarrow ArHC{=}CH{-}H_2C{-}CH{=}CH{-}CH_2{-}CH_2{-}CH{=}CH{-}CH_3 \quad (12)$$

The position of the double bond in the product depends to some extent on the catalyst used and on the reaction conditions. A mixture of isomers with the double bond in various positions is generally obtained, 1-aryl-1,4,8-decatrienes predominating. The co-oligomers of styrene and butadiene, *i.e.* the phenyldecatrienes, are particularly interesting from a technical point of view. They can be readily hydrogenated to n-decylbenzene, a convenient starting material for the preparation of soft detergents.

The co-oligomerization proceeds with the evolution of about 410 cal/g and is best carried out at 90–100 °C using nickel catalysts which cyclize pure butadiene to cyclododecatriene or cyclooctadiene.

Consequently, these homo-oligomers occur as by-products. Their formation can be largely suppressed, however, by working in the presence of excess styrene. In a continuous process in a pilot-plant, 75% of the butadiene feed was converted into phenyldecatriene in the presence of a 30% excess of styrene. The yield, based on the styrene, was practically quantitative.

Catalysts with ligands containing phosphorus were found to be less suitable than nickel(0) olefin complexes or nickel carbonyl. The phosphorus-free nickel complexes give the purest phenyldecatriene and are also extremely active. Depending on the contact time, it is possible to obtain 500–1000 kg of phenyldecatriene per mole of nickel compound.

Co-oligomerization to form cyclic products predominates in the reaction with ethylene and leads to the formation of cyclodecadiene, but occurs only to a small extent with styrene. Here cyclization is evidently hindered by the conjugation of the vinyl group with the aromatic nucleus, which still persists in the phenyldecatrienes, so that the reaction leads to the energetically favored open-chain hydrocarbon. This is probably also why vinylcyclohexene reacts much less readily than styrene.

By analogy to the reaction with butadiene, styrene derivatives also react with butadiene or other 1,3-dienes. For example, styrene reacts smoothly with isoprene to form 1-phenyl-4,8-dimethyldecatriene *(13)*, and vinylnaphthalene on reaction with butadiene yields 1-naph-

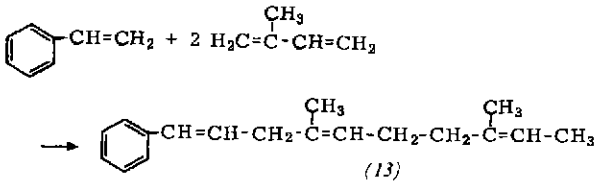
[32] U.S.-Patent 2599249 (1950/52), Sinclear Refining Comp., inventor: *B. S. Friedmann.*

[33] U.S.-Patent 3013066 (1961/62), Du Pont, inventor: *Th. Alderson.*

[34] French Patent 1319578 (1962/63), Du Pont, inventor: *J. Verbanc.*

[35] Belgian Patent 622195 (1961/63), BASF, inventors: *H. Lautenschlager, E. Scharf, D. Wittenberg,* and *H. Müller.*

thyldecatriene. With divinylbenzene, both vinyl groups can take part in the reaction, and the products include



(13)

didecatrienylbenzene and vinyldecatrienylbenzene. α-Substituted styrenes such as α-methylstyrene are much less reactive than styrene itself. Consequently, the competing homo-oligomerization of butadiene predominates, and the co-oligomers are obtained in yields of only 5–10%.

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Formation of Free Radicals in Polyamide Fibers during Drawing

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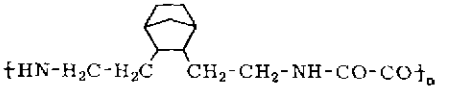
The formation of free radicals during the process of drawing of spun fibers was observed for the first time with two polyoxamides. The fibers turn red, and an ESR signal can be detected. Both, color and ESR absorption are not permanent. The decrease in the intensity of the ESR absorption and the change in the optical reflectance with time, as well as the dependence of the decoloration on temperature were investigated. The action of high-energy radiation on the polyoxamides also leads to a red coloration and gives rise to ESR signals. It is concluded that the red color is due to free radicals associated with the oxamido group.

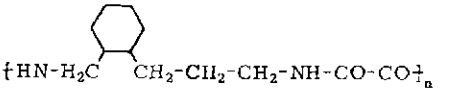
Introduction

Free-radical formation in polymers as a result of mechanical stress has until now been observed only when the stress was very great, *e. g.* during pulverisation in a mill [1–5]. Investigations of this type on polyamides have been described by *Bresler* et al. [3], who observed free-radical formation in polycaprolactam on grinding at −196 °C, although no free radicals were detected after grinding at room temperature.

We have now found that free radicals can be formed in certain polyoxamides as a result of mechanical stress of a different nature, namely during drawing, at room temperature, of fibers spun from the melt. The following polymers were examined:



"Polyoxamide I"



"Polyoxamide II"

If these polyoxamides are spun at a temperature at which the melt is very viscous, *i. e.* between 200 and 230 °C, the fibers assume an intense red coloration on drawing at room temperature (Fig. 1). This phenomenon is not observed if the fibers are spun at higher temperatures. The red color is unstable, particularly in the presence of oxygen, and the rate of decoloration depends on the temperature. Fibers of polyoxamide I which turned red on drawing are no longer soluble in cresol, even after spontaneous decoloration.

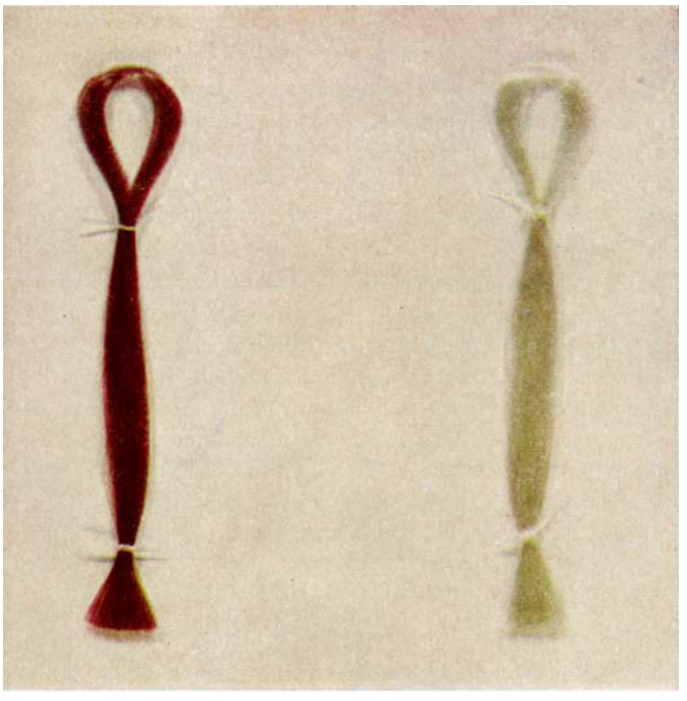
[1] *P. Y. Butyagin, A. A. Berlin, A. E. Kalmanson,* and *L. A. Blyumenfeld,* Vysokomol. Soed. (U.S.S.R.) *1,* 865 (1959).

[2] *P. Y. Butyagin,* Dokl. Akad. Nauk U.S.S.R. *140,* 145 (1961).

[3] *S. E. Bresler, S. N. Zhurkov, E. N. Kazbekov, E. M. Saminskii,* and *E. E. Tomashevskii,* Rubber Chem. Technol. *33,* 358 (1960).

[4] *S. N. Zhurkov, E. E. Tomashevskii,* and *V. A. Zakrevskii,* Fiz. Tverdogo Tela (U.S.S.R.) *3,* 2841 (1961).

[5] *S. E. Bresler, E. N. Kazbekov, V. N. Fornichev, F. Sech,* and *P. Smeitek,* Fiz. Tverdogo Tela (U.S.S.R.) *5,* 675 (1963).



a b

Fig. 1. Fibers of polyoxamide I: a) drawn; b) undrawn.

1. Electron Spin Resonance

The red drawn fibers of both polyoxamides give electron spin resonance (ESR) signals, which indicate the presence of unpaired electrons. The ESR spectra are shown in Figure 2, the curves recorded being the first derivatives of the absorption spectra. As in the ESR spectra of most solids, the hyperfine structure is poorly resolved. The fact that hyperfine structure is at all present, indicates interaction of the unpaired electron with nitrogen or hydrogen nuclei.

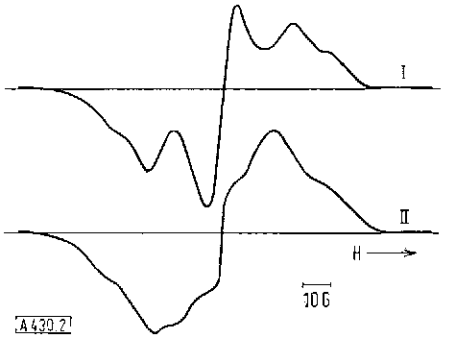


Fig. 2. ESR spectra of drawn fibers of polyoxamides I and II. Ordinate: $d\chi''/dH$.
χ'' = imaginary part of the complex high-frequency susceptibility; H = magnetic field strength.

The form of the spectrum depends slightly on the orientation of the fibers in the magnetic field. The spectra in Figure 2 were obtained from fibers with their axes parallel to the magnetic field; for fibers with their axes perpendicular to the magnetic field, the middle line becomes weaker relative to the outer lines.

The intensity of the ESR signal corresponds to about 10^{16} spins per gram. Thus there is roughly one unpaired electron for every 3×10^5 structural units in the polymer. The intensity of the signal decreases with time, as does the red color. The rate of the decrease of intensity and the form of the spectrum during the return to normal are influenced by the presence of oxygen.

2. Kinetic Measurements

The intensity of the ESR signal of freshly drawn polyoxamide I decreases with time. The results of measurements in air at room temperature (Fig. 3) can be evaluated with the aid of the equation for the kinetics of a first order reaction:

$$2.303 \log I/I_0 = -kt$$

(I = intensity of the ESR signal; I_0 = initial value).

A number of measurements gave values of k between 0.2 and 0.8 h^{-1}. The disappearance of the radicals evidently is a pseudounimolecular reaction, the concentration of oxygen in the fibers being included as a constant factor in k.

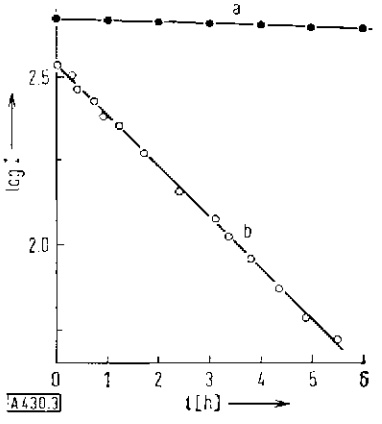


Fig. 3. Decay of the ESR signal of polyoxamide I; a) under nitrogen; b) in air; I = intensity.

On investigating polyoxamide I under nitrogen, it is found that the ESR absorption falls off about one-hundred times more slowly (Fig. 3). Here the decrease in the ESR intensity no longer corresponds to a simple reaction order when the investigation is continued over long periods (400 h). Furthermore, the intensity of the middle line decreases more slowly than that of the outer lines.

Using the method described by *Kubelka* and *Munk* [6, 7], the absorption spectrum was found from the light reflection [7a]. The maximum is located at a wavelength of 505 mμ. The quantity $(1 - R)^2/2R$ (where R = the absolute reflectance of an infinitely thick layer), which is proportional to the concentration of red color centers, also decreases with first order kinetics in the presence of air. The rate constant for the decrease (0.7 h^{-1}) is within the range found from the ESR measurements.

The decrease in the optical extinction also proceeds more slowly under nitrogen than in air. The decrease under nitrogen could not be followed quantitatively with the apparatus available.

[6] *P. Kubelka* and *F. Munk*, Z. techn. Physik *12*, 593 (1931).
[7] *P. Kubelka*, J. opt. Soc. America *38*, 448 (1948).
[7a] It was assumed that the scattering coefficients of colored and decolorized fibers are the same. This is probably correct to a good approximation.

3. Temperature Dependence of the Decoloration

In order to obtain a measure of the influence of temperature and oxygen concentration on the decoloration of the red fibers, the time τ required for loss of visible color was determined at various temperatures under otherwise identical conditions (size of the bundle of fibers, extent of drawing). τ is in fact the time in which the extinction falls to a constant fraction of its initial value.

Figure 4 shows the temperature-dependence of τ for polyoxamide I in air and in the absence of air between 0 and 160 °C. It can be seen that τ decreases with increasing temperature. A plot of log τ against $1/T$ gives a straight line in the absence of oxygen, but in the presence of air the line exhibits a break. The position of this break depends to some extent upon the pretreatment of the fiber. In the experiments on which Figure 4 is based, the break occurred at about 90 °C. Below this temperature, the decoloration times are shorter in the presence of oxygen than in its absence, while above this temperature oxygen has no significant effect. From the fact that the curves are straight it follows that log τ is proportional to the logarithm of the rate constant. The activation energies of the reactions can be calculated from the gradients of the straight lines. The values obtained are 9 kcal/mole for the right-hand branch of Curve (b), and about 30 kcal/mole for the left-hand branch of Curve (b) and for Curve (a). Similar results were obtained with polyoxamide II.

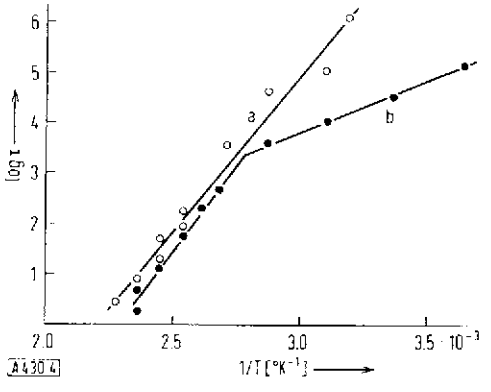


Fig. 4. Temperature-dependence of the decoloration time τ [sec]; a) in the absence of air; b) in air; T = absolute temperature.

4. Irradiation of the Polyoxamides and of Related Monomeric Substances with High-Energy Radiation

The usual method of producing free radicals in solid high polymers is by the action of high-energy radiation. It was desirable, therefore, to find whether irradiation of polyoxamides I and II gives the same red coloration and the same ESR spectra as are observed on drawing. *Zimmerman* [8] has described a red coloration of the polyamide prepared from 2-methylhexamethylenediamine and oxalic acid on irradiation with 2 MeV electrons. No ESR measurements were reported.

Our investigations have shown that polyoxamides I and II, as well as 8,2-polyamide and 12,2-polyamide, assume a red color on irradiation with 2 MeV electrons or with ultraviolet light [8a]. No red coloration is observed with polyamides which do not contain the –COCO– group.

The ESR spectra of the irradiated polyoxamides I and II contain 5 lines each (Fig. 5), exactly as the spectra of the drawn polyoxamides. In some of the irradiation experiments, the spectra of the products had the same form as those of drawn fibers; however, in other cases, the middle line of the quintet was more intense. The reason for this difference is unknown. The ESR spectrum of the irradiated 12,2-polyamide also contains a quintet in which the middle line is more intense than the others.

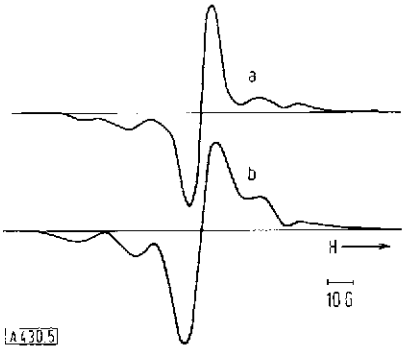


Fig. 5. ESR spectra of polyoxamide I (a) and of oxamide (b) after irradiation.

Ordinate: $d\chi''/dH$.

χ'' = imaginary part of the complex high-frequency susceptibility; H = magnetic field strength.

The extinction and the signal intensity in the ESR spectrum of polyoxamide I increase with the radiation dose over the range investigated (0.5–6.0 Mrad). At low doses, the increase is proportional to the dose, but becomes somewhat slower at higher doses, indicating that the extinction and the signal intensity are approaching a saturation value. Both the intensity of the ESR signal and the extinction of irradiated polyoxamide I decrease in the presence of air. However, the changes did not correspond to a first order reaction.

In an attempt to find the relationship between the red color produced by irradiation and the chemical structure, monomeric derivatives of oxalic acid were irradiated with electrons. It was found that oxamide and *N,N'*-dipropyloxamide also give red colorations. The cyclic oxamide of *N,N'*-dimethyl-1,3-diaminopropane, which contains no hydrogen atoms on the nitrogens, assumes a yellow-orange color. A more or less strong yellow coloration is obtained with oxalic acid, sodium oxalate, dimethyl oxalate, butyl oxamate, and di-t-butyl oxalate.

All the oxalic acid derivatives examined give ESR spectra with hyperfine structure after irradiation. The spectrum of oxamide contains 5 lines (Fig. 5b); those of the other compounds are more complex.

[8] *J. Zimmermann*, J. appl. Polymer Sci. *2*, 181 (1959).

[8a] In order to ensure that the results obtained were as far as possible due to the radicals formed initially, the irradiation was carried out at −78 or −196 °C.

5. Discussion

The ESR absorption of the drawn polyoxamides I and II shows that free radicals are formed during the mechanical deformation. The fact that only fibers which have turned red on drawing become insoluble is also evidence for the formation of free radicals, with subsequent cross-linking of the material.

Under certain conditions, the ESR spectra of drawn fibers and of material which has been irradiated with high-energy electrons are identical. It can therefore be concluded that radicals of the same type are formed under mechanical stress and during irradiation. *Butyagin* [2] has made similar observations on other high polymers. As this author also assumed, the initial products in both cases are excited molecules, which then react further in an identical manner to form relatively stable free radicals. These radicals are detected in the ESR spectrum.

It is striking that the formation of free radicals in fibers during drawing has so far been observed only with the polyoxamides I and II[8b]. Each of these polymers consists of relatively rigid molecular chains with a bulky group projecting laterally. It is conceivable that, during drawing of the fiber, molecular chains that should be slipping past one another occasionally become interlocked, resulting in a local build-up of energy which can lead to excitation of the molecule. This explanation is supported by the fact that the phenomenon is observed only with fibers which are spun at relatively low temperatures. These are already internally strained owing to draw-down during spinning, so that movement of the molecular chains over one another is difficult. Since the second-order transition temperatures T_g [8c] of polyoxamides are appreciably higher than those of normal polyamides (polyoxamide I: T_g = 135 °C, polyoxamide II: T_g = 115 °C), the formation of free radicals should be favored by cold drawing, and their life-time should be prolonged to such an extent as to allow their concentration to exceed the limit of detection.

The excited molecule could conceivably undergo the following reactions:

1. rupture of the main chain;
2. elimination of a hydrogen atom or a side group, possibly followed by addition onto a carbonyl group;
3. removal of an electron which then becomes trapped by the solid high polymer, *e.g.* in the vicinity of a carbonyl group.

No conclusions on the structure of the radicals can be drawn from the investigations carried out so far. The ESR spectra of irradiated polyamides (our own investigations and [9–16]) differ in shape from those of polyoxamides I and II. The structures proposed for the free radicals in polyamides cannot therefore be used to interpret our spectra. Nothing is known of the structure of the free radicals formed on irradiation of monomeric and polymeric oxalic acid derivatives.

The ESR quintet observed with red drawn fibers of polyoxamides I and II is due either to a single type of free radical or to superposition of the spectra of two or more types of free radicals. If the former alternative is correct, the explanation for the differences in the decay of the various lines (in the absence of oxygen) would be that the disappearance of the free radical is accompanied by the formation of another more stable radical. The latter would then be responsible for a singlet occurring at the same position as the middle line of the quintet.

The difference between the spectra of polyoxamides I and II (the middle line of II is much weaker than that of I) can be explained by a larger line-width in the case of polyoxamide II or by a superposition of two signals having different ratios for the polyoxamides I and II.

It seems certain that the red color is associated with the group –NH–COCO–NH–, since even in monomeric oxalic acid derivatives, it occurs only when the oxamide group is present. Since the intensities of the red color and of the ESR signal of polyoxamide I decrease with time in a similar manner, whether the material has been drawn or irradiated, and since both quantities increase at the same rate with the radiation dose, we must conclude that the red color is due to a free radical which is detected by ESR spectroscopy.

The destruction of the free radicals involves various processes, depending on the external conditions. In the presence of air at room temperature, a first order reaction with an activation energy of 9 kcal/mole occurs. This energy can probably be related to the diffusion of oxygen in solid polyoxamide (values of this order of magnitude are given in the literature for the diffusion of oxygen in solid polymers [17]). The reaction of oxygen with the free radical probably proceeds rapidly and with no appreciable activation energy. As the temperature increases (see Fig. 4, Curve b), a competing reaction of unknown order begins to predominate. It seems likely that this is a reaction between two radical sites. The activation energy of about 30 kcal/mole found for Curve (a) and for the left-hand branch of Curve (b) in Figure 4 presumably corresponds to the "diffusion" of free-radical sites. This process may involve both direct diffusion of chain segments and migration of free-radical sites by transfer of hydrogen atoms.

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[8b] Note added in proof: Recently similar color changes were observed with a polyamide from hexamethylenediamine and isophthalic acid (Kunststofflaboratorium, BASF). This polyamide turns blue when it is extruded and subsequently subjected to mechanical strain. This is the case, for example, when spun fibers are stretched or when extruded strands are granulated. The same coloration occurs on irradiation. The ESR spectrum of the blue material consitsts of five bands.

[8c] The second-order transition temperature was measured by the penetrometer method, cf. *O. B. Edgar*, J. chem. Soc. (London) *1952*, 2638. In this method the polymer sample is heated in silicone oil at a rate of 1 °C/min. At the same time a cylindrical piston rests on the sample with a load of 1.3 kg/cm². The thickness of the sample and the downward movement of the piston on softening are measured and plotted versus temperature. Below the softening point the slope of the curve depends on the coefficient of expansion, whereas above it depends on the rate of downward movement of the piston. The second-order transition temperature Tg is given by the point of intersection of the tangents at both branches of the curve.

[9] *R. J. Abraham* and *D. H. Whiffen*, Trans. Faraday Soc. *54*, 1291 (1958).
[10] *S. Onishi, Y. Ikeda, M. Kashiwagi*, and *I. Nitta*, Polymer (London) *2*, 119 (1961).
[11] *M. Kashiwagi*, J. Polymer Sci. *A 1*, 189 (1963).
[12] *H. Fischer* and *K.-H. Hellwege*, Z. Naturforsch. *18a*, 994 (1963).
[13] *E. J. Burrell*, J. Amer. chem. Soc. *83*, 574 (1961).
[14] *W. Damerau, G. Lassmann*, and *H.-G. Thom*, Z. physik. Chem. *223*, 59 (1963).
[15] *C. T. Graves* and *M. G. Ormerod*, Polymer(London) *4*, 81 (1963).
[16] *D. S. Ballantine* and *Y. Shinohara*, Fifth International Symposium on Free Radicals, Uppsala (Sweden), July 6th–7th, 1961.
[17] *G. J. van Amerongen*, J. Polymer Sci. *5*, 307 (1950).

N-Substituted Tetrahydro-1,4-oxazines – A New Class of Fungicidal Compounds

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Tetrahydro-1,4-oxazines with large alicyclic or long alkyl groups [*] attached to the nitrogen exhibit good or very good fungicidal activities against fungus diseases of crops, particularly against the true mildew varieties. – By examining several hundred compounds, the relations between chemical constitution and fungicidal action were investigated in an attempt to find the most effective compounds. The factors varied were the nature, chain length, and ring size of the N-substituent, and the nature, number, and positions of the C-substituents on the heterocyclic system. Furthermore, the lone electron pair at the nitrogen atom was incorporated by alkylation, formation of amine oxides or salts, or by complexing with heavy metal salts, and the resulting changes in the fungicidal activity were determined.

I. Introduction

Every year, fungus diseases cause great damage to crops, and thus appreciably lower their yield. Fungal damage in the U. S. A. in 1954 was responsible for a reduction of 7% or 2.8 billion dollars in the agricultural and forestry returns [1]. In Ceylon, the cultivation of coffee beans had to be abandoned owing to the extensive incidence of leaf rust. The cultivation of tobacco in South Africa was severely reduced by a powerful attack of mildew. The fact that practically no winter barley is grown in Denmark and Sweden is due to barley mildew. European viniculture came to the brink of extinction around 1870 following the *Peronospora* epidemic after the disease had found its way here from overseas. It was only thanks to the discovery, or rather the rediscovery, of the Bordeaux spray that the attack was weakened in subsequent years. Great losses were suffered by the tobacco harvest as a result of the blue mold in 1959 and 1960, especially in Germany and the neighboring countries. Practically the entire potato harvest failed in Germany in 1917 because of the fungus *Phytophthora infestans*, and this event was largely responsible for the so-called "turnip winter" in 1917–1918. Fungi can damage fruit even after harvesting, for example in the citrus family, rendering the fruit unpalatable within a few days. The task of developing new fungicides is therefore of great economic importance.

In comparison with the number of herbicides and insecticides, the number of organic compounds possessing fungicidal activity is small. The broadest possible spectrum, good plant tolerance, and a simple and cheap synthesis are the essential criteria of a fungicide.

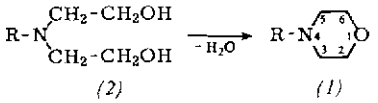
Occasionally nitrogenous compounds with long alkyl chains exhibit considerable biological activity. Thus a herbicidal action is shown by *N*-laurylhexamethyleneimine, while 2-heptadecylimidazoline acetate and laurylguanidine acetate are particularly active against apple scab (*Venturia inaequalis*).

Although easy to prepare by known methods, tetrahydro-1,4-oxazines have not yet been tested for their plant-protecting action. 2-Phenyl-3-methylmorpholine has been the only biologically active oxazine to achieve importance as a drug.

II. The Preparation of Tetrahydro-1,4-oxazines

1. Syntheses of the Ring System

Tetrahydro-1,4-oxazine, *i.e.* morpholine *(1)*, R = H, is obtained in good yield by dehydration and cyclization of bis-(2-hydroxyethyl)amines *(2)*, R = H, by sulfuric acid [2], hydrogen halides, acid halides, or dehydrating catalysts [3] at 160–260 °C. Considerably better yields are



(2) *(1)*

generally obtained and lower temperatures (80–140 °C) are needed when the amino hydrogen of the bis-(2-hydroxyalkyl)amine is replaced by a hydrocarbon group [R ≠ H in *(2)*]. Moreover, ring closure is facilitated when the carbon atoms carrying the OH-groups are tertiary or quaternary [see *(5)* → *(6)*; *(7)* → *(8)*].

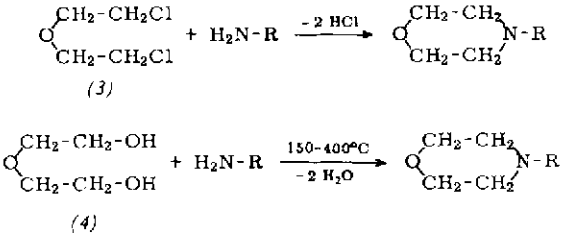
[*] Compounds of this type are the subject of German and other patent applications.

[1] *E. G. Sharvelle*: The Nature and Uses of Modern Fungicides. Burgess Publishing Comp., Minneapolis 1961, p. 30.

[2] *L. Knorr*, Ber. dtsch. chem. Ges. *16*, 1267 (1883); *22*, 2084 (1889); Liebigs Ann. Chem. *301*, 1 (1898); *L. Medard*, Bull. Soc. chim. France *3*, 1338 (1936).

[3] U.S.-Pat. 2597260 (May 20th, 1952), Armour and Co., inventor: *R. A. Reck*; German Pat. 844006 (Sept. 28th, 1950), BASF, inventor: *E. Weiss*.

Other possibilities are the ring-closure of bis-(2-halogenoethyl) ethers *(3)* [4] or bis-(2-hydroxyethyl) ethers *(4)*, as well as the ring closure of glycols with amines [5].

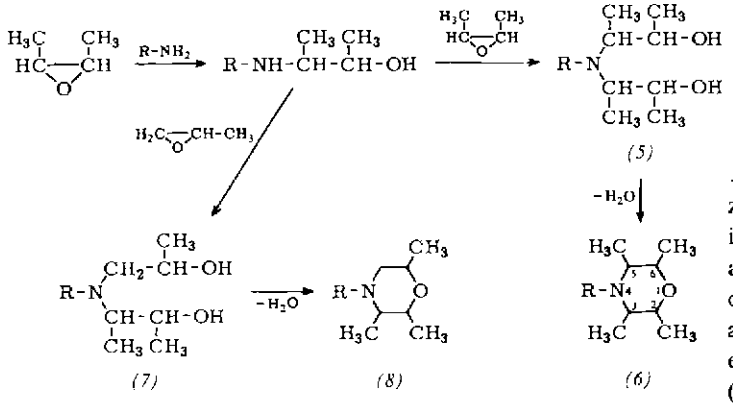


(3)

(4)

2. Introduction of Substituents at the Carbon Atoms

Bis-(2-hydroxyalkyl)amines can be prepared by adding ammonia or primary amines [2] to 1,2-alkylene oxides, a wide range of the latter being available from petroleum products. If 2 moles of the same epoxide or 1 mole each of two different epoxides (*e.g.* 2,3-butylene oxide and propylene oxide) are reacted with 1 mole of ammonia or a primary amine, then symmetrically *(5)* or unsymmetrically *(7)* substituted bis-(2-hydroxyalkyl)amines are obtained, which on dehydrating cyclization yield symmetric *(6)* or unsymmetric *(8)* tetrahydro-1,4-oxazines.

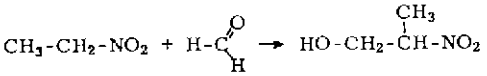


(5)

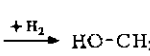
(7) *(8)* *(6)*

Substituents can in this way be introduced at positions 2 and/or 6, and, by using a symmetric epoxide, at positions 3 and 5 as well. On adding an unsymmetric 1,2-epoxide to an amine, the epoxide ring will usually be opened in such a way that the OH-group is attached to the carbon atom carrying the least number of hydrogens [6]. Using the same amine, ring opening of the 1,2-alkylene oxides becomes more difficult as the number of substituents in the latter increases (or, in the case of epoxides with the same number of substituents, as the symmetry of the epoxide increases).

For the introduction of only one substituent at position 3, or only two substituents at positions 3 and 5 of tetrahydro-1,4-oxazine, the starting material must be a 1-amino-2-hydroxyethane *(9)* that is substituted on the carbon atom adjacent to the nitrogen. These 1,2-amino alcohols are prepared by base-catalysed addition of nitroalkanes containing acidic hydrogen atoms to carbonyl compounds such as formaldehyde, acetaldehyde, or acetone, and catalytic hydrogenation of the resultant 1,2-nitroalcohols, *e.g. (9a)* [7]. 1,2-Alkylene oxides convert the 1,2-amino alcohols, *via* bis-(2-hydroxyalkyl)amines, into 2- and/or 5-substituted tetrahydro-1,4-oxazines, for example *(10)*.



(9a)



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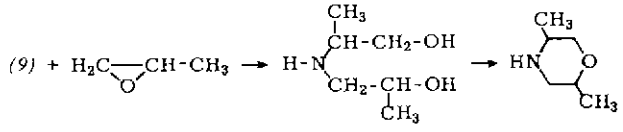


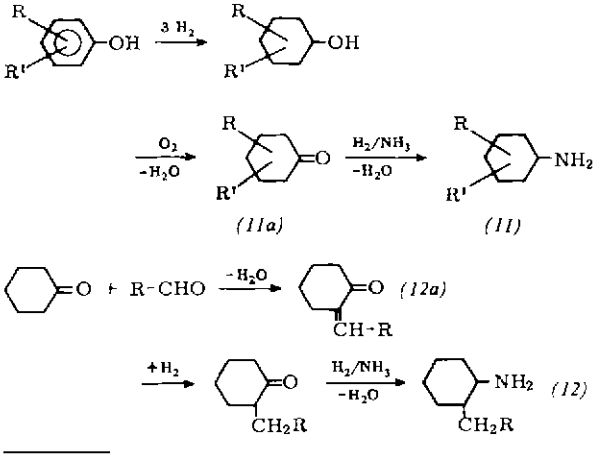
(10)

If the amine to be cyclized carries two substituents on different carbon atoms, two sterically different products are obtained on ring closure in about equal amounts. They can be detected by gas chromatography as, for example, in the case of the 2,6-dialkylmorpholines.

3. Introduction of Substituents at the Nitrogen Atom

Alkylation of the nitrogen atom in tetrahydro-1,4-oxazines by means of alkyl halides is successful with aliphatic compounds, but it is frequently unsuccessful with alicyclic halides which are dehydrohalogenated to cycloalkenes. It is therefore practical, particularly in the alicyclic series, to synthesize by hydroxyalkylation with epoxides *N*-substituted amines which are then cyclized (cf. Section II.2), or to react a cyclic ketone with the tetrahydro-1,4-oxazine, which is unsubstitued on the nitrogen atom, and hydrogenate the resulting enamine.

The primary alicyclic amines *(11)* and *(12)* needed for the first procedure were prepared by the usual methods



(11a) *(11)*

(12a)

(12)

[4] *O. Kamm* and *J. H. Waldo*, J. Amer. chem. Soc. *43*, 2225 (1921); *L. H. Cretcher, J. A. Koch*, and *W. H. Pittenger*, ibid. *47*, 1174 (1925).

[5] In the presence of catalysts for hydrogenation/dehydrogenation and hydrogen. See German Published Patent Application 1049864 (May 2nd, 1957), Wyandotte Chemical Corp.; Brit. Pat. 813957 (May 8th, 1957), Jefferson Chemical Comp.

[6] *K. Krassusky* et al., C. R. hebd. Séances Acad. Sci. *146*, 236 (1908); J. prakt. Chem. [2] *77*, 84 (1908).

[7] *E. Schmidt* and *R. Wilkendorf*, Ber. dtsch. chem. Ges. *52*, 389 (1919); *55*, 316 (1922).

Table 1. *Increase of the fungicidal action on passing from amino alcohols to the corresponding morpholines (R = morpholino group; R′ = 2,6-dimethylmorpholino group) [*].*

Compound	B.p. [°C/mm]	Infection of the leaves after spraying with an x % solution of the compound				
		x = 0.2	0.1	0.025	0.006	0.0015
n-$C_{12}H_{25}$—$N(CH_2CH_2OH)_2$	180—190/1.5	2*	2	5	5	5
n-$C_{12}H_{25}$—R	137—145/2.0	***	**	1*	3	5
n-$C_{12}H_{25}$—$N[CH_2—CH(CH_3)—OH]_2$	173—178/1.5	1*	3	5	5	5
n-$C_{12}H_{25}$—R′	155—160/5.0	***	***	**	2	5
i-$C_{13}H_{27}$—$N(CH_2CH_2OH)_2$	190—202/1.5	0**	0**	0	3	5
i-$C_{13}H_{27}$—R	152—160/1.5	***	***	0*	2	4
i-$C_{13}H_{27}$—$N[CH_2—CH(CH_3)—OH]_2$	175—180/2.5	**	0*	0	3	5
i-$C_{13}H_{27}$—R′	130—142/1.3 $n_D^{25} = 1.4568$	***	***	0	0	1
Cyclooctyl—NH—CH_2—$CH(CH_3)$—OH	91—93/0.01	0	0	2	5	5
Cyclooctyl—$N[CH_2—CH(CH_3)—OH]_2$	140—144/0.2	0	1	2	3	5
Cyclooctyl—R′	103/0.4 $n_D^{25} = 1.4855$	1	1	2	2	3
Cyclododecyl—NH—CH_2—$CH(CH_3)$—OH	150—153/0.5	2	3	3	4	4
Cyclododecyl—$N[CH_2—CH(CH_3)—OH]_2$	195—197/1.0	1	2	3	3	4
Cyclododecyl—R′	161—162/1.5 $n_D^{25} = 1.4907$	***	0*	0	0	1

[*] Key to Tables 1—5: 0 = no infection, ranging to 5 = total infection.
* = slight leaf damage, ranging to = *** total damage.

Table 2. *Influence of the N-substituent on the fungicidal action of 2,6-dimethyltetrahydro-1,4-oxazines (R′ = 2,6-dimethylmorpholino group)*

Compound	B.p. [°C/mm]	Infection of the leaves after spraying with an x % solution of the compound				
		x = 0.2	0.1	0.025	0.006	0.0015
i-C_9H_{19}—R′	98—100/1.0 $n_D^{25} = 1.4525$	**	2*	3	5	5
i-$C_{10}H_{21}$—R′	93/0.4 $n_D^{25} = 1.4521$	1**	1**	5	5	5
n-$C_{12}H_{25}$—R′	155—160/5.0	***	***	**	2	4
i-$C_{13}H_{27}$—R′	139—142/1.3 $n_D^{25} = 1.4568$	***	***	0	0	1
n-$C_{18}H_{37}$—R′	200—208/1.5	0*	0	0	1	2
Cyclohexyl—R′	74/0.4	1	2	3	3	5
Cycloheptyl—R′	80—81/0.5	1	2	2	2	4
Cyclooctyl—R′	103/0.4 $n_D^{25} = 1.4855$	1	1	2	2	3
Cyclododecyl—R′	161—162/1.5 $n_D^{25} = 1.4907$	***	0*	0	0	1
4-Methylcyclohexyl—R′	132—137/1.2	0	1	2	3	5
4-(2-Methylbut-2-yl)cyclohexyl—R′	100—103/0.1	***	0*	0	0	2
4-Nonylcyclohexyl—R′	147—151/0.2	***	0*	0	1	2
β-Naphthyl—R′	141—148/0.1	5*	5	5	5	5
4-Cyclohexylcyclohexyl—R′	136—138/0.2	***	2**	5	5	5
4-(2′-Isopropylcyclohexyl)cyclohexyl—R′	169—174/0.4	0*	0	0	2	3
CH_3-$(CH_2)_3$-$C(C_2H_5)H$-CH_2-O-$(CH_2)_3$—R′	129—138/0.6	1**	1*	1	2	3
i-C_7H_{15}—(*p*-C_6H_4)—O—CH_2—CH_2—R′	170—182/0.5	0*	0*	0	1	1
C_9H_{19}—(*p*-C_6H_4)—O—$C(CH_3)H$—CH_2—R′	184—190/0.1	0**	0*	0	1	2

[8], mainly by complete hydrogenation of the easily available alkylphenols, followed by dehydrogenation of the resulting alcohols to yield ketones *(11a)*, and reductive amination of the latter. Alternatively, carbonyl compounds were condensed with cycloalkanones, followed by hydrogenation and reductive amination of the resulting cycloalkylidenealkanones *(12a)*.

Some tetrahydro-1,4-oxazines, particularly those carrying large alicyclic substituents, behave as sterically hindered strong bases ("Hünig bases"), and are difficult to peralkylate with the usual reagents [*].

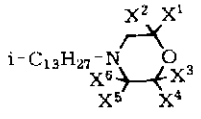
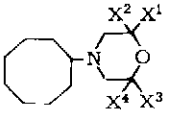
III. Relations between the Chemical Constitution and the Fungicidal Action of Tetrahydro-1,4-oxazines, Their Precursors, and Analogues

For the sake of clarity, the following Tables list only the results obtained on treating *Erysiphe graminis* (powdery mildew of barley).

Most morpholines are active against powdery mildews (such as the mildews of cereals, cucumbers, roses, gooseberries, scorzonera, and apples), against fungi causing plant rusts such as grain rust, against *Sigatoka*, a fungus disease of banana leaves, and also against the molds attacking citrus fruits. Some morpholines are also active against downy mildew fungi such as *Peronospora* and *Phytophthora*. The compounds included in the Tables represent only a small fraction of the large number of substances examined.

Table 1 shows that the fungicidal action is generally stronger for tetrahydro-1,4-oxazines than for the corresponding amino alcohols. It is immaterial whether the amino alcohol contains one or two OH-groups. The great influence of the *N*-substituent of the tetrahydro-1,4-oxazine upon the fungicidal action is shown in Table 2.

Table 3. Variation of the fungicidal action with the *C*-substituents at the tetrahydro-1,4-oxazine ring.

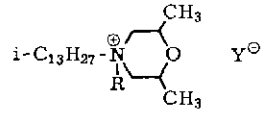
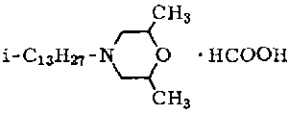
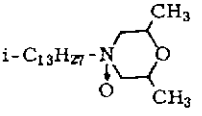
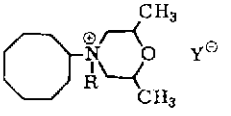
Compound	B.p. [°C/mm]	Infection of the leaves after spraying with an x % solution of the compound				
		x = 0.2	0.1	0.025	0.006	0.0015
X^1 to X^6 = H 	160/1.5	***	***	0*	2	4
$X^1 = X^3 = CH_3$; $X^2 = X^4 = X^5 = X^6 = H$	139–142/1.3 $n_D^{25} = 1.4568$	***	**	0	0	1
$X^1 = X^5 = CH_3$; $X^2 = X^3 = X^4 = X^6 = H$	167–172/3.0	***	0*	0	2	4
$X^5 = X^6 = CH_3$; X^1 to $X^4 = H$	111–112/0.1 $n_D^{25} = 1.4607$	***	0**	0*	0	0
$X^1 = X^5 = X^6 = CH_3$; $X^2 = X^3 = X^4 = H$	119–124/0.3 $n_D^{25} = 1.4573$	***	***	0*	1	2
X^1 to $X^4 = CH_3$; $X^5 = X^6 = H$	135–136/0.8 $n_D^{25} = 1.4580$	***	0*	0	1	3
$X^1 = CH_3$; $X^3 = C_6H_5$; $X^2 = X^4 = X^5 = X^6 = H$	198–205/1.5	0*	0	0	2	3
X^1 to $X^4 = H$ 	116/1.1 $n_D^{25} = 1.4950$	0	1	2	2	3
$X^1 = CH_3$; $X^2 = X^3 = X^4 = H$	106–107/0.6 $n_D^{25} = 1.4920$	0*	0	1	3	4
$X^1 = X^3 = CH_3$; $X^2 = X^4 = H$	103/0.4 $n_D^{25} = 1.4855$	1	1	2	2	3
$X^1 = X^2 = CH_3$; $X^3 = X^4 = H$	92–94/0.2 $n_D^{25} = 1.4878$	0	1	1	3	4
$X^1 = X^2 = X^3 = CH_3$; $X^4 = H$	109–112/0.3 $n_D^{25} = 1.4820$	0	2	2	4	5
$X^1 = CH_3$; $X^3 = C_2H_5$; $X^2 = X^4 = H$	118–119/0.5 $n_D^{25} = 1.4872$	0**	0*	0	2	5
X^1 to $X^4 = CH_3$	111–114/0.4 $n_D^{25} = 1.4850$	1	1	2	3	5
$X^1 = C_6H_5$; $X^2 = X^3 = X^4 = H$	163–165/0.5	0*	1	3	3	4
$X^1 = X^3 = C_6H_5$; $X^2 = X^4 = H$	217–225/0.5	2	3	5	5	5

N-Alkyltetrahydro-1,4-oxazines (except *N*-butylmorpholine) exhibit good fungicidal action, especially when the hydrocarbon chain attached to the nitrogen

[8] *H. Schröter* in *Houben-Weyl*: Methoden der organischen Chemie. 4th Edit., Thieme, Stuttgart 1957, Vol. 11, p. 602.

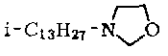
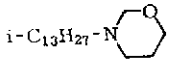
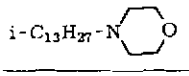
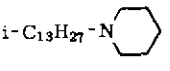
[*] The quaternary tetrahydro-oxazonium salts were investigated especially by Dr. *A. Steimmig*.

Table 4. The effect of quaternization on the fungicidal action and on the phytotoxicity of tetrahydro-1,4-oxazines [*].

Compound	Infection of the leaves after spraying with an x % solution of the compound				
	x = 0.2	0.1	0.025	0.006	0.0015
 $R = CH_3$; $Y = O_3SOCH_3$	0*	0	0	0	1
$R = C_2H_5$; $Y = O_3SOC_2H_5$	0	0	0	0	0
$R = CH_2{-}C_6H_5$; $Y = Br$	0	0	0	0	1
	***	0**	0	0	0
	***	0**	0*	0*	0
$R = CH_3$; $Y =$ 	0	0	1	2	3
$R = CH_3$; $Y = O_3SOCH_3$	0	0	0	0	3
N-Cyclohexyl-2,6-dimethylmorpholine adipate	0	0	0	0	1
N-Cyclohexyl-2,6-dimethylmorpholine benzoate	0*	0	0	0	0

[*] These compounds were obtained in solution only.

Table 5. The fungicidal action of tridecylamine derivatives.

Compound	B. p. [°C/mm]	Infection of the leaves after spraying with an x % solution of the compound				
		x = 0.2	0.1	0.025	0.006	0.0015
	160/1.5	***	***	0*	2	4
	133—138/1.6 $n_D^{25} = 1.4631$	***	0**	0	1	3
	129—133/2.0 $n_D^{25} = 1.4595$	***	0**	1	3	4
	117—120/0.5 $n_D^{25} = 1.4608$	***	***	***	0*	1
$i\text{-}C_{13}H_{27}{-}NR^1R^2$; $R^1 = H$; $R^2 =$ Cyclohexyl	157—167/0.5	***	0*	0	0	1
$R^1 = H$; $R^2 =$ Cyclohexyl; HOOC—COOH-adduct	oil	0	0	0	0	1
$R^1 = H$; $R^2 =$ Cyclohexyl; 1/2 $Ni(CH_3CO_2)$-adduct	oil	0*	0*	0	0	1
$R^1 = CH_3$; $R^2 =$ Cyclohexyl	152—156/0.3	***	0**	0	1	4
$R^1 = H$; $R^2 = s\text{-}C_4H_9$	114—129/0.5	***	***	0*	1	2
$R^1 = CH_2{-}C(CH_3)_2{-}OH$ $R^2 = CH(CH_3){-}COOH$	oil	0*	0*	0	0	3
$R^1 = CH(CH_3){-}COOH$; $R^2 =$ Cyclooctyl	oil $n_D^{25} = 1.4808$	0*	0*	0	1	1

contains 12 to 18 carbon atoms. With alicyclic *N*-substituents, the fungicidal properties are considerable even when the alicyclic group contains only 7–8 carbon atoms. Alkylated cyclohexyl groups or bicyclic substituents usually do not lead to the same activity as larger ring systems (*e.g.* the cyclododecyl group). Tetrahydro-1,4-oxazines with aromatic *N*-substituents generally do not exhibit good fungicidal properties. However, when the aromatic group is linked to the nitrogen atom by an aliphatic residue, the fungicidal action will be strongly increased, particularly if the aromatic group is further substituted with a fairly large aliphatic residue (cf. Table 2).

Table 3 shows that the fungicidal activity of tetrahydro-1,4-oxazines is enhanced (relative to unsubstituted or aromatically substituted compounds of the same type) by lower alkyl substituents on the C-atoms. Particularly good fungicidal properties, coupled with low phytotoxicity, are observed when the carbon atoms in positions 2 and 6 of the tetrahydro-1,4-oxazine ring carry hydrogen atoms and lower alkyl groups. The fungicidal activity changes only slightly when the free electron pair on the nitrogen atom of the morpholine ring is blocked (see Table 4). However, the anion of the resulting quaternary salt may exert a greater influence.

It can also be seen from Tables 1–4 that compounds containing alicyclic *N*-substituents generally have a lower phytotoxicity than derivatives of comparable or somewhat better fungicidal action which carry an open-chain aliphatic substituent. This applies in particular to the *N*-tridecyltetrahydro-1,4-oxazines. The tridecyl group clearly is exceptional among aliphatic substituents, since many tridecylamine derivatives are good fungicides; in this respect it is of minor importance whether the nitrogen atom is further substituted. This is shown in Table 5 which lists ring systems differing from tetrahydro-1,4-oxazine.

In conclusion it can be said that substitution of the nitrogen in tetrahydro-1,4-oxazine by an alicyclic group containing more than 7–8 carbon atoms frequently results in good fungicidal properties. A further increase in the fungicidal activity is caused by aliphatic or alicyclic *N*-substituents containing 12–18 carbons, and by one or two lower alkyl substituents, preferably in positions 2 and 6 of the tetrahydro-1,4-oxazine ring.

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The Function of the Promotors in the Technical Ammonia Catalyst

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An attempt is made to give a phenomenological description of the relationships between the catalytic activity and the distribution of the promotors in the reduced ammonia catalyst. Investigations were carried out on series of catalysts whose compositions were gradually brought closer to that of technical ammonia catalysts by the addition to iron of one new activator (Al_2O_3, K_2O, CaO, MgO, SiO_2) at a time.

Following the elucidation of the composition of a catalyst suitable for the technical synthesis of ammonia by *Mittasch* [1], numerous investigations were carried out on the function of the activators. Publications on this topic up to 1955 are reviewed in monographs by *Frankenburg* [2], *Bokhoven*, *van Heerden*, *Westrik*, and *Zwietering* [3], and *Nielsen* [4]. More recent papers have dealt with the kinetics of the reaction over singly and multiply promoted catalysts [5–7d], the mechanism of reversible poisoning [8], and the reaction kinetics in the

[1] *A. Mittasch*: Geschichte der Ammoniaksynthese. Verlag Chemie, Weinheim/Bergstr. 1951.

[2] *W. G. Frankenburg* in *P. H. Emmett*: Catalysis. Reinhold Publishing Corp., New York 1955, Vol. III.

[3] *C. Bokhoven, C. van Heerden, R. Westrik*, and *P. Zwietering* in *P. H. Emmett*: Catalysis, Reinhold Publishing Corp., New York 1955, Vol. III.

[4] *A. Nielsen*: An Investigation on Promoted Iron Catalyts for the Synthesis of Ammonia. 2nd Edit., Jul. Gjellerups, Copenhagen 1956.

[5] *A. Ozaki, H. Taylor*, and *M. Boudart*, Proc. Roy. Soc. (London) Ser. A. *258*, 47 (1960).

[6] *R. Krabetz* and *Cl. Peters*, Ber. Bunsenges. physik. Chem. *67*, 381 (1963).

[7] *R. Brill* and *S. Tauster*, J. chem. Physics *36*, 2100 (1962).

[7a] *H. Kubota* and *M. Shindo*, Chem. Engng. (Japan) *23*, 242 (1959).

[7b] *J. Scholten*, Thesis, Delft 1959.

[7c] *K. Tamaru*: Actes 2. Congrès International de Catalyse Technip, Paris 1961, Vol. I, p. 325.

[7d] *S. Enomoto* and *J. Horiuti*, J. Res. Inst. Catalysis Hokkaido Univ. *2*, 87 (1953).

[8] *A. V. Krylova* and *E. Ch. Jenikejew*, Chem. Techn. *15*, 231 (1963).

presence of catalysts poisoned with sulfur [9,10]. A more detailed picture of the influence of alumina on the surface structure of the reduced catalysts has been obtained [11]. Attempts have been made to explain the action of potassium in the light of current views on heterogeneous catalysis [8,12].

As the requirements placed upon the ammonia catalyst became increasingly stringent, its composition became more and more complex. The first BASF technical catalyst consisted essentially of iron and two promotors (alumina and potassium oxide); calcium oxide was later added to give a triply promoted catalyst. Recently, quadruply and quintuply promoted catalysts containing magnesium or beryllium and silica as well as alumina, potassium oxide, and calcium oxide, have gained technical importance.

1. Experimental

a) Preparation

The catalysts were prepared by oxidative melting [1], using iron carbonyl and analytically pure additives.

b) Reduction and Activity Testing

The catalysts were both reduced and tested for activity with a stoichiometric nitrogen/hydrogen mixture at atmospheric pressure. The gases were so pure that the activity of an unpromoted catalyst remained unaltered for several weeks of use. The catalyst samples were reduced at 450 °C and subsequently at 480 °C until the concentration of ammonia in the final gas showed no increase (about 80 h). The catalytic activity was tested with 4 g samples of sieve fractions between 0.4 and 0.6 mm mesh size, at a space velocity of 10000 l of gas per liter of catalyst per hour. The quantity of ammonia in moles-% of the total gas formed under these conditions at 370 °C was taken as a measure of the catalytic activity.

c) Determination of the Total Surface Area

The total surface area was determined from the quantity of nitrogen adsorbed at −195 °C, using the method described by *Brunauer*, *Emmett*, and *Teller* [13]. The value taken for the area occupied by an adsorbed molecule of nitrogen was that reported by *Livingstone* [14], *viz.* 15.4 Å^2.

d) Distribution of the Promotors in the Catalyst Surface

The proportions of "free-iron surface area" and "free-potassium surface area" to the total surface area of the catalyst were determined by the method of *Brunauer* and *Emmett* [15].

The proportion of "free-iron surface area" to the total surface area is defined as the ratio of the quantity of carbon monoxide chemisorbed at −183 °C to the quantity of physically adsorbed carbon monoxide. Similarly, the proportion of "free-potassium surface area" to the total surface area is given by the ratio of the quantities of carbon dioxide chemisorbed and physically adsorbed at −78 °C. Although carbon dioxide is also chemisorbed on calcium and magnesium oxides under these conditions, we shall retain the term "free-potassium surface area" for catalysts which contain alkaline earth oxides as well.

e) Pore Size Distribution

The pore size distribution for very small pore sizes (10–500 Å in diameter) was determined from the capillary condensation, using the method proposed by *Barret*, *Joyner*, and *Halenda* [16]. The size distribution of pores with diameters between 150 and 300000 Å was determined by impregnation with mercury (at pressures of up to 1100 atm), as described by *Drake* and *Ritter* [17].

f) Water-Soluble Potassium

The water-soluble portion of the potassium oxide in the unreduced catalyst samples was determined by extraction with water for 24 hours, using uniform sieve fractions (900 to 1600 meshes/cm^2).

2. Results

a) Fe—Al_2O_3 Catalysts

We have dealt in detail with the influence of alumina in an earlier paper [11]. The catalytic activity reaches a maximum at 3% alumina. The total surface area increases rapidly with alumina contents of up to 3%, but beyond this concentration, the increase becomes slower, and the proportion of free iron in the surface decreases. Like the activity, the free-iron surface area reaches a maximum at an alumina content of 3%.

The principal function of the alumina is to stabilize a porous iron structure with a large surface area. The 3 to 4% alumina is probably the quantity which is dissolved in the magnetite lattice and which separates out at the surface on reduction as an intimate mixture with the iron atoms. A further portion of the Al_2O_3 separates out together with magnetite between the iron regions, in the form of mixed spinels which are difficult to reduce. This portion makes no substantial contribution to the formation of the surface, but simply decreases the proportion of free iron in the surface.

Stabenow [17a] has carried out electron-microscopic studies on ultrathin sections of catalysts which were singly promoted with various quantities of alumina. The samples were prepared by oxidative melting and were reduced at 500 °C. They exhibited a structure intermediate between the two extremes [3,4] of a continuous solid iron phase with many pores (sponge structure) and a loose packing of iron particles in which the interstitial

[9] *R. Krabetz* and *Cl. Peters*, Ber. Bunsenges. physik. Chem. *67*, 522 (1963).

[10] *R. Brill* and *S. Tauster*, Ber. Bunsenges. physik. Chem. *67*, 390 (1963).

[11] *Cl. Peters*, *K. Schäfer*, and *R. Krabetz*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *64*, 1194 (1960).

[12] *G. M. Schwab* and *R. Putzar*, Z. physik. Chem. *31*, 341 (1942).

[13] *S. Brunauer*, *P. H. Emmett*, and *E. Teller*, J. Amer. chem. Soc. *60*, 309 (1938).

[14] *H. K. Livingstone*, J. Colloid Sci. *4*, 447 (1949).

[15] *P. H. Emmett* and *S. Brunauer*, J. Amer. chem. Soc. *62*, 1732 (1940).

[16] *E. P. Barret*, *L. G. Joyner*, and *P. Halenda*, J. Amer. chem. Soc. *73*, 373 (1951).

[17] *L. C. Drake* and *H. Ritter*, Ind. Engng. Chem., analyt. Edit. *17*, 45 (1945).

[17a] *J. Stabenow*, BASF, personal communication.

spaces form the "pores". The dimensions of the irregular, continuous cavities were found to vary from less than 100 to over 1000 Å, in agreement with the values obtained from pore size distribution curves. The sizes of the iron particles are similar to those of the pores.

Another function of the alumina is probably to prevent the thermal transformation of particularly active crystal faces, *e.g.* the (111) face. When magnetite is carefully reduced at about 300 °C, the reduced iron chemisorbs roughly one molecule of carbon monoxide per atom of iron, when it is assumed that the exposed crystal face is the (111) face [18]. If the catalyst is then heated to 600 °C, the quantity of carbon monoxide chemisorbed per atom of iron decreases by 50%, which indicates that the iron surface has been sintered to more closely packed crystal faces. The quantity of carbon monoxide chemisorbed on the sample containing 3% alumina was the same before and after heating at 600 °C.

The sensitivity of the catalyst towards inactivation by sulfur or chlorine decreases with increasing alumina content [18a].

b) Fe—Al_2O_3—K_2O Catalysts

Small quantities of a potassium compound are added during the preparation of the catalyst by the melting method. This leads to an increase in activity, but only in catalysts which contain difficultly reducible oxides of metals of Groups III and IV. The catalytic activity of pure iron is reduced on introduction of potassium oxide. The change in the activity of catalysts containing alumina depends on the quantity of potassium oxide added (see Fig. 1).

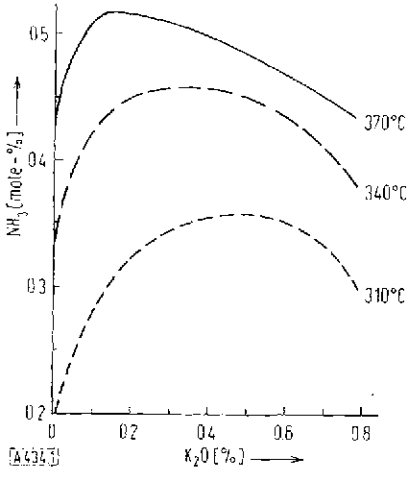

Fig. 1. Influence of the potassium content on the yield of ammonia obtained over an Fe—Al_2O_3—K_2O catalyst containing 2.5% Al_2O_3, after reduction at 480 °C.

In contrast to the situation with singly promoted catalysts, here the action of the promotor is not related to the total surface area or to the free-iron surface area, both of which decrease with increasing potassium content (see Fig. 2). Any increase in the potassium content simply leads to an increase in the concentration of potassium at the surface. This quantity again bears no direct relationship to the catalytic activity, since the activity falls off again when the surface concentration of potassium exceeds 30%, corresponding to a potassium oxide content of 0.78%.

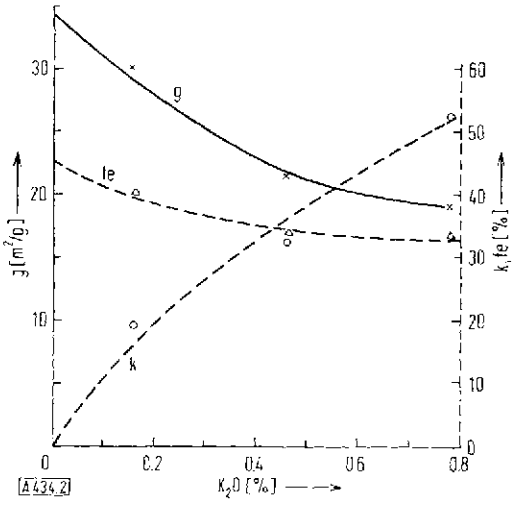

Fig. 2. Influence of the potassium content on the total surface area (g), the percentage of free-potassium surface area (k), and the percentage of free-iron surface area (fe) for Fe—Al_2O_3—K_2O catalysts.

The observation that samples containing potassium have smaller internal surface areas than those without it indicates that potassium promotes recrystallization of the iron crystallites. This effect is particularly noticeable when the reducing or synthesis gas contains oxygen compounds. Table 1 shows the ammonia yields at 370 °C and the total surface areas for catalysts with increasing potassium content immediately after reduction (I), after ageing in extremely pure gas at 600 °C (II), and after ageing at 600 °C in a gas containing oxygen (III). In addition to the acceleration of the decrease in surface area in the presence of small quantities of oxygen, this table clearly shows that high potassium contents decrease the stability of the catalysts towards overheating.

Table 1. Resistance of catalysts containing potassium and 2.2% of Al_2O_3 towards sintering, after various pretreatments (cf. text).

Total K_2O [%]	Total surface area [m^2/g]			NH_3 yield at 370 °C [%]			K_2O in the surface [%]
	I	II	III	I	II	III	I
0.18	30.1	22.3	20.5	0.518	0.510	0.456	19.3
0.46	(21.6)	18.9	15.3	0.486	0.425	0.401	32.3
0.78	19.2	18.1	14.6	0.433	0.361	0.336	52.3

The pore structure also undergoes a typical change during recrystallization. Figure 3 shows the distribution of pore size for a sample containing no potassium, a second with a low potassium content, and a third with a high potassium content after heating at 600 °C.

The fine pores (100–400 Å) of the potassium-free catalyst are replaced by larger pores (400–1600 Å) on addition of potassium. The mean pore diameter was calculated from the inner surface area O [*] and the pore

[18] *R. Westrik* and *P. Zwietering*, Proc., Kon. nederl. Akad. Wetensch., Ser. B. *56*, 492 (1953).

[18a] Unpublished observation of the BASF Ammoniak Laboratorium.

[*] Determined by the method of *Brunauer*, *Emmett*, and *Teller*.

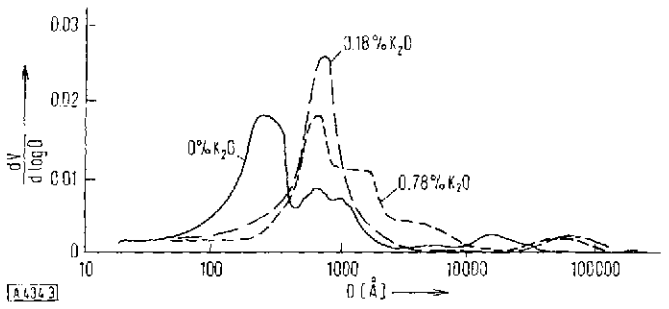

Fig. 3. Influence of the potassium content on the pore size distribution in $Fe-Al_2O_3-K_2O$ catalysts.

Abscissa: Pore diameter D [Å].

Ordinate: $\frac{dV}{d \log D}$, *i.e.* the distribution of pore volumes V corresponding to the various pore diameters D.

volume V_p [*] of a catalyst sample, using the formula $\overline{D} = 4V_p/O$. The values obtained were 284 Å for the sample containing no potassium, 364 Å for the catalyst with the low potassium content, and 484 Å for that with the high potassium content. The total pore volume is practically the same for all the catalysts (0.15 cm^3/g).

The fact that the ammonia yield is maximum at a certain potassium content can be explained by the opposing influences of the potassium increasing the catalytic activity on the one hand, and decreasing the free-iron surface area by accelerating recrystallization on the other.

However, the optimum potassium content varies from one type of catalyst to another, and also according to production conditions, since the properties of the potassium-activated catalysts are governed not only by the concentration of the activator, but also by its distribution in the surface. The close relationship between structure and properties of the reduced catalyst and the distribution of the potassium in the unreduced sample can be seen from the following experiment.

Fused magnetite containing 2.5% alumina and 0.5% potassium oxide was cooled at three different rates in tubes of different diameters. The sample which was cooled slowest (Fig. 4a) had a more homogeneous structure than the other two, which solidified faster. Since only the potassium was dissolved out at the dark patches in the polished surfaces, photomicrographs give a first indication of the distribution of the potassium.

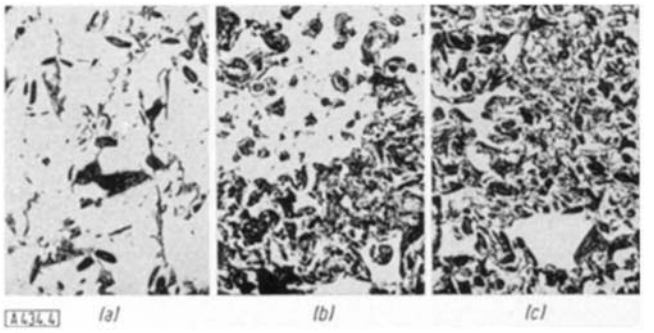

Fig. 4. Photomicrographs (magnification 100×) of $Fe-Al_2O_3-K_2O$ catalyst melts solidified at various rates, after surface polishing and etching with dilute HCl.

[*] V_p is found from the true and the apparent densities of the catalyst. The true density was determined by gas pycnometry using helium and the apparent density by liquid pycnometry using mercury.

A further indication is given by the quantity of potassium which can be extracted with water. The "water-soluble potassium" [19] occurs as a separate phase at the boundaries between the secondary particles which can be seen under the light microscope and the primary particles which can be recognized in the electron microscope and is partly responsible for the structure obtained on etching. According to *Wykoff* and *Crittenden* [20], the "water-insoluble potassium" probably forms a solid solution as aluminate or ferrite with the magnetite, without mixed crystal formation. It is therefore relatively well distributed inside the particles. On reduction, it separates out as finely divided aluminate on the surface of the iron crystallites [21]. As can be seen from Column 4 in Table 2, the proportion of water-insoluble potassium is greater in the samples cooled slowly, which have more homogeneous structures.

Table 2. Analysis of unreduced $Fe-Al_2O_3-K_2O$ catalysts (Al_2O_3 = 2.8%) cooled at various rates, and the surface properties of the reduced samples.

Relative cooling time	FeO/Fe_2O_3	K_2O insoluble [%]	K_2O total [%]	Total surface area [m^2/g]	Free-iron surface area [m^2/g]	K_2O coating [% of total surface area]	NH_3 yield at 370 °C [%]
2.86	0.93	0.18	0.54	16.25	3.75	21.4	0.46
2.50	1.05	0.20	0.66	16.7	3.75	21.9	0.475
1.67	1.09	0.31	0.53	17.4	4.58	24.7	0.496
1.25	1.11	0.29	0.56	20.7	4.91	24.5	0.506
1.00	1.1	0.28	0.51	19.35	5.48	27.3	0.514

According to Table 2, these samples have a higher potassium concentration in the surface and a greater free-iron surface area after reduction than the samples with lower proportions of water-insoluble potassium. The catalytic activity and the proportion of insoluble potassium fall off again if the melt is cooled slowly [22].

Potassium also changes the resistance of the catalysts toward poisons. We found that catalysts containing potassium adsorb more hydrogen sulfide per unit area, and are poisoned to a lesser degree by a given surface coating of sulfur than samples activated with alumina alone [9]. Conversely, potassium increases the sensitivity of the catalysts toward gaseous oxygen compounds.

c) $Fe-Al_2O_3-K_2O-CaO(MgO)$ Catalysts

Catalysts activated with calcium or magnesium alone have smaller surface areas and poorer catalytic activity than samples activated with alumina ($CaO < MgO < Al_2O_3$).

[19] *R. Brill*: Structure and Properties of Solid Surface. The University of Chicago Press, Chicago 1953, p. 437.

[20] *R. W. G. Wykoff* and *E. D. Crittenden*, J. Amer. chem. Soc. *47*, 2866 (1925).

[21] *P. H. Emmett* and *S. Brunauer*, J. Amer. chem. Soc. *59*, 310 (1937).

[22] *H. Uchida* and *N. Todo*, Bull. chem. Soc. Japan *29*, 20 (1956).

However, alkaline earth oxides in combination with Al_2O_3 and K_2O have gained some technical importance. Three catalysts with constant alumina and potassium-oxide contents, but containing increasing quantities of calcium oxide, were reduced at 500 °C and then aged at 600 °C in synthesis gas containing oxygen. Table 3 shows the total surface areas after ageing and the ammonia yields before and after ageing. It can be seen from these data that the sample with the highest calcium content was the least damaged by heat treatment.

Catalysts containing calcium are also less sensitive toward irreversible poisoning by hydrogen sulfide or chlorine compounds [18a].

Table 3. Resistance of catalysts (Al_2O_3 = 2.2 %; K_2O = 0.42–0.5 %) containing calcium towards sintering.

CaO [%]	Total surface area after aging [m²/g]	NH_3 yield before aging [%]	NH_3 yield after aging [%]
0.14	11.7	0.506	0.410
0.53	13.9	0.492	0.460
1.95	16.0	0.505	0.484

Magnesium did not have the same effect as calcium in catalysts containing alumina and potassium. This is remarkable, since according to our results magnesium stabilizes an iron structure with a large surface area more efficiently than calcium, in the absence of other activators. On the other hand, if part of the calcium in a catalyst activated with 2.5% alumina, 0.5% potassium oxide, and 2.0% calcium oxide, is replaced by magnesium, the activity is increased. The ammonia yield reaches a maximum when about half of the calcium has been replaced by magnesium. This "mutual reinforcement" of calcium and magnesium is illustrated in Figure 5.

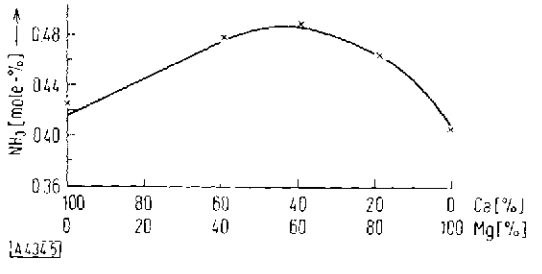

Fig. 5. Influence of the calcium/magnesium ratio on the catalytic activity of Fe–Al_2O_3–K_2O–CaO(MgO) catalysts at 370 °C.

d) Fe—Al_2O_3—K_2O—CaO(MgO)—SiO_2 Catalysts

Catalysts containing silica together with the usual activators alumina, potassium oxide, and calcium oxide have recently become technically important. Moreover, the technical Fe–Al_2O_3–K_2O–CaO catalyst contains about 0.5% silica as an impurity.

As can be seen from Table 4, the proportion of water-soluble potassium in the unreduced catalyst decreases with increasing silica content. The silica evidently leads to a more uniform distribution of the potassium inside the secondary particles, probably by formation of potassium alkaline earth silicates. The properties of catalysts containing silica are listed in Table 4. The total surface area (Column 5) increases with the silica content (Column 3), but the percentage of the total surface covered with free potassium and alkaline earth metals (Column 4) decreases. The catalytic activity (Column 6) passes through a maximum.

Table 4. Analysis of unreduced catalysts containing silica (Al_2O_3 = 2.6 %; CaO = 1.2 %; MgO = 1.5 %) and surface properties of the reduced samples.

Total K_2O [%]	Water-soluble K_2O [%]	SiO_2 [%]	K_2O(+ CaO) coverage [% of total surface area]	Total surface area [m²/g]	NH_3 yield at 340 °C [%]
0.74	0.32	0.35	41	21.3	0.320
0.69	0.17	0.55	27	23.3	0.395
0.99	0.03	2.23	17	29.7	0.374
0.83	0.03	2.72	9	30.9	0.344

Thus, a better distribution of the potassium, the alumina, and the silica during the reduction stabilizes reduced iron structures with larger surface areas. However, the catalytic activity depends not only on the total surface area, but probably also on the concentration of free potassium in the surface, which is greatly reduced by silica. This assumption was initially rather hypothetical but is supported by the following experiment.

Three series of catalysts were prepared containing respectively 0, 2.2, and 4.2% silica. The potassium content was varied over a wide range within each series. The upper part of Figure 6 shows a plot of the ammonia yield at 370 °C against the percent by weight of potassium oxide in the unreduced samples. As with the simpler Fe–Al_2O_3–K_2O catalysts, the catalytic activity passes through a maximum at a certain potassium content, which increases with the silica content. Thus, while only

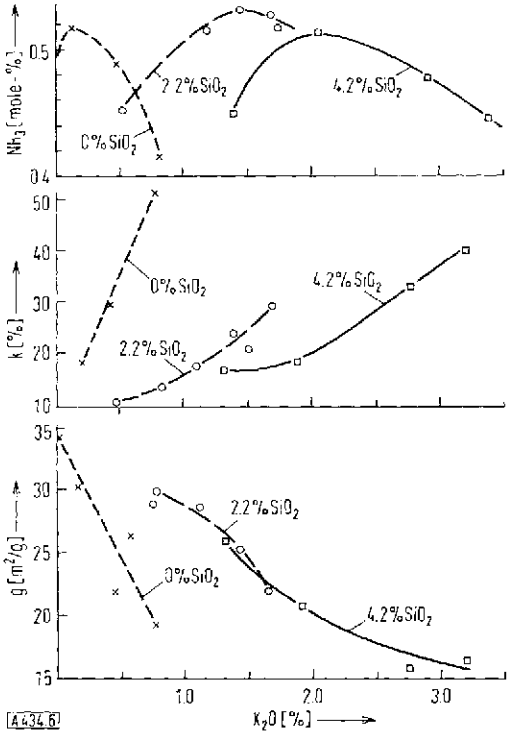

Fig. 6. Influence of the potassium content on the catalytic activity, percentage free-potassium surface area (k), and total surface area (g) for Fe–Al_2O_3–K_2O–CaO–(MgO)SiO_2 catalysts with various SiO_2 contents.

0.4% potassium oxide is required for maximum conversium with a catalyst containing no silica, 2% potassium oxide is necessary in the presence of 4.2% silica. The lower part of Figure 6 shows that the total surface area (g) within each series (*i.e.* at constant silica contents) decreases with increasing potassium content, whereas the concentration of potassium in the surface increases (Fig. 6, middle).

Figure 7 shows the ammonia yields not as a function of the potassium content of the unreduced catalyst but as a function of the percentage of potassium at the surface of the reduced sample. It is now possible to correlate the catalytic activities of the various series of catalysts in Figure 6. In Figure 7 it is shown that the best catalysts always have a potassium concentration of 25 to 30% in the surface, irrespective of the absolute quantities of silica and potassium oxide present.

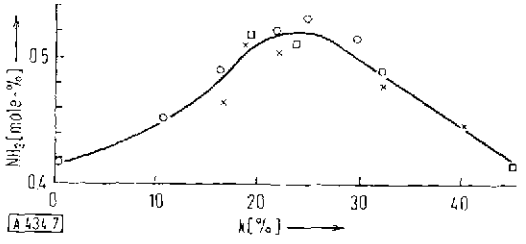

Fig. 7. Dependence of the catalytic activity on the percentage of free-potassium surface area (k) with respect to the total surface area (surface concentration of free potassium) for
Fe–Al_2O_3–K_2O–CaO(MgO)–SiO_2 catalysts.
□: without SiO_2.
○: with 2.2% by weight of SiO_2.
×: with 4.2% by weight of SiO_2.

3. Discussion

The metal oxides added to magnetite as activators can be grouped according to their influence on the surface structure and on the catalytic action of the reduced ammonia catalyst. Acidic and amphoteric oxides such as silica and alumina stabilize a fine-pored iron structure with a large surface area during reduction and use, and prevent the sintering of high-energy crystal faces which are particularly active catalytically or which are geometrically favorable to adsorption. The differences in the activities of the oxides are partly caused by different solubilities and distributions in the magnetite. The advantageous effect of alumina on technical ammonia catalysts is undoubtedly due to the ease with which the relatively small trivalent aluminum ion can replace the trivalent iron ions in the magnetite lattice or can occupy vacant interstitial sites without altering the crystal structure [3].

The alkaline earth oxides have a similar stabilizing effect, particularly when used in combination with acidic or amphoteric oxides. The divalent alkaline earth ions can replace ferrous ions in the magnetite lattice, the smaller magnesium ion being more easily accommodated than the calcium ion. The resultant ease of distribution of magnesium in the magnetite may explain the fact that magnesium has a more efficient stabilizing action than calcium in the absence of other promotors.

The mutually reinforcing effects of calcium and aluminum or of calcium and magnesium may be related to the effect described by *Nielsen* [4], *viz.* that the introduction of larger cations into the magnetite lattice is facilitated by the presence of smaller ions already dissolved therein. This picture is undoubtedly still too incomplete to explain all the differences in the stabilizing actions, *e.g.* of magnesium and aluminum. Magnesium inhibits recrystallization to a lesser extent than aluminum, although it can enter the magnetite lattice without difficulty. It may be possible to interpret differences of this kind on the basis of a theory of recrystallization advanced by *Kummer* [*].

Investigations on tungsten and nickel with the aid of the field-emission microscope suggest that the surface layer of the ammonia catalyst is constantly reorganized during the course of the synthesis as a result of chemisorption and desorption. Certain crystal faces have a stronger tendency to grow than others, and smaller crystallites tend to coalesce to larger ones. This coalescence can obviously be hindered by a surface barrier of promotors. The effect will increase with decreasing permeability of the barrier, *i.e.* with decreasing diffusion coefficient of the iron atoms or iron ions in the lattice of the promoting oxide. This will depend both on the crystal structure of the oxide and on the lattice disorder. For example, our investigations have shown that in the presence of traces of gaseous oxygen compounds, catalysts promoted with alumina alone probably form mixed spinels between magnetite or γ-alumina and the iron-alumina spinel. These mixed spinels are probably more permeable to diffusing iron atoms than the pure γ-alumina spinel, which is presumably the material of which the barrier is formed when the synthesis gas does not contain oxygen. This explains the acceleration of the recrystallization caused by oxygen compounds.

The alkali metal oxides have quite a different effect. Although these compounds accelerate rather than inhibit the recrystallization, they increase the ammonia output per unit of total surface area, particularly at high pressures. Singly promoted catalysts containing acidic or amphoteric oxides and the catalysts containing potassium also show fundamental differences in their effect on the decomposition and synthesis of ammonia, the rate of hydrogen-deuterium exchange, or the adsorption capacity for nitrogen and hydrogen. Table 7 contains a list of the various effects compiled by *Frankenburg* [2] and supplemented by ourselves on the basis of more recent work.

Frankenburg believes that the surface of the reduced catalyst stabilized by metal oxides such as alumina consists of atoms of metallic iron, intimately mixed with weakly acidic oxide centers. Proton acidity may be due to the adsorption of water, which is always present in traces in the synthesis gas. This view is in agreement with both the greater capacity of singly promoted catalysts for the chemisorption of hydrogen at −195 °C, and the ability of the catalysts containing no alkali to catalyse hydrogen-deuterium exchange at this temperature, if these properties are attributed to acidic centers (as in cracking catalysts). A further argument for the acidic character of the alkali-free catalysts is the formation of

[*] Quoted by *A. Nielsen* [4].

Table 5. Comparison of singly promoted Fe—Al_2O_3 catalysts with doubly promoted catalysts containing potassium.

Properties of the catalysts	Singly promoted with Al_2O_3	Doubly promoted with Al_2O_3 and potassium	Ref.
Chemisorption of hydrogen at −195 °C	Occurs	Extremely slight	[2]
Rate of H_2/D_2 exchange at −195 °C	half-life = 0.06 sec	half-life = 6000 sec	[2]
Influence of preadsorbed N_2 on the chemisorption of H_2 at −195 °C	Increase in chemisorption indicates formation of NH and NH_2 groups in the adsorption layer	Decrease in chemisorption	[2]
Kinetics of the decomposition of ammonia	Anomalous kinetics between 400 and 420 °C: rate of reaction decreases with pNH_3 and increases with pH_2	Rate of reaction increases uniformly with pNH_3 and decreases with pH_2 over the entire temperature range	[2]
Kinetics of the synthesis of ammonia	Satisfies a rate equation deduced on the assumption that the surface is covered with NH radicals; the rate-determining step is the adsorption of nitrogen[*]	Satisfies the Temkin rate equation deduced on the assumption that the surface is preferentially covered with adsorbed nitrogen atoms; the rate-determining step is the chemisorption of N_2. On partial poisoning with O_2, the kinetics are as for potassium-free catalysts[*]	[5-7d, 23]
Adsorption of H_2S at 400—500 °C	The potassium-activated catalyst adsorbs more sulfur per unit of area than catalysts activated by alumina alone		[9]
Specific catalytic activity	The specific catalytic activity of potassium-activated catalysts is greater than that of catalysts activated by alumina alone, particularly at high pressures		[3]

[*] It has repeatedly been assumed [7c, 7d] that a step following the adsorption of nitrogen is rate-determining. However, it has also been doubted [23] that a rate-determining step exists at all.

stable NH and NH_2 radicals on the catalyst surface during the decomposition and synthesis of ammonia; this may be compared to the poisoning of cracking catalysts by nitrogen bases. The lower adsorption capacity of the singly promoted iron-alumina catalysts for hydrogen sulfide points in the same direction.

Neutralization of the surface with alkali or more strongly basic alkaline earth oxides leads to the disappearance of these effects, but gives rise to a new type of catalyst. This is the simplest explanation for the fact that the activity of catalysts containing potassium is not related to the total content of potassium oxide, but to the basicity of the surface of the reduced catalyst. The promoting action of potassium can thus be explained from a more chemical point of view: potassium eliminates the inhibition of the ammonia synthesis caused on potassium-free catalysts by adsorbed NH, NH_2, and NH_3 particles, by accelerating further reactions of the radicals or desorption of the ammonia formed.

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Translated by Express Translation Service, London

[23] *M. Boudart*, Chem. Engng. Progress *58*, 73 (1962).

Mechanization of Chemical Documentation

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The principal reasons for the failure of mechanized documentation to gain wide acceptance in chemistry are the inflexibility of the systems used and the difficulties encountered in precisely formulating all search questions. The present paper describes documentation methods for structural formulae, reaction types, and other data; these methods are more flexible than those commonly used. To avoid the use of electronic computers for simple enquiries, it is suggested that small card files should be supplied ready-encoded from a central store, and mechanically sorted in accordance with the code which best suits the particular case

Chemistry, more than any other branch of science, is founded upon innumerable experimental experiences, which may be repeated at any time, and which are described in the technical literature. It is therefore particularly important to make this literature readily accessible; consequently, chemical documentation has become highly developed.

In his search for literature references, the chemist is aided by the well-known reference books (*e.g.* "Gmelin", "Beilstein", "Houben-Weyl", *etc.*) and by the indexes of the abstracting

journals (Chemisches Zentralblatt, Chemical Abstracts). As the technical literature increases in volume, however, queries must be fitted more closely to the problem at hand, with the result that these traditional aids are becoming increasingly inadequate. For this reason, individual card files have been compiled. These files are growing at an alarming rate, and a great deal of work is involved in the classification and filing of newly published material. The obvious solution is to make use of mechanical aids and data processing equipment.

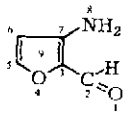
The great difficulty in documentation lies in the volume of the material to be processed and in the wide variety of possible questions. A good documentation system should be sufficiently flexible to permit the storage and retrieval of information of an entirely new nature without changing the code book. Also the store should be able to answer questions which were not foreseen when it was compiled. It must be possible to formulate questions to the store so precisely that a minimum of irrelevant material is retrieved, while at the same time no important information is missed. And finally the costs of encoding, storage, and retrieval must not be excessively high.

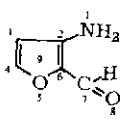
It is only when these requirements are met that mechanized documentation systems will be satisfactory even for very large quantities of data. The development of methods and equipment in this field is still in its infancy. The first objective, therefore, is to evolve sufficiently flexible systems. Two methods of coding are described in the present paper, neither of which has yet fully proved its value in practice. They are nevertheless published at this stage in order to promote the exchange and progress of ideas.

1. Documentation of Structural Formulae

One aspect of chemical documentation is concerned with information which can be conveyed by structural formulae. This information consists of "hard" data, *i.e.* of data the meaning of which is unambiguous and sharply defined. On the other hand, the number of criteria involved here and of their possible combinations is particularly large. This justifies the application of methods other than those used in dealing with information which cannot be represented by formulae. Nevertheless, both documentation systems must be capable of combination, since many questions relate to structures as well as to other criteria.

The chemist must be able to ask for any desired structure or partial structure. As early as 1951, *C. N. Mooers* [1] pointed out that queries regarding partial structures are possible if a topological coding system [2] is used. In this system, the atoms of a molecule are numbered, in any order; the code for each atom includes, in addition to its number and symbol, the numbers of the atoms to which it is attached (Fig. 1). Multiple bonds and other special features can be denoted by additional code numbers, together with the numbers of the atoms involved.





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25344	007	019	+	017	028	018	+	018	017	019	031	+	019	007	018	031	020	+	020	019	+
25344	028	039	017	041	+	031	019	018	042	+	039	051	028	+	041	028	042	+	042	041	031
25344	+	051	039	063	+	063	051	076	+	065	076	066	+	066	065	079	+	076	063	065	089
25344	+	079	066	090	091	+	089	076	090	+	090	089	079	091	+	091	079	090	103	092	+
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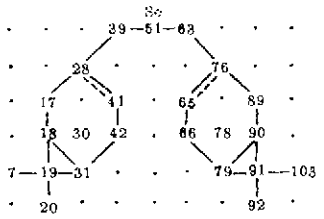


Fig. 3. Topological representation (top, read horizontally from left to right) and formula, showing the numbering of the grid positions.

The punched tape is then passed to an electronic data processor, which prepares the topological representation (Fig. 3, top) and simultaneously prints out the formula (Fig. 4, top), so providing a check on the coding

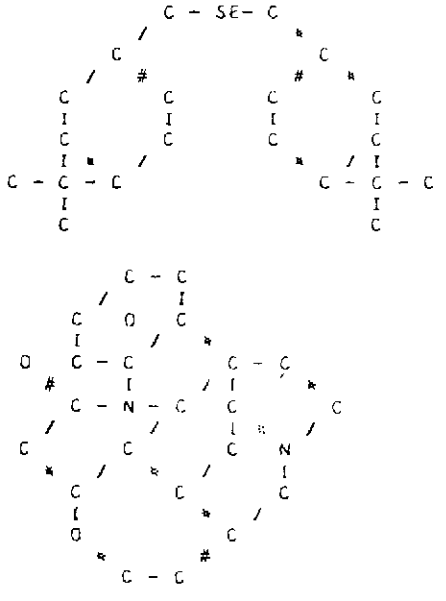


Fig. 4. Structural formulae reconstructed by the computer from topological representations (bottom: strychnine).

The topological method is complicated by the need to store and enquire about incompletely defined structural formulae (*e.g.* with substituents at undefined locations in a ring), formulae with variable substituents (Markush formulae [4]), and even chemical reaction schemes. However, these problems can be solved. For example, reactions are encoded [4a] by superimposing transparent gridded sheets containing the formulae of the starting materials and the final products in such a way that identical atoms obtain the same grid point numbers.

As an example, Figure 5 shows the reaction of a bromo compound (sheet A) with acetoacetic ester (sheet B) to yield a ketone (sheet C). Ethanol and carbon dioxide, which are also formed, are trivial in this connection and are therefore omitted. Later, queries can be largely varied: it is possible to enquire about syntheses using acetoacetic ester in general, or about syntheses with acetoacetic ester and α,β-unsaturated bromo compounds. Even more specific, reactions involving α,β-unsaturated β-branched or α,β:ε,ζ-unsaturated bromo compounds can be searched for. To this end, the reaction scheme must be keyed onto the tape together with the index numbers of the individual gridded sheets (A, B, and C in the case of Figure 5). It is then possible at a later date to enquire not only about any conceivable partial structure, but also about any type of reaction which can be represented by a series of partial structures. This is an important feature, since most of the queries from preparative chemists are basically concerned with reactions.

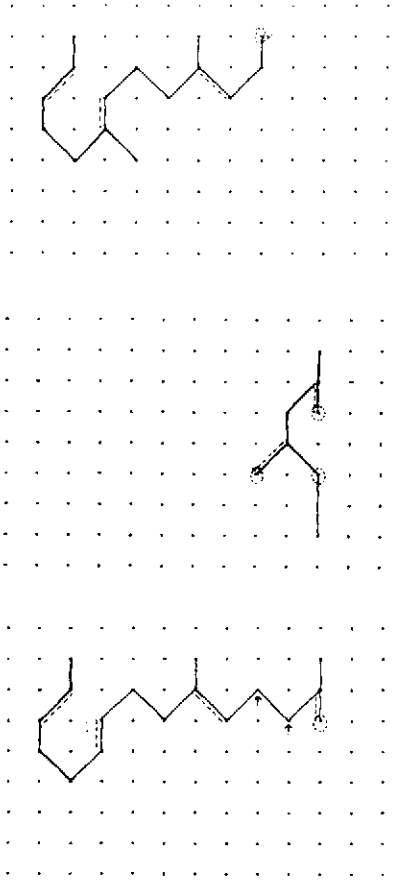
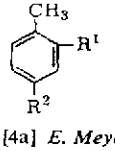


Fig. 5. Encoding of chemical reactions (cf. text). Partial structures of various sizes in the starting materials and products can later be searched for. If equivalent atoms in these structures are topographically identical, *i.e.* occupy equivalent positions on the gridded sheets, all reactions are obtained which can be described by the given scheme of partial structures.

[4] *Markush* established the permissibility, in U.S. Patent law, of claims which protect groups of substances. For this reason, the term "Markush formula" is given to a formula which represents several definite compounds by the use of variable substituents, *e.g.*



$R^1 = NH_2, NHCH_3, OCH_3;$

$R^2 = NO_2, CF_3.$

[4a] *E. Meyer*, Nachr. Dokumentat. *13*, 144 (1962); ADI Annual Meeting 1963, Short Papers, Part 2, p. 131.

Thus satisfactory solutions to the problem of topological coding had been found [5]. There remained the question whether searches could be carried out at acceptable costs. Preliminary tests with an IBM 704 showed that the time required for comparing a structural formula, atom by atom, with all the formulae in the store is too long by at least one order of magnitude. Therefore, the number of comparisons required for each query must be reduced to comprise only about one percent of the formulae in the store.

In searches for single compounds, this would present no difficulties. The machine would first check the empirical formula, the number of rings, double bonds, *etc.*, and would then have only a small number of isomers to examine for topological equivalence with the formula in question. However, a search of this type can be more easily accomplished by the old method, using a formula index. The problem becomes more severe when searching for classes of compounds which can be described only by partial structures. Here it is necessary to use other criteria for the preliminary examination of the structures in the store. For example, the topological representations may be prefixed by code signs indicating characteristic groupings in the compounds. This would double the work involved in coding, however, and would be acceptable only if the code for preliminary examination could be produced mechanically and automatically from the topological representations of the compounds. Work is being carried out at present on machine programs for transcoding operations of this type. In addition, new methods of topological comparison have been developed at Harvard University [9] which seem to be less time-consuming than those used by us. It can therefore be expected that topological systems will soon find practical application.

2. Documentation of Other Information

Data regarding processing, applications and other topics should also be stored in such a form, that they can be searched for by machine and from as many viewpoints as possible. At present, these data are coded by pure classification: key words or criteria relating to a given document (*i.e.* to a literature reference) are selected from a questionnaire or code book, and are punched and stored. This procedure has the disadvantage that concepts which do not fit accurately into the scheme of the code (in particular those which are new) cannot be satisfactorily characterized. The code must be modified and supplemented at regular intervals, with the result that the store becomes increasingly heterogeneous, and search becomes increasingly difficult.

In the case of large stores, the documents must be very thoroughly analysed. Not only must the code book include a very large number of terms, but a very large number of criteria must also be recorded for each document. This makes coding more difficult and increases the volume of unwanted material retrieved by multiplying the number of spurious combinations of code terms which do not, in fact, relate to the document in question.

Is was therefore attempted to move away from pure classification and, as in language, to establish syntactical relationships between the code terms, which can be searched mechanically. At the same time this would make possible the synthesis of composite terms, thus permitting a considerable reduction in the size of the vocabulary or code. The "links" and "role indicators" [9a] which are occasionally used may be regarded as first steps in this direction. Since the store is only intended to supply sufficient information for reliable retrieval, the vocabulary and syntax of "machine language" can be much more limited than in natural language. In order to keep the costs of searching as low as possible, the vocabulary and syntactical relationships must be standardized. Moreover, the code for chemical compounds (even the topological code) must be compatible with this system, to permit the inclusion of structural features and reaction types in a complex statement of facts. The most important requirement, however, is that there should be no significant increase in the work involved in coding. All these requirements are largely satisfied by the following procedure.

The first step in coding is to select the various key concepts from the document and to list these in any order in the form of their notations [9b], or in the case of chemical compounds, in the form of their topological representations. The notations used should be such that the machine can recognize the broader concept to which any subconcept belongs; this condition is automatically satisfied by the topological representations.

Each concept on the list is assigned an identification number, which relates only to the particular document in question. The operator pencils these numbers against the appropriate key words or formulae in the document. The next step is to build up "sentences", which give an unambiguous representation of the essential information contained in the document. These "sentences" consist of the appropriate identification numbers syntactically linked by functional signs (Table 1), just as the individual quantities in a mathematical expression are linked by operators.

[5] In the meantime, two methods involving acceptable costs have been developed in the U.S.A. However, one of these [6] seems not to permit the coding of reactions; the other [7] requires considerably more manual work, although it does not involve the use of a special machine. A method [8] of optical scanning using a commercially available device (television camera) is also under development, but the cost of data processing by this method will probably be rather high.

[6] *A. Feldman, D. B. Holland,* and *D. P. Jacobus,* J. chem. Documentat. *3*, 187 (1963).

[7] *P. Horowitz* and *E. M. Crane,* Paper presented at ACS Meeting, Sept. 11th, 1962.

[8] *W. E. Cossum, M. E. Hardenbrook,* and *R. N. Wolfe,* Proc. Amer. Documentat. Instit. *1964*, 269.

[9] *G. Salton* and *E. W. Sussenguth jr.*, ADI Annual Meeting 1963, Short Papers, Part 2, p. 143; Scientific Report No. ISR-6 to The National Science Foundation, April 1964.

[9a] "Links" are code signs which are attached to two or more key words or notations, and which represent a particularly close relationship between these. "Role indicators" show the sense or connection in which the concepts are used, *i.e.* the role played by a concept in a statement.

[9b] "Notation" here means a sign, preferably an alphanumeric code, representing a concept.

Table 1. Syntactical operators.

Symbol and transcription	Explanation
A "as"	adjectival relationship, physical state, *e.g.* "oxidation *in* the gas phase", "azeotropic mixture". The number corresponding to the broader concept precedes, that corresponding to the explanatory concept follows operator A.
C "with"	equivalent substances or agents, *e.g.* reaction of "carboxylic acids *with* olefins"
E "with or without"	substances or agents which should or may be present, but are not necessarily so, *e.g.* dyeing of "polyester fibers *with or without* added wool".
G "of"	relationship between process and substrate, *e.g.* "esterification *of* carboxylic acids".
I "from"	relationship between end product and starting material, *e.g.* "aromatic compounds *from* alicyclic compounds".
L "by"	"in the presence of" (auxiliary substances, apparatus), *e.g.* "hydrogenation *with* Raney nickel", "atomization *by* a nozzle"
N "for"	use, application, purpose, *e.g.* "phenols *as* stabilizers".
P "at"	quantitative statement of reaction conditions, *e.g.* "decarboxylation *at* 120 to 150 °C".
R "then", "before"	chronological order, *e.g.* distillation *followed* by drying.
v "or"	disjunction, links alternatives, *e.g.* "with phosgene *or* thionyl chloride".
– "not"	"in the absence of" (negation); precedes the identification number in question and is used together with one of the signs A through R.
( )	brackets are used as in mathematics to indicate a closer connection or to form subgroups in a sentence.
"period"	(end of sentence); terminates a proposition which completely describes a state of affairs.

The machine program can be designed in such a way that concepts associated with certain operators (*e.g.* v, A, E, N, P, and R) can be retrieved, even when the operators are not named in the question, whereas other operators must be specifically requested or allowed for. As a result, the machine will retrieve those documents, too, in which things are described and encoded in greater detail than in the question.

The use of brackets and disjunction operators ("v") permits the expression of complex relationships and affords the analyst considerable freedom in representing them, so that he is not too much restricted by the need to choose the correct formulation. The machine resolves these composite expressions during the search (or even during the storage operation) in accordance with the rules of Boolean algebra [10]. To avoid the need for large numbers of brackets in establishing unambiguous relationships, an order of precedence is set up for the operators: an earlier letter of the alphabet represents a closer relationship than a later one (just as the multiplication sign takes precedence over the addition sign in algebra).

[10] Boolean algebra is a method of expressing logical relationships ("and", "or", "not") by matematically exact formulae. These formulae can be manipulated in accordance with certain rules, just as equations are used to carry out calculations in ordinary algebra.

As an example, we shall now illustrate the procedure for encoding the following abstract [10a]:

"Catalytic ⑥ alkylation ⑤ of an isoparaffin ② with an olefin ③. An excess ① of the isoparaffin, *e.g.* isobutane ②, is brought into contact with the olefin ③ in a reaction zone, in the presence of an acidic ⑬ catalyst ⑥ such as sulfuric acid ④. The mixture consisting of the catalyst, the excess isoparaffin, and the reaction product is removed from the reaction zone. The catalyst ⑥ is almost completely eliminated ⑫ from the mixture, and the residual hydrocarbon phase is led into a fractionating zone. The improved procedure consists in subjecting at least the greater part of the hydrocarbon phase to flash ⑦ evaporation ⑧ before it enters the fractionating zone. The isoparaffin ② vapor released during the flash evaporation is condensed ⑨, and the condensate is returned ⑩ to the reaction zone".

The list of concepts used for coding here is as follows:

1 ..... (notation for "excess")
2 ..... (notation or topological representation for "isobutane", which is a sub-class of the class of "isoparaffins")
3 ..... (notation or topological representation for "olefins")
4 ..... (notation or topological representation for "sulfuric acid")
5 ..... (notation for "alkylation")
6 ..... (notation for "catalyst, catalysis")
7 ..... (notation for "rapid")
8 ..... (notation for "evaporation")
9 ..... (notation for "condensation")
10 ..... (notation for "recycling")
11 ..... (notation for "fractionation")
12 ..... (notation for "removal, separation")
13 ..... (notation for "acid, acidic")

Using the operators of Table 1, the following sentences are obtained:

5 A 6 G 2 C 3.

2 A 1 C 3 L (4 v 6 A 13) R 12 G (4 v 6) R 8 A 7 R 11 R 9 G 2 R 10 G 2.

From these sentences the abstract can be reconstructed, just as a structural formula can be reconstructed from its topological representation (although somewhat less accurately): "Catalytic alkylation of isobutane with olefins. Excess isobutane (reacts) with olefin in the presence of sulfuric acid or an (other) acidic catalyst; then separation of the sulfuric acid (or) of the catalyst; then rapid evaporation; then fractionation; then condensation of isobutane; then recycling of isobutane."

As has already been mentioned, the notations should show a "hierarchy" of concepts. For example, if the concept "acids" was assigned the notation "47", "mineral acids" could be represented by "47.1", and "sulfuric acid" by "47.1.1". Then if the machine is questioned about "47", *i.e.* about acids in general, the references in which sulfuric acid is named will automatically be included in the documents selected. The same applies to the series: isobutane – isoparaffins – paraffins. If the store gives no answer to a query, the question can be generalized step by step until suitable references are obtained.

The code sentence thus contains the essential facts completely and unambiguously, so that any piece of information which is implicit in the coded abstract can be sought out mechanically, just as partial structures can be retrieved from a topological representation. Admittedly, the length of the machine program required for this search will be considerable; however, the computer time needed will not be as long, since the notations specified in the question are first checked

[10a] The numbers to the key words were not present in the original abstract but were inserted by the analyst.

against the list of concepts, so that it is unnecessary in the majority of cases to recheck the sentences printed by the machine.

3. Supplying Other Card Indexes

A great disadvantage of the methods described, as in all mechanized documentation with very large stores, is that they require the use of punched-card machines or electronic data processing equipment. This makes it difficult for these methods to gain acceptance, since even simple queries must first be translated into machine language and punched on tape or cards. The answer will then be obtained after the next machine run at the earliest. Owing to these difficulties, many questions which could be answered immediately by a card index, undoubtedly would remain unasked.

Card indexes become too large unless they are confined to selected fields. They are useful only if the code book used is specially designed for that particular field, and this is the main reason why it has not so far been possible to coordinate them and provide them with ready-coded material from a central supply. However, electronic data processing may also provide a solution to this problem. Thus if all the criteria used by a customer in his code book can be retreived individually from a large electronic store, then the document numbers supplied by the machine can be punched into IBM cards each containing *e.g.* 500 punching positions. One card per set is provided for each criterion, with holes in the positions corresponding to the documents which exhibit this criterion.

At first, these punched cards are used as peephole cards, *i.e.* the cards corresponding to the criteria in question are placed on top of one another and held up to the light. The punch positions of the documents containing all the criteria requested then shine through. When 5000 documents (*i.e.* ten sets of punched cards) have been processed, the cards are transferred to a single set of normal peephole cards to facilitate handling during further enquiry; this operation can be carried out with special machines.

It may be possible in this way to reduce the high cost of independent handling and encoding of the same technical literature in many small card indexes. However, a prerequisite (apart from the existence of suitable machine programs) is a large mechanized information store permitting great flexibility in the formulation of queries.

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Translated by Express Translation Service, London

COMMUNICATIONS

Hydrogermylation of Aromatic Compounds

By S. P. Kolesnikov and Dr. O. M. Nefedov

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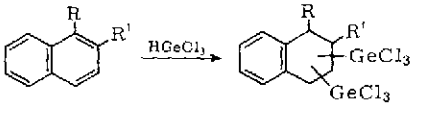
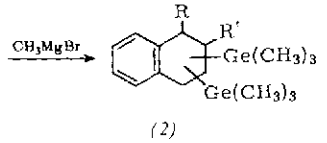
When 0.05 mole of naphthalene is heated for 10–15 min at 110–130 °C with 0.05 mole of $HGeCl_3$ and the mixture is subsequently methylated with excess methylmagnesium bromide in ether, a 52.5 % yield of 1,3-bis(trimethylgermyl)-1,2,3,4-tetrahydronaphthalene *(2)*, R = R′ = H, b.p. 100 to 102 °C/0.2 mm, is obtained.



(1)



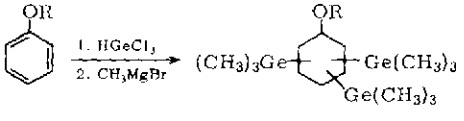
(2)

The structure of this product was proved by its infrared spectrum. Its NMR spectrum at 60 Mc with tetramethylsilane as internal standard contains signals at 0.06 and 0.12 ppm for the methyl groups on the germanium, at 2.75 and 2.49 to 2.60 ppm for non-aromatic methine protons, and at 6.86 and 6.94 ppm for aromatic protons, plus two multiplets at 1.90 and 2.58 ppm for the methylene groups. Dehydrogenation of the new compound *(2)* with selenium for 3 h at 290–300 °C or by refluxing it with chloranil in xylene for 10 h yields naphthalene in 65–80 % yield.

Apart from *(1)*, R = R′ = H, pentakis(trichlorogermyl)decahydronaphthalene is formed in 10–20 % yield during the reaction of naphthalene with $HGeCl_3$.

Hydrogermylation of 1-methylnaphthalene under identical conditions leads within 5 min to a bistrichlorogermyl derivative, which on methylation affords a 1-methylbis(trimethylgermyl)-1,2,3,4-tetrahydronaphthalene, b.p. 101 to 104 °C, in an overall yield of 62 %. The addition of $HGeCl_3$ onto dimethylnaphthalenes or anthracene, phenanthrene, and their derivatives proceeds with equal ease.

$HGeCl_3$ does not react with benzene, toluene, or the xylenes under these conditions. Alkoxybenzenes, on the other hand, do yield adducts. For example, when anisole is heated for 8.5 h with an equimolar amount of $HGeCl_3$ at 110 °C and the product is then methylated, a mixture of isomeric methoxytris(trimethylgermyl)cyclohexanes *(3)*, R = CH_3, is produced.



(3)

1-Methoxy-1,3,5-tris(trimethyl)cyclohexane, m.p. 66 °C, b.p. 105–107 °C/0.6 mm, can be isolated in 32 % yield from this mixture by distillation. The infrared spectrum of this compound contains bands characteristic of its methylgermyl and methoxy groups. Its NMR spectrum contains two singlets at 0.07 and 0.13 ppm (intensity ratio 2:1) due to the methyl groups on the germanium atoms, a multiplet at

1.0–2.0 ppm due to the methylene and methine protons, and a singlet at 3.14 ppm due to the methoxy group.

Heating of ethoxybenzene with $HGeCl_3$ for 0.5 h at 110 to 130 °C and subsequent methylation lead to the ethoxy derivatives corresponding to *(3)*.

It is remarkable that the reaction of alkoxybenzenes and $HGeCl_3$ does not give rise to trichlorogermylbenzene, since refluxing of dialkyl ethers with $HGeCl_3$ produces alkyltrichlorogermanes in yields of 35–40 % [1].

Received: December 11th, 1964; supplemented: January 26th, 1965
[Z 905/728 IE]
German version: Angew. Chem. 77, 345 (1965)

[1] *O. M. Nefedov, S. P. Kolesnikov*, and *W. Y. Scheichenko*, Angew. Chem. *76*, 498 (1964); Angew. Chem. internat. Edit. *3*, 508 (1964); Doklady Akad. Nauk U.S.S.R., in the press.

1,2,3,4-Tetrachlorobenzo[g]sesquifulvalene [1]

By Prof. Dr. Y. Kitahara, Dr. I. Murata, and Dr. S. Katagiri

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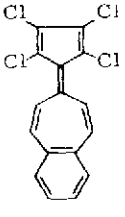
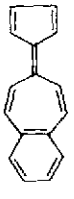
We have found that the reaction of tropone with 1,2,3,4-tetrachlorocyclopentadiene in methanol affords a mixture of 1,2,3-trichloro-6-(*o*-methoxyphenyl)fulvene and the corresponding *p*-isomer [2]. The formation of fulvene derivatives can be avoided by using benzo[*d*]tropone. Thus, treatment of 3.12 g (0.02 mole) of benzo[*d*]tropone with 4.08 g (0.02 mole) of 1,2,3,4-tetrachlorocyclopentadiene in 150 ml of methanol at room temperature leads within about 44 h to 1,2,34,-tetrachlorobenzo[*g*]sesquifulvalene *(1)* in a maximum yield of 15 % (0.51 g).



(1)



(2)

The structure *(1)* was confirmed by X-ray crystallography [3]. The new compound crystallizes in violet needles, m.p. 234 °C (decomp.), λ_{max} in methanol at 241 mμ (log ε = 4.38), 320 mμ (3.95), and 480 mμ (4.44). The dipole moment in benzene at 25 °C is 5.20 D. This implies a strong π-electron displacement from the seven-membered ring into the five-membered ring, leading to a highly polar structure. If the dipole moment of the four chlorine atoms is subtracted (−1.1 D) [4], a dipole moment of 4.1 D results for benzo[g]-sesquifulvalene *(2)*. This (theoretical) dipole moment is the highest ever calculated for a hydrocarbon.

Received: December 15th, 1964 [Z 903/726 IE]
German version: Angew. Chem. 77, 345 (1965)

[1] Reported at a Tohoku Local Meeting of the Chemical Society of Japan (Morioka), Sept. 24th, 1964.

[2] *Y. Kitahara, I. Murata, M. Funamizu*, and *T. Asano*, Bull. chem. Soc. Japan *37*, 1399 (1964).

[3] *Y. Ogawa, T. Ashida, Y. Sasada*, and *M. Kakudo*, unpublished experiments.

[4] This value is calculated from the dipole moment of cyclopentadiene (μ_{exp} = 0.45 D) and that of its tetrachloro derivative (μ_{exp} = 1.55 D).

Uvanite, a Swelling Uranyl Vanadate with a Layer Structure

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der Universität Heidelberg (Germany)

Uvanite [1] is a rare, earth-like, brownish-yellow mineral, whose structural formula should be written as follows:

$$\underbrace{M^{\oplus}(H_2O)_x}_{\text{exchangeable cations and swelling liquid}} \quad \underbrace{[UO_2 V_3O_9]^{\ominus}}_{\text{anionic layer lattice}}$$

So far we have been unable to decide with certainty whether part of the water is attached to the trimetavanadate ion. In the formula given for the mineral in the literature [2], the exchangeable cations are neglected as impurities. The anionic layer lattice has a trigonal structure with a = 6.87 Å. It is decomposed by aqueous alkaline solutions. The unit cell contains only one formula unit.

The cations $M^{\oplus}$ can be interchanged with other cations, including primary or quaternary alkylammonium cations. The exchange capacity is about 177 mval per 100 g of mineral after drying at 110 °C. The water content and basal plane spacing depend on the atmospheric humidity and the nature of the exchangeable cations in the sample. When alkylammonium ions are present, swelling also occurs with numerous polar organic compounds (see Table). The basal cell edge remains unaltered.

The X-ray diffraction pattern contains only (hk) bands, which tail off toward larger angles (cross-lattice interferences), and (001) reflexes.

M^+	Basal plane spacing [Å] under: H_2O	Ethylene glycol	Nitroethane	n-Octanol	n-Decanol	n-Alkylamine with the same number of carbon atoms as the cation
Li^+	14.8	11.1	no swelling			Irregular spacings with n-alkylamines. Partial ion exchange in the presence of water
Na^+	13.3	9.6				
Mg^{2+}	15.0	12.6				
UO_2^{2+}	15.1	13.6				
$n\text{-}C_8H_{17}NH_3^+$	cannot be measured with certainty	22.2 [*]	23.8	26.8	32.3	28.6
$n\text{-}C_{10}H_{21}NH_3^+$		24.1 [*]	25.0	28.4	33.8	33.1
$n\text{-}C_{12}H_{25}NH_3^+$		26.0 [*]	26.6	30.2	35.6	40.0
$n\text{-}C_{14}H_{29}NH_3^+$		27.3 [*]	28.1	32.0	37.4	45.7
$n\text{-}C_{18}H_{37}NH_3^+$		32.2 [*]	30.3	34.1	40.0	54.0
$n\text{-}C_{16}H_{33}N(CH_3)_3^+$		30.3 [*]	31.0	35.1	41.8	—

[*] Random interstratification.

Received: January 21st, 1965 [Z 901/743 IE]
German version: Angew. Chem. 77, 347 (1965)

[1] The sample examined was kindly supplied by the U.S. National Museum in Washington, D.C. (U.S.A.), where it is registered under Catalogue No. 102765.

[2] *F. L. Hess* and *W. T. Schaller*, Washington Acad. Sci. J. *4*, 576 (1914).

Redox Potentials of Phenol-Phenoxyl Systems

By Priv.-Doz. Dr. H. Mauser and Dipl.-Chem. B. Nickel

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Up to the present, redox potentials of phenoxyl radicals could not be measured directly. Platinum is unsuitable as electrode material because it catalyses electrolytic oxidation of the solvent too strongly at high electrode potentials.

We have found that sintered boron carbide electrodes [1, 2] react reversibly to the redox equilibrium

$$C_6H_5OH \rightleftharpoons C_6H_5O\cdot + H^{\oplus} + e_0^{\ominus}$$

in acetate-buffered ethanolic solution (but not in 0.01 N HCl in ethanol). The e.m.f. of the cells

$$Pt/Hg/[Hg_2Ac_2]\ldots/\ldots C_6H_5OH,\ C_6H_5O\cdot/B_4C/Hg/Pt$$

and

$$Pt/Hg/[Hg_2Ac_2]\ldots/\ldots/H_2,\ Pt$$

(electrolyte: $C_2H_5OH/[NaAc]$, $[HAc] \leq 0.1$ mole/l)

was measured at 15.0 °C. The difference E between the two e.m.f.'s is independent of the pH, provided the electrolyte composition is the same in both cells.

$$E = E_0^h + \frac{RT}{F} \ln \frac{[C_6H_5O\cdot]}{[C_6H_5OH]} + \frac{RT}{2F} \ln p_{H_2}$$

E_0^h is the redox potential.

Substance [a]	λ_{max} [mμ]	ε_{max} [l/mole/cm]	10^4 K [mole/l]	E^h_{redox} [mv]	100 k [h]
(1)	694 ± 5	712 ± 20	1.07	1203.6 ± 0.5	52
(2)	694 ± 5	795 ± 40	0.50	1203.4 ± 0.5	54
(3)	629 ± 5	411 ± 10	∞	1023.2 ± 1.0	0.6
(4)	496 ± 2	2780 ± 50	∞	1008.8 ± 1.0	0.23

[a] *(1)* = 2,6-Di-t-butyl-4-methoxycarbonylphenoxyl; *(2)* = 2,6-di-t-butyl-4-ethoxycarbonylphenoxyl; *(3)* = 2,4,6-tri-t-butylphenoxyl; and *(4)* = 2,6-di-t-butyl-4-phenylphenoxyl.

The dimeric phenoxyls *(1)* and *(2)* were prepared according to [3] and recrystallized under nitrogen at −40 °C from petroleum ether/benzene (10:1). In solution, the blue-green monomeric phenoxyl radicals are present in equilibrium with their colorless dimers. The dissociation constants $K = [C_6H_5O\cdot]^2/[(C_6H_5O\cdot)_2]$ and the molar extinction coefficient ε_{max} were determined from the concentration dependence of the optical density $A = d\cdot\varepsilon_{max}\cdot[C_6H_5O\cdot]$ at the maximum of the long-wave absorption band. The phenoxyls *(3)* and *(4)* were prepared by partial electrolytic oxidation of solutions of the corresponding phenols directly within the spectroscopy cell.

The gradation of the redox potentials (see Table) cannot be expressed using the Hammett σ constants.

The decomposition of the phenoxyls is a first order reaction (rate constant k) relative to the concentration of the monomeric phenoxyl.

Received: January 25th, 1965 [Z 921/751 IE]
German version: Angew. Chem. 77, 378 (1965)

[1] From Elektroschmelzwerk Kempten GmbH.; Norton International Inc., Worcester 6, Mass. (U.S.A.).

[2] *T. R. Mueller* and *R. N. Adams*, Anal. Chim. Acta *23*, 467 (1960), describe the purification and installation of sintered boron carbide electrodes but in a different connection.

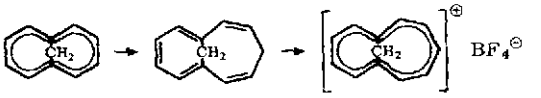
[3] *E. Müller, A. Rieker, R. Mayer*, and *K. Scheffler*, Liebigs Ann. Chem. *645*, 36 (1961).

Synthesis of the Bicyclo[5,4,1]dodecapentaenylium Cation — a Carbonium Ion with 10 π-Electrons

By Dr. W. Grimme, Dipl.-Chem. H. Hoffmann, and Prof. Dr. E. Vogel

Institut für Organische Chemie der Universität Köln (Germany)

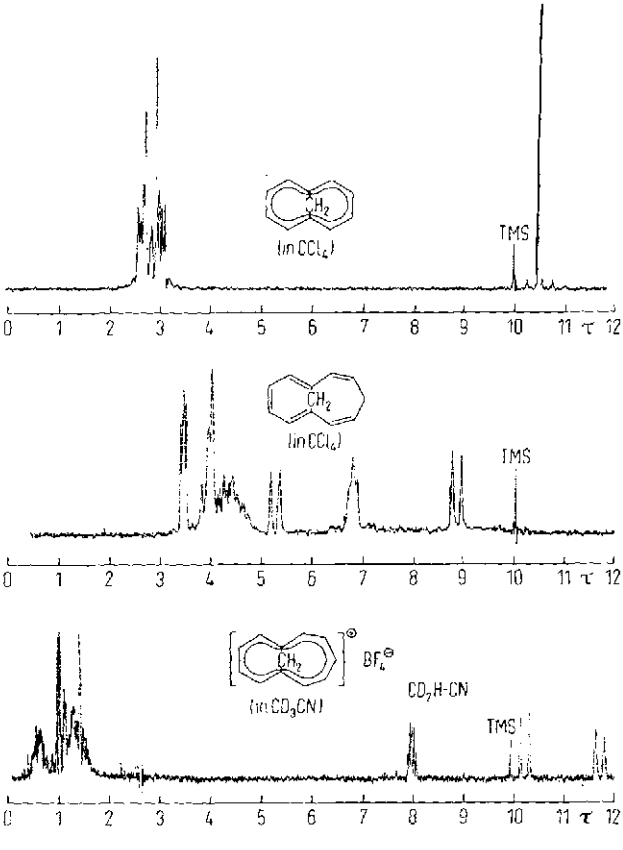
The fact that 1,6-methanocyclodecapentaene *(1)* [1] has a largely delocalized 10 π-electron system made it appear likely that the carbonium ion *(3)* [2] is capable of existence. The conversion of benzene *via* norcaradiene and cycloheptatriene into the tropylium cation served as a guide for the synthesis of *(3)*.



(1) *(2)* *(3)*

When *(1)* is treated with diazomethane in the presence of CuCl, the bright yellow olefin *(2)* is obtained, possibly in admixture with other isomers; *(2)* has a b.p. of 98 °C/1 mm, $n_D^{20} = 1.6375$, and λ_{max} in cyclohexane at 215 mμ (ε = 17500), 250 (13300), and 335 (3500). The conversion of *(1)* into *(2)* is clearly shown by NMR spectroscopy (see Figure): owing to the loss of the cyclic conjugation, the resonance signals for the vinylic protons shift from 2.3–3.2 τ for *(1)* to 3.3–4.7 τ for *(2)*, and the signal for the bridge protons, originally a singlet at 10.5 τ, splits into an AB system at 5.3 and 8.8 τ with J = 11 cps. The remaining signal group in the NMR spectrum of *(2)* at 6.2–7.2 τ is due to the methylene protons in the C_{11}-perimeter.

Reaction of *(2)* and triphenylmethyl fluoroborate [3] in acetonitrile gives rise by hydride transfer to a stable salt of formula $[C_{12}H_{11}]^{\oplus}BF_4^{\ominus}$ [4], yellow-orange needles from acetic acid, m.p. 185 °C (decomp.); this product has λ_{max} in 60% sulfuric acid at 272 mμ (ε = 31600), 302 (51800), 320 (14100), 385 (2300), and 423 (4000). The aromatic structure *(3)* ascribed



to this compound is again based largely on its NMR spectrum (see Figure), in which the signals for the ring- and bridge protons exhibit the expected large shifts to lower (0.4–1.7 τ) and higher fields (10.3 and 11.8 τ, $J = 10$ cps), respectively, relative to the signals in the spectrum of *(2)*. Compound *(2)* and the salt *(3)* must have the same carbon skeleton, for on catalytic hydrogenation both give the same saturated hydrocarbon $C_{12}H_{22}$, which we consider to be bicyclo[5,4,1]dodecane.

The NMR and ultraviolet spectra of *(3)* resemble those of the benzotropylium cation [5].

Received: January 29th, 1965 [Z 914/738 IE]
German version: Angew. Chem. 77, 348 (1965)

[1] *E. Vogel* and *H. D. Roth*, Angew. Chem. *76*, 145 (1964); Angew. Chem. internat. Edit. *3*, 228 (1964); *E. Vogel* and *W. A. Böll*, Angew. Chem. *76*, 784 (1964); Angew. Chem. internat. Edit. *3*, 642 (1964).

[2] For the synthesis of aromatic carbanions with 10 π-electrons, see *T. J. Katz* et al., J. Amer. chem. Soc. *86*, 5194 (1964), and earlier publications; *E. A. LaLancette* and *R. E. Benson*, ibid. *85*, 2853 (1963).

[3] *H. J. Dauben*, Jr., *F. A. Gadecki*, *K. M. Harmon*, and *D. L. Pearson*, J. Amer. chem. Soc. *79*, 4557 (1957).

[4] $[C_{12}H_{11}]^{\oplus}ClO_4^{\ominus}$, m.p. 194 °C (decomp.), was obtained analogously.

[5] *H. H. Rennhard*, *E. Heilbronner*, and *A. Eschenmoser*, Chem. and Ind. *1955*, 415; *G. Naville*, *H. Strauss*, and *E. Heilbronner*, Helv. chim. Acta *43*, 1221 (1960).

Reaction of Triphenylaluminum with Cyclohexyl Isonitrile

By Prof. Dr. G. Hesse, Dr. H. Witte, and cand. chem. P. Mischke [*]

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When triphenylaluminum and cyclohexyl isonitrile are heated in xylene at 50–60 °C, compound *(1)* – the first representative of a new class of organoaluminum derivatives – is formed; it crystallizes out of the solution at −20 °C after removal of most of the xylene and addition of anhydrous petroleum ether.

$$(C_6\text{–}\overset{\ominus}{C}H_5)_3Al{=}\overset{\ominus}{N}\text{–}C_6H_{11} \qquad (1)$$

The product is colorless and is stable under pure nitrogen. It dissolves readily in benzene, ether, or carbon tetrachloride but is only slightly soluble in petroleum ether. It decomposes in air with liberation of cyclohexyl isonitrile. When heated, it begins to soften and to decompose slowly above 75 °C. Its structure was verified by its elemental analysis and infrared spectrum (sharp band due to the $-C{\equiv}\overset{\oplus}{N}$ group at 2215 cm^{-1}; $\tilde{\nu}_{-N\equiv C}$ for cyclohexyl isonitrile is at 2125 cm^{-1}).

The same compound was obtained by the following quantitative metathesis reaction:

$$(C_6H_5)_3\overset{\ominus}{B}\text{–}C\text{–}\overset{\ominus}{N}{\equiv}C_6H_{11}\ [1] + Al(C_2H_5)_3 \rightarrow (C_6H_5)_3\overset{\ominus}{Al}\text{–}C{\equiv}\overset{\oplus}{N}\text{–}C_6H_{11} + B(C_2H_5)_3$$

Here the method described by *Köster* [2] for the preparation of triethylboron from boric esters was used; the reaction product was crystallized and purified with petroleum ether.

Received: January 29th, 1965; supplemented: March 5th, 1965
[Z 930/756 IE]
German version: Angew. Chem. 77, 380 (1965)

[*] *P. Mischke*, Diploma Thesis, Universität Erlangen-Nürnberg, 1965.

[1] *G. Hesse*, *H. Witte*, and *G. Bittner*, Liebigs Ann. Chem., in the press; *G. Bittner*, Diploma Thesis, Universität Erlangen-Nürnberg, 1964.

[2] *R. Köster*, Liebigs Ann. Chem. *618*, 38 (1958).

Isolation of Benzoyl Radicals [1]

By Prof. Dr. Ulrich Schmidt, Dr. K. H. Kabitzke, and Dipl.-Chem. K. Markau

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The formation of aldehydes, diketones, and numerous acyl compounds on irradiation of acyl chlorides and acyl bromides in solution [1,2] can be explained only by the photochemical formation of free acyl radicals. We have now succeeded in capturing the free acyl radicals formed on irradiation of aromatic acyl bromides *in vacuo* by condensation in a cold trap behind the site of exposure.

Despite its extremely low resonance energy (about 10 kcal/mole), the orange-red free benzoyl radical is stable at 70 °K and combines only above 140 °K with a bromine radical to yield benzoyl bromide within a few minutes. The free-radical nature of the condensate was proved by measurement of its strong electron spin resonance signal. The color and ESR signal disappear simultaneously on warming. The benzoyl radical was also detected and captured following photolysis of benzaldehyde. Homolytic cleavage of the C-H bond in aldehydes resulting from attack by a radical former has previously been assumed in order to explain the course of radical additions of aldehydes onto olefinic double bonds [3]. The ESR signals for the benzoyl radicals made from benzoyl bromide or from benzaldehyde were identical.

When *p*-chlorobenzoyl bromide and *p*-methoxybenzoyl bromide were photolysed, red-brown *p*-chlorobenzoyl and green *p*-methoxybenzoyl radicals, respectively, were caught in the cold trap. The ESR signals have a width (peak-peak) of about 15 gauss and exhibit slight anisotropy. The average g factors are about 2.006.

Received: February 1st, 1965 [Z 908/732 IE]
German version: Angew. Chem. 77, 378 (1965)

[1] Photoreactions of Carboxylic Acid Derivatives, Part 4. Part 3: *U. Schmidt*, Angew. Chem. *77*, 216 (1965); Angew. Chem. internat. Edit. *4*, 239 (1965).

[2] *U. Schmidt*, Angew. Chem. *77*, 169 (1965); Angew. Chem. internat. Edit. *4*, 146 (1965).

[3] Reviewed by *Ch. Walling*: Free Radicals in Solution. Wiley, New York 1957, p. 273.

Thermolysis of Cycloalkyl Esters Yielding Cycloalkanones

By Ing. Hansdieter Hofman [*]

Forschungslaboratorien der H. J. Zimmer AG., Frankfurt/Main (Germany)

Cycloalkyl esters are cleaved at 330–450 °C on dehydrogenating catalysts to produce good yields of the corresponding cycloalkanones; cycloalkanols and cycloalkenes are formed as by-products. The rate of the reaction depends mainly upon the nature of the acyl group and decreases in the order formyl ≫ acetyl > propionyl > butyryl, valeryl. In the presence of hydrogen, the yield of cycloalkanone is 8–20 % higher. The catalyst used was zinc oxide containing 6.7 % CaO, 4.5 % Al_2O_3, and 1.6 % Cr_2O_3.

Cyclohexanol/cyclohexanone mixtures containing cyclohexyl esters such as are obtained by oxidation of cyclohexane with air can also be dehydrogenated to cyclohexanone by this procedure. For example, a mixture consisting of 64.3 % cyclohexanol, 28.3 % cyclohexanone, and 2.7 % cyclohexyl esters (calculated as acetate) were pyrolysed at 370 °C. The conversion of cyclohexanol and cyclohexyl ester was 80.3 %. The yield of cyclohexanone based on the amount of mixture

Cycloalkyl ester	Temp. [°C]	Conversion [%]	Cycloalkanone (yield [%])	Cycloalkene (yield [%])
Cyclopentyl acetate	400	76.1	cyclopentanone (65.5)	cyclopentene ([a])
Cyclohexyl formate	400	99.7	cyclohexanone (77.4)	cyclohexene (0.8)
Cyclohexyl acetate	400	82.6	cyclohexanone (50.3)	cyclohexene (20.8)
Cyclohexyl valerate	420	76.6	cyclohexanone (42.9)	cyclohexene (50.7)
Cycloheptyl acetate	410	94.6	cycloheptanone (49.2)	cycloheptene (33)
Cyclododecyl formate	420	97.2	cyclododecanone (71.6)	cyclododecene ([a])
Cyclohexyl formate [b]	400	100	cyclohexanone (trace)	cyclohexene (97.3)
Cyclohexyl formate [c]	410	5		cyclohexene (2.5)

[a] Yield not determined.

[b] Catalyst: γ-Al_2O_3.

[c] Catalyst: glass Raschig rings.

charged was around 97.8 mole-%. About 0.36 mole-% cyclohexene was formed as a by-product. The residual content of cyclohexyl esters (calculated as acetate) was only 0.3 %.

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supplemented: February 15th, 1965
[Z 918/745 IE]
German version: Angew. Chem. 77, 346 (1965)

[*] In collaboration with *G. Forberger*, *S. Janacek*, and *F. Langohr*.

Synthesis of Cyclotri-L-prolyl, a Cyclotripeptide Having a Nine-Membered Ring [1]

By Priv.-Doz. Dr. M. Rothe and Dipl.-Chem. K.-D. Steffen, in collaboration with Dr. Ilse Rothe

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der Universität Mainz (Germany)

No synthesis of cyclotripeptides has hitherto been achieved because linear tripeptides normally undergo dimerization during ring closure to give cyclohexapeptides with an unstrained 18-membered ring.

On cyclization of tri-L-proline [hemihydrate, m.p. 125 to 130 °C (decomp.)] using either the *p*-nitrophenyl ester or the phosphite method [2] and simultaneously applying the dilution principle, we obtained an 88 % yield of readily crystallizable, sublimable cyclotri-L-prolyl in thin-layer chromatographic and analytical purity [m.p. 338 °C (decomp.), $[\alpha]_D^{25} = +48.5°$ (c = 0.48 in methanol)]. The size of the ring is indicated by the partial hydrolysis of the compound with 0.1 N $Ba(OH)_2$ [5 min at 100 °C] to give proline, diproline, and triproline, and by the results of molecular-weight estimations (calc. 291; found by the method of Rast in 1,4-cyclohexanecarbolactam: 293; by mass spectrometry: 291 [3]).

L-Prolyl-L-prolylglycine, on the other hand, yields only the cyclohexapeptide [trihydrate, m.p. 242 °C (decomp.); $[\alpha]_D^{25} = -140.0°$ (c = 0.57 in water)] in 21 % yield by both ring closure methods. Here the infrared spectrum contains an amide II band at 1550 cm^{-1}, indicating *trans*-amide configuration of the 18-membered ring. Partial hydrolysis here gives rise to linear hexapeptides of molecular weight 502 (determined by mass spectrometry; calc.: 502).

Received: February 11th, 1965 [Z 916/740 IE]
German version: Angew. Chem. 77, 347 (1965)

[1] Cyclic Peptides, Part XI. – Part X: *M. Rothe* et al., Angew. Chem. *75*, 1206 (1963); Angew. Chem. internat. Edit. *3*, 64 (1964).

[2] *M. Rothe* et al., Angew. Chem. *71*, 700 (1959).

[3] Determined by *Dr. Reling*, Frankfurt/Main-Hoechst (Germany).

Optically Active Trisbiphenylenephosphates

By Dr. D. Hellwinkel

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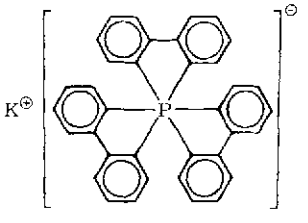
The formal resemblance between the trisbiphenylenephosphate anion [1] and the chelate complexes of hexacoordinated transition metals [2] made it appear likely that this ate-complex *(1)* of pentavalent phosphorus would have an octahedral structure and should therefore be separable into optically active antipodes.

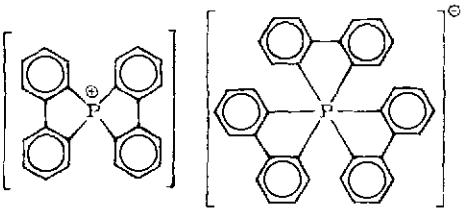
Treatment of lithium trisbiphenylenephosphate with an equivalent amount of *N*-methylbrucinium iodide in methanol results in quantitative precipitation of a mixture of the two diastereoisomeric *N*-methylbrucinium trisbiphenylenephosphates. Several recrystallizations from acetone led to a 25 % yield of pure (−)-methylbrucinium (−)-trisbiphenylenephosphate, m.p. 234–236 °C, $[\alpha]_{578}^{24.5} = 1250 \pm 15°$ (c = 0.8–1.0 in CH_2Cl_2). After removal of all crystalline fractions from the mother liquors, (−)-methylbrucinium (+)-trisbiphenylenephosphate, which does not crystallize out, can be precipitated with methanol; m.p. 230–234 °C. Here the highest rotations measured were $[\alpha]_{578}^{24.5} = 950 \pm 50°$ (c = 0.8–1.0 in CH_2Cl_2).

The diastereoisomeric salts react smoothly with potassium iodide in acetone to give *N*-methylbrucinium iodide and colorless potassium trisbiphenylenephosphates *(1)*, which have the remarkably high specific rotations $[\alpha]_{578}^{24.5} = \mp 1930 \pm 20°$ (c = 0.4–0.7 in acetone); $[M]_{578}^{24.5} = \mp 10150 \pm 100°$; m.p. 295–298 °C (decomp.).



(1)

When the optically active potassium or sodium salts *(1)* were treated with bisbiphenylenephosphonium iodide [1] in methanol, the two stereoisomeric yellow phosphonium phosphate complexes *(2)*, $[\alpha]_{578}^{24.5} = \mp 1265 \pm 15°$ (c = 0.7–1.0 in dimethylformamide), $[M]_{578}^{24.5} = \mp 10\,410 \pm 120°$, m.p. 247 to 250 °C (decomp.), were obtained.



(2)

Received: February 12th, 1965 [Z 917/750 IE]
German version: Angew. Chem. 77, 378 (1965)

[1] *D. Hellwinkel*, Chem. Ber. *98*, 576 (1965).

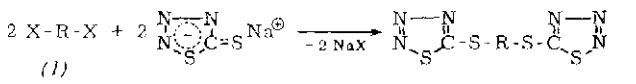
[2] *F. P. Dwyer* and *D. P. Mellor*: Chelating Agents and Metal Chelates. Academic Press, New York 1964.

Bis-(1,2,3,4-thiatriazol-5-yl)thio Compounds with High-Explosive Properties

By Dr. K. Pilgram and Prof. Dr. F. Korte

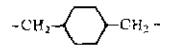
Shell Grundlagenforschungs-Gesellschaft m.b.H.,
Schloß Birlinghoven/Siegkreis (Germany)

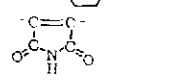
Sodium 1,2,3,4-thiatriazol-5-thiolate *(2)*, which can be prepared readily from sodium azide and carbon disulfide [1], reacts with α,ω-dihalogenoalkanes *(1)* in acetone/water (3:1 v/v) within several hours at about 10 °C to form α,ω-bis-[(1,2,3,4-thiatriazol-5-yl)thio]alkanes *(3)*.



(1) *(2)* *(3)*, R = $-(CH_2)_n-$, n = 1–4

X = Br, I

(4), R = 

(5), R = 

n	*(3)* Yield [%]	M.p. [°C] [a]
1	89.0	82 [b], 99
2	28.3	92
3	22.6	85
4	20.9	75

[a] With decomposition.

[b] Nitrogen is evolved without melting of the sample.

1,4-Bisiodomethylcyclohexane, m.p. 76–77 °C, reacts analogously with *(2)* to form *(4)* [2], m.p. 92 °C (decomp.), in 39.9 % yield. Dichloromaleimide reacts with *(2)* at only −15 to −10 °C in aqueous acetone to afford 58 % *(5)*, m.p. 92 °C (decomp.). The structures of *(3)*, *(4)*, and *(5)* were confirmed by elemental analysis, infrared spectroscopy, and thermoanalysis. Thermolysis of *(3)* between 50 and 75 °C in inert solvents affords nitrogen, sulfur, and α,ω-bisthiocyanatoalkanes *(7)*, which absorb in the infrared at 4.6 μ. The formation of isothiocyanates was not observed.

$$N\equiv C-S-(CH_2)_n-S-C\equiv N \quad (7)$$

Compounds *(3)* and *(5)* are stable at room temperature, but decompose when struck with a loud clear report. During melting-point determinations in a Büchi apparatus, the temperature of decomposition also was often indicated by a clear report.

Received: February 16th, 1965 [Z 919/744 IE]
German version: Angew. Chem. 77, 348 (1965)

[1] *L. F. Audrieth*, Chem. Reviews *15*, 169 (1934), where further references are given.

[2] The stereochemistry of this compound has not yet been investigated.

Resolution of the Silicon Complex with 2-Hydroxypyridine N-Oxide into Its Enantiomers – Evidence for Octahedrally Coordinated Silicon

By Dr. D. R. Harvey and Prof. Dr. Armin Weiss

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Partial resolution of the complex of silicon with 2-hydroxypyridine *N*-oxide (HPNO) [1] into its optical enantiomers by treatment with disodium (−)-dibenzoyl-L-tartrate (Na_2BT) confirms that silicon is 6-coordinated in this compound. The diastereoisomer (−)-$[Si(PNO)_3]HBT$ is less soluble than the other and precipitates preferentially from aqueous solution. A saturated aqueous solution of this precipitate gave a negative rotation which decreased with time (became more positive) as the asymmetric silicon complex decomposed, and finally reached a constant negative value due to the monohydrogen (−)-dibenzoyl-(L)-tartrate anion. The filtrate from the precipitation reaction gave a high positive rotation, which decayed according to first order kinetics at pH 1.8–1.9 and 25 °C with a half-life of about 70 minutes.

2-Hydroxypyridine *N*-oxide thus resembles acetylacetone in forming a cationic complex with silicon, in which the central silicon atom is octahedrally surrounded by six oxygen atoms [2]. However, whereas HPNO forms a complex with silicic acid even in aqueous solution, acetylacetone does not react under the same conditions.

HPNO also forms complexes analogous to those already known for acetylacetone with other elements, *e.g.* $Al(PNO)_3$, $Fe(PNO)_3$ or $[Sn(PNO)_3]_2SnCl_6$ (cf. also [3,4]).

Received: February 17th, 1965 [Z 920/741 IE]
German version: Angew. Chem. 77, 347 (1965)

[1] *A. Weiss* and *D. R. Harvey*, Angew. Chem. *76*, 818 (1964); Angew. Chem. internat. Edit. *3*, 698 (1964).

[2] *S. K. Dhar*, *V. Doron*, and *S. Kirschner*, J. Amer. chem. Soc. *81*, 6372 (1959).

[3] *G. T. Newbold* and *F. S. Spring*, J. chem. Soc. (London) *1948*, 1864; *E. Shaw*, J. Amer. chem. Soc. *71*, 67 (1949).

[4] *A. Albert*, *C. W. Rees*, and *A. J. H. Tomlinson*, Recueil Trav. chim. Pays-Bas *75*, 819 (1956).

Reactions of *N*-Sulfinylsulfonamides with Organophosphorus Compounds

By fil. lic. A. Senning

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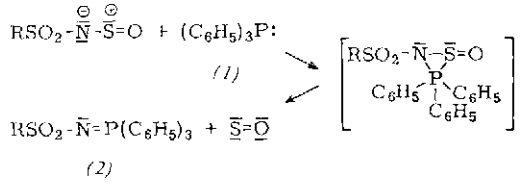
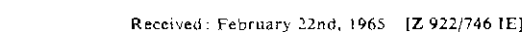
A new type of reaction was discovered when *N*-sulfinyl compounds were treated with triphenylphosphine *(1)*. Reaction of *N*-sulfinylmethanesulfonamide and *(1)* in a molar ratio of 1:1 in refluxing benzene affords 95 % methanesulfonyliminotriphenylphosphorane *(2)*, R = CH_3; analogously, *N*-sulfinyl-*p*-toluenesulfonamide and *(1)* give rise to 50 % of the corresponding iminophosphorane *(2)* with R = *p*-$CH_3C_6H_4$.



(1) *(2)*

The reaction can be interpreted in terms of attack by the coordinately unsaturated phosphorus atom (with expansion of its valence shell) at the semipolar nitrogen-sulfur bond. With triphenylphosphine sulfide, a quasi-Wittig reaction takes place [1]. Here, too, *p*-toluenesulfonyliminotriphenylphosphorane *(2)*, R = *p*-$CH_3C_6H_5$, is formed in about 50 % yield from *N*-sulfinyl-*p*-toluenesulfonamide.



Received: February 22nd, 1965 [Z 922/746 IE]
German version: Angew. Chem. 77, 379 (1965)

[1] *A. Senning*, Acta chem. scand. *18*, 1958 (1964).

Synthesis of Ethyl Nitrodiazoacetate

By Prof. Dr. U. Schöllkopf and Dr. H. Schäfer

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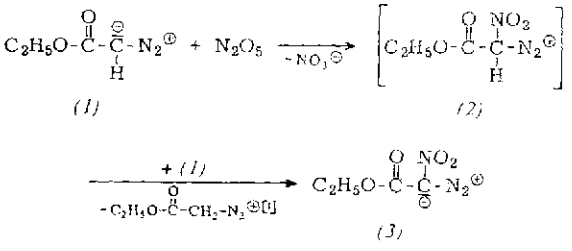
der Universität Göttingen (Germany)

Ethyl nitrodiazoacetate *(3)* is formed in 35 % yield as a yellow oil (absorptions at 2140, 1730, and 1500 cm^{-1}; m.p. of triphenylphosphazine deriv. 133–134 °C) when 1 mole of an approx. 1 M solution of dinitrogen pentoxide in carbon tetrachloride is added dropwise at −20 °C to a solution of 2 moles of ethyl diazoacetate *(1)* in CCl_4. After removal of the solvent and the nitric acid ester of ethyl glycollate (b.p. 41–42 °C/0.1 mm), the nitro derivative *(3)* is isolated by chromatography on silica gel (petroleum ether/ether 3 : 1).



(1) *(2)* *(3)*

Probably the diazonium ion *(2)* is an intermediate and is deprotonated by the second mole of *(1)*. Compound *(3)* is the first diazoalkane derivative with a nitro group on the diazo-substituted carbon atom.

Received: February 22nd, 1965 [Z 923/747 IE]
German version: Angew. Chem. 77, 379 (1965)

[1] Isolated as $C_2H_5O_2C{-}CH_2ONO_2$ after elimination of N_2.

The Crystal Structure of Lithium Silicide Li_2Si

By Dipl.-Chem. H. Axel, Dr. Herbert Schäfer,
and Prof. Dr. Armin Weiss

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der Universität Heidelberg (Germany)

The silicon sublattices in the silicides of the Group I and II metals investigated to date exhibit a great variety of forms. In addition to three-dimensional networks ($SrSi_2$) [1], structures with Si layers ($CaSi_2$) [2], Si chains (CaSi [3], SrSi [4], and BaSi [5]), isolated Si_4 tetrahedra (NaSi [6], KSi, RbSi, CsSi [7], and $BaSi_2$ [8]), and isolated silicon atoms (Ca_2Si [9] and Mg_2Si [10]) have been reported.

We have now found a new structural group in Li_2Si, namely Si_2 dumbbells. The Si–Si distance is 2.37 Å and is thus in the same order of magnitude as the Si–Si bonds in elemental silicon. The shortest Si–Si distance between neighboring dumbbells is 4.41 Å. Each silicon atom of a Si_2 dumbbell has 7 lithium atoms as nearest neighbors at distances of 2.58_5 to 2.77_1 Å.

Crystallographic data for Li_2Si:

Monoclinic; space group $C2/m - C_{2h}^3$
$a = 7.70$ Å; $b = 4.41$ Å; $c = 6.56$ Å; $\beta = 113.4°$
$d_{exp} = 1.38_5$ g/cm³; $d_x = 1.36$ g/cm³; $Z = 4$

Equivalent positions:

4 Si in (4i) $x,0,z$; $\bar{x},0,\bar{z}$; $1/2+x, 1/2, z$; $1/2-x, 1/2, \bar{z}$ with $x = 0.067$ and $z = 0.197$
4 Li_I in (4i) with $x = 0.375$ and $z = 0.120$
4 Li_{II} in (4i) with $x = 0.788$ and $z = 0.365$

The discrepancy indices R obtained for a series of planes were: (h0l): $R = 0.10_7$; (0kl): $R = 0.09_0$; (1kl): $R = 0.12_9$; (2kl): $R = 0.12_4$; (3kl): $R = 0.10_7$.

In order to obtain Li_2Si single crystals, a stoichiometric mixture of lithium and silicon was heated in an iron crucible for 3.5 h at 800 °C in an atmosphere of argon and then cooled slowly.

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German version: Angew. Chem. 77, 379 (1965)

[1] *K. Janzon, H. Schäfer*, and *A. Weiss*, Angew. Chem. *77*, 258 (1965); Angew. Chem. internat. Edit. *4*, 245 (1965).

[2] *J. Böhm* and *O. Hassel*, Z. anorg. Chem. *160*, 152 (1927).

[3] *E. Heller*, Z. anorg. Chem. *261*, 226 (1950).

[4] *G. Rocktäschel* and *A. Weiss*, Z. anorg. Chem. *316*, 231 (1962).

[5] *G. Rocktäschel*, Ph. D. Thesis, Technische Hochschule Darmstadt, 1962.

[6] *J. Witte* and *H. G. Schnering*, Z. anorg. Chem. *327*, 260 (1964).

[7] *E. Busmann*, Naturwissenschaften *47*, 82 (1960); Z. anorg. Chem. *313*, 90 (1961).

[8] *H. Schäfer, K. Janzon*, and *A. Weiss*, Angew. Chem. *75*, 451 (1963); Angew. Chem. internat. Edit. *2*, 393 (1963).

[9] *P. Eckerlin* and *E. Wölfel*, Z. anorg. Chem. *280*, 321 (1955).

[10] *E. A. Owen* and *G. D. Preston*, Proc. physic. Soc. *36*, 341 (1924).

α-Formyl Ketones from Aminoalkenes by Vilsmeier Formylation

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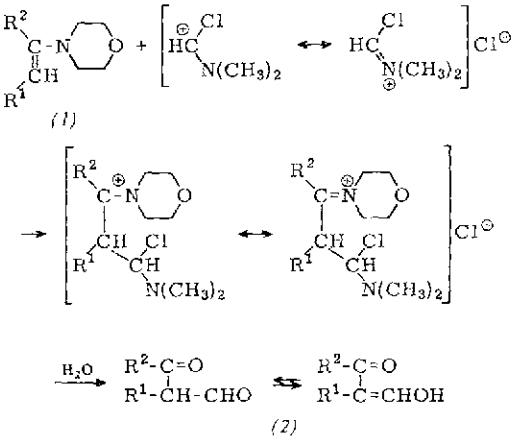
α-Hydroxymethylene ketones, which are tautomers of α-formyl ketones, were hitherto usually prepared by formylation of ketones with ethyl formate in the presence of sodium. α-Alkoxyformylalkenes or α-alkoxyformylcycloalkenes and the corresponding α-chloro compounds have been synthesized from ketals or ketones or from acetylenic compounds using Vilsmeier complexes prepared from *N*-substituted formamides and acid chlorides, *e.g.* $POCl_3$ or $COCl_2$ [1, 2].

We have observed that α-formyl ketones *(2)* can be obtained with Vilsmeier complexes from the aminoalkenes *(1)* [3].

The unstable β-dicarbonyls *(2)*, of which the formyl group is largely enolized if $R^1 + R^2$ are cyclic, generally can be characterized as monoanils or *o*-phenylenediamine derivatives [4].



(1)

(2)

(1), $R^2{-}C{=}CH{-}R^1$	Yield [%] [a]	*(2)* B.p. [°C/mm] or m.p. [°C]
Cyclopentenyl	ca. 20	71–72
Cyclohexenyl	52 [b]	40–42/1
Cycloheptenyl	48	58–60/1.5
3,4-Dihydronaphthyl	92	123–125/2
Cyclododecenyl	59	115–116/1

[a] Based on *(1)*.
[b] With 1-piperidinocyclohexene, the yield is 50 %.

α-Formylcyclohexanone: A solution of 73 g of dimethylformamide in 300 g of dichloromethane is stirred with exclusion of moisture at 5–10 °C, and a solution of 100 g of phosgene in 300 g of dichloromethane is added dropwise. The mixture is left standing for 3 h, and then 167 g of 1-morpholinocyclohexene are added gradually with stirring at room temperature. The solution is heated for 30 min at about 40 °C under reflux; 400 g of ice water are then added, and the whole is left standing overnight. The products are extracted with ether, the ether extract is washed several times with water, dried with sodium sulfate, and concentrated *in vacuo*. The residue is vacuum distilled over a Vigreux column 30 cm long, yielding 65 g of α-formylcyclohexanone as an oil ($n_D^{20} = 1.5128$) which rapidly turns brown. It reacts exothermally with aniline in dimethylformamide to yield the anil, m.p. 151 °C from dimethylformamide.

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[1] *Z. Arnold* and *J. Ženlička*, Coll. czechosl. chem. Commun. *24*, 786, 2385 (1959); *23*, 452 (1958).

[2] *W. Ziegenbein* and *W. Franke*, Angew. Chem. *71*, 573 (1959); German Patent 1071684 (Dec. 19th, 1957/Dec. 24th, 1959) Chemische Werke Hüls AG., inventors: *W. Ziegenbein* and *W. Franke*; *W. Ziegenbein* and *W. Lang*, Chem. Ber. *93*, 2743 (1960); *95*, 2321 (1962).

[3] The German Published Patent Application 1165007 (June 2nd, 1962/March 12th, 1964) BASF, inventors: *H. Spänig* and *W. Schönleben*, describes the synthesis of disubstituted malonodialdehydes by a similar route; this has induced us to report our results. – See also *R. Sciaky* and *U. Pallini*, Tetrahedron Letters *1964*, 1839.

[4] *M. Weissenfels*, Z. Chem. *4*, 459 (1964); J. prakt. Chem. *20*, 117 (1963).

Synthesis of Phosphoryl and Thiophosphoryl Compounds from Sulfur Dioxide and Phosphorus Compounds with a Coordination Number of Three

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During attempts to prepare phosphorus triisocyanate from PCl_3 and KOCN in liquid SO_2, we obtained after a reaction time of several months a quantitative yield of $OPCl_3$ instead of the expected product.

We then found that any compound containing phosphorus with a coordination number of three reacts with sulfur dioxide. The reactions are generally straightforward and run to completion within a short time at about 50 °C (in a sealed tube or an autoclave) and in the presence of catalytic amounts of PBr_3, $OPBr_3$, or $OPCl_3$; they can therefore be used for the synthesis under mild conditions of phosphoryl and thiophosphoryl compounds.

Depending on the nature of the original phosphorus compound and on the excess of sulfur dioxide the reactions proceed according to Equation (a) or Equation (b):

$$2\ P(XYZ) + SO_2 \rightarrow 2\ OP(XYZ) + {}^1/_8\ S_8 \quad (a)$$

$$3\ P(XYZ) + SO_2 \rightarrow 2\ OP(XYZ) + SP(XYX) \quad (b)$$

where X, Y, and Z = alkyl, aryl, alkoxyl, aroxyl, Cl, Br, NCS, or NCO; X and Y or X, Y, and Z may be identical. When a large excess of SO_2 is used, the reaction according to Equation (b) is followed by a reaction according to Equation (c).

$$2\ SP(XYZ) + SO_2 \rightarrow 2\ OP(XYZ) + {}^3/_8\ S_8 \quad (c)$$

Mixtures of phosphoryl and thiophosphoryl compounds can generally be separated making use of the differences in boiling points or solubilities.

Compound	Reacts according to Eq.	Products	Catalyst	Reaction time [a]
PBr_3	(b)	$OPBr_3$, $SPBr_3$	–	72 h
$P(NCS)_3$	(b)	$OP(NCS)_3$ + $SP(NCS)_3$ (≈2:1)	–	24 h
$P(C_6H_5)Cl_2$	(b)	$OP(C_6H_5)Cl_2$, $SP(C_6H_5)Cl_2$	–	42 days
	(b)	$OP(C_6H_5)Cl_2$, $SP(C_6H_5)Cl_2$ [b]	PBr_3	10 days
$P(C_6H_5)_2Cl$	(a)	$OP(C_6H_5)_2Cl$, S_8	–	24 h
$P(C_6H_5)_3$	(a)	$OP(C_6H_5)_3$, S_8	PBr_3 or $OPBr_3$	24 h
$P(C_6H_5)_3$	(b)	$OP(C_6H_5)_3$, $SP(C_6H_5)_3$	–	42 days
$P(OC_6H_5)_3$	(b)	$OP(OC_6H_5)_3$, $SP(OC_6H_5)_3$	–	35 days
$SP(C_6H_5)Cl_2$	(c)	$OP(C_6H_5)Cl_2$	PBr_3	42 days

[a] Complete consumption of the original phosphorus compound determined by ^{31}P-NMR spectroscopy; reaction temperature 50 °C; molar ratio of starting material to liquid $SO_2 \approx 1:10$.

[b] After 42 days, all the $SP(C_6H_5)Cl_2$ had been transformed into $OP(C_6H_5)Cl_2$.

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CONFERENCE REPORTS

Symposium on Coordination Chemistry

A Symposium on Coordination Chemistry organized by the Hungarian Chemical Society was held between September 14th and 17th, 1964. About 120 scientists met at Tihany (Hungary).

R. S. Nyholm, London (England), reported on complexes such as $(C_6H_5)_3PAu\text{-}V(CO_6)$, $(TA)Cu\text{-}Co(CO)_4$, (TA = $H_3CAs[o\text{-}C_6H_4As(CH_3)_2]_2$), and $[(TA)Ag]_2Fe(CO)_4$. The last complex has octahedrally coordinated iron. The CO absorption band of these and similar carbonyl compounds is shifted to smaller wave numbers as the difference in the electronegativities of the metals decreases.

In his lecture on "Assumptions and Facts about Polyions", *L. G. Sillén*, Stockholm (Sweden), showed that the composition of polyions in aqueous solution frequently differs from the composition of the solid products that can be separated from these solutions. Values determined in solution (mostly by e.m.f. measurements) can be used to attain a "best" description of the state of polyions in solution. If a quantity U is defined as a measure for the discrepancy between the calculated and experimental values, then the best approximation for the real states can be found using the relationship U(BE) = U[DA-EQ(BE)] in combination with a computation program

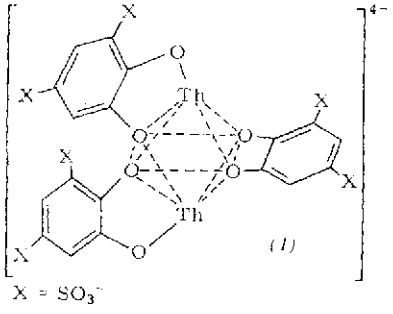
[EQ(BE) is a set of equations for the best description, DA is a set of experimental data]. For the complexes in the system $Be^{2\oplus}/OH^{\ominus}$, the formation constants β_{pm} for the equilibria

$$p\ Be^{2\oplus} + m\ H_2O \rightleftharpoons Be_p(OH)_m^{(2p-m)\oplus} + m\ H^{\oplus}$$

were found to be $\log\beta_{33} = -8.66$ and $\log\beta_{21} = -3.22$. In addition, small amounts of $Be(OH)_2$ must be taken into account; no indications were found for the occurrence of $[Be_4(OH)_4]^{4\oplus}$. Evaluation of the experimental results for a minimum in U led to the following formation constants: $10^4\cdot\beta_{12} = 6.73 \pm 0.07$, $10^9\cdot\beta_{33} = 2.068 \pm 0.013$, and $10^{10}\cdot\beta_{21} = 1.56 \pm 0.6$. Negative formation constants were obtained for 2:2, 4:4, and 1:1 complexes.

The relationships between the light absorption and the electronic configurations of complexes were discussed by *C. J. Jorgensen*, Cologny (Switzerland). To a first approximation, the wave-number of the electron-transfer band is proportional to the difference in electronegativity between the central atom and the most strongly reducing ligand. The position of this band is at higher wave numbers for complexes with two ligand spheres (*e. g.* $[Cr(OH_2)_6SO_4]^{\oplus}$) than for those with only one ligand sphere (*e. g.* $[Cr(OH_2)_4SO_4]^{\oplus}$) and can therefore be used to distinguish complex types. The reason for this shift is a charge-separation effect which is connected with the interelectronic repulsion caused by the second-order density matrix. Examination of anisotropic Cu(II) and U(VI) complexes, ion pairs, and complexes with two ligand spheres of the ions $Sm^{3\oplus}$, $Eu^{3\oplus}$, $Y^{3\oplus}$, and $Np^{4\oplus}$ showed that it was sometimes possible to differentiate by spectroscopy between normal anion complexes, anisotropic complexes, and complexes with two ligand spheres and to show that participation of 5f orbitals in the complex formation probably occurred. This finding was confirmed by *B. Jezowska-Trzebiatowska*, Warsaw (Poland), for complexes of $U^{4\oplus}$ and $U^{6\oplus}$. The spectroscopic series ROH<tributyl phosphate<$Cl^{\ominus}$<RCN<H_2O<tetrahydrofuran was found for $U^{4\oplus}$, and the series $F^{\ominus}$<$Cl^{\ominus}$<$NO_3^{\ominus}$<acetate<$SO_4^{2\ominus}$<acetylacetonate for $UO_2^{2\oplus}$ in non-aqueous systems. The series for $U^{4\oplus}$ applies for the $^3P_2$-$^3P_1$ electronic transition with reference to the quantity $\vartheta_{3P} = \Delta\nu/(J+1)$, where $\Delta\nu = \nu_{3P2} - \nu_{3P1}$ and $J + 1 = 2$. For the $UO_2^{2\oplus}$ complexes, either ν_1' in the electronic spectra or the position of the ν_1'' and ν_3'' vibrations in the infrared spectra was taken as criterion.

Numerous other lectures were devoted to complex formation, equilibria and exchange reactions in solution. For example, *P. Szarvas*, Debrecen (Hungary) found that the formation of dodecatungstate upon acidification of tungstate solutions is strongly suppressed by tartaric acid or malic acid, owing to the formation of 1:1 complexes. The formation of dodecatungstate begins only below pH 3.2. A proton is split off readily from the tartrato and malato complexes.



(*I*)

X = SO_3^-

The formation of binuclear and higher complexes of $Fe^{3\oplus}$, $Th^{4\oplus}$, $Zr^{4\oplus}$, $VO^{3\oplus}$, and $UO_2^{2\oplus}$ involving hydroxyl bridges can be blocked by the addition of chelating agents (catechol-3,5-disulfonate), according to *A. E. Martell*, Chicago, Ill. (U.S.A.). Several complexes can be prepared from $UO_2^{2\oplus}$; while $Th^{4\oplus}$ gives a 2:3 complex, probably of structure (*I*). On the other hand, the formation of a binuclear complex from uranyl citrate, which is present only in dilute solution, is non-specific. *A. Gergely*, Debrecen (Hungary), found that $Nd^{3\oplus}$ and D-glucosaminic acid (= G) forms an equilibrium mixture of four complexes: $Nd(H_3G)^{2\oplus}$, $Nd(H_3G)OH^{\oplus}$, $Nd_2(H_3G)(OH)_4^{2\oplus}$, and $Nd_2(H_3G)(OH)_2^{4\oplus}$.

Their equilibrium constants are:

$K_1 = 1.54 \times 10^{-7}$ for $Nd^{3\oplus} + H_4G \rightleftharpoons Nd(H_3G)^{2\oplus} + H^{\oplus}$

$K_2 = 3.86 \times 10^{-5}$ for $Nd^{3\oplus} + H_3G^{\ominus} + H_2O \rightleftharpoons Nd(H_3G)(OH)^{\oplus} + H^{\oplus}$

$K_3 = 5.92 \times 10^{-8}$ for $2\ Nd(H_3G)(OH)^{\oplus} + H^{\oplus} \rightleftharpoons Nd_2(H_3G)(OH)_2^{3\oplus} + H_4G$

K_4 for the equilibrium

$$Nd_2(H_3G)(OH)_2^{3\oplus} + 2\ H_2O \rightleftharpoons Nd_2(H_3G)(OH)_4^{\oplus} + 2\ H^{\oplus}$$

was not determined.

V. Gutmann, Vienna (Austria), reported that triethylammonium azide in non-aqueous solvents, *e. g.* acetonitrile, is a better azide-ion donor than alkali azides. Triethylammonium azide reacts in acetonitrile with $Co^{2\oplus}$ to yield $CoN_3^{\oplus}$, $Co(N_3)_2$, and $Co(N_3)_3^{\ominus}$, and with $Cu^{2\oplus}$ to give $CuN_3^{\oplus}$, $Cu(N_3)_2$, $Cu(N_3)_3^{\ominus}$, and $Cu(N_3)_4^{2\ominus}$. It does not react with $Ni^{2\oplus}$, but $V^{3\oplus}$ affords $V(N_3)_3$.

The attainment of the equilibrium

$$cis\text{-}[Cr(ox)_2(H_2O)_2]^{\ominus} + 2H_3O^{\oplus} \rightleftharpoons [Cr(ox)(H_2O)_4]^{\oplus} + H_2C_2O_4$$

was followed spectrophotometrically by *H. L. Schläfer*, Frankfurt/Main (Germany). The rate-determining step was found to be

$$[Cr(ox)(H_2O)_3oxH] \rightarrow [Cr(ox)(H_2O)_4]^{\oplus} + H_2C_2O_4$$

It follows a fast protonation of *cis*-$[Cr(ox)_2(H_2O)_2]^{\ominus}$ (ox = oxalate).

Optical rotatory dispersion was used by *S. Kirschner*, Detroit, Mich. (U.S.A.), to differentiate between bidentate, monodentate, and non-coordinated tartrate in the complexes $[Co(NH_3)_4(D\text{-tart})]^{\oplus}$, $[Co(NH_3)_5(D\text{-tart})]^{2\oplus}$, and $[Co(NH_3)_6](D\text{-tart})_3$. The last compound shows no Cotton effect in the visible region of the spectrum. The existence of complexes in which the thiosulfato and salicylato groups are in the outer sphere was demonstrated by *R. Larsson*, Lund (Sweden) in the systems $[Co(en)_3]^{3\oplus}/S_2O_3^{2\ominus}$ and $[Co(en)_3]^{3\oplus}$/salicylate using optical rotatory dispersion spectroscopy (en = ethylene diamine). The complex formation constants were given relative to the concentration of $[Co(en)_3]^{3\oplus}$. With thiosulfate, four complexes MA_n are formed (where n = 1,2,3, or 4, M = $[Co(en)_3]^{3\oplus}$, and A = anion). Their complex formation constants are $\beta_1 = 150\ M^{-1}$, $\beta_2 = 7.5 \times 10^3\ M^{-2}$, $\beta_3 = 1.5 \times 10^4\ M^{-3}$, and $\beta_4 = 1.5 \times 10^5\ M^{-3}$. Correspondingly, for salicylate complexes, $\beta_1 = 22\ M^{-1}$, $\beta_2 = 46\ M^{-2}$, and $\beta_3 = 3\ M^{-3}$.

The fact that the stability of mixed complexes MA_nB_m is higher than that of compounds MA_{n+m} and MB_{n+m} was explained by *Y. Marcus*, Rehovot (Israel), using essentially polarization effects due to ion-ion, ion-dipole, and dipole-dipole interactions. The enthalpies of formation calculated for mercury halides agree well with those found by experiment.

Since $F_3CCOO^{\ominus}$ and $(NH_3)_5Co(OH)^{2\oplus}$ do not exchange oxygen with $^{18}OH_2$, *H. Taube*, Stanford, Calif. (U.S.A.), was able to determine whether water attacks the Co-O bond or the C-O bond in $(NH_3)_5Co(OCOCF_3)^{2\oplus}$ by examining the concentration of ^{18}O in the hydrolysis products. At high $OH^{\ominus}$ concentrations and low temperatures, only the C-O bond is hydrolysed, whereas at low alkalinity and high temperature, the Co-O bond is cleaved preferentially. Addition of $^{18}OH^{\ominus}$ to the complex and competition between proton and cobalt transfer in the intermediate complex are suggested to occur during the reaction.

The exchange reaction of $U^{4\oplus}$ with $UO_2^{2\oplus}$ in $NaClO_4/HClO_4$ at an ion strength of 2.0 M is accelerated in the series malonic acid<maleic acid<malic acid<tartaric acid. *C. H. Brubaker*, East Lansing, Mich. (U.S.A.), found that the rate law

$$R = F + k_2C + k_3C[UO_2^{2\oplus}]$$

applies, where $k_2 = 7.3 \times 10^{-4}$ min^{-1}, $k_3 = 1.2 \times 10^{-3}$ min^{-1}, $C = [U^{4\oplus}]\,[H_2tart]/[H^{\oplus}]^2$, and $F = [U^{4\oplus}]^2[UO_2^{2\oplus}]/[H^{\oplus}]^4$. Uranium(V) may be formed as an intermediate.

G. N. Nord-Waind, Copenhagen (Denmark), found that the slow exchange of Tl in the system $Tl^{\oplus}/Tl3^{\oplus}/Cl^{\ominus}$ at low chloride concentrations is due to the low rate of exchange of the $Tl^{3\oplus}$, which is present as a complex. On the other hand, the faster Tl exchange observed with increasing $Cl^{\ominus}$ concentration can be explained by an increase in the rates of exchange of both oxidation states of the Tl.

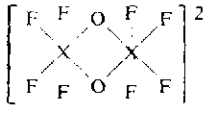
Condensed fluoro-oxo complexes were obtained from monomeric fluoro-oxo complexes by *L. Kolditz*, Berlin (Germany), by thermal condensation. The condensation may be caused either by dehydration

$$n\ K_2[SnF_4(OH)_2] \rightarrow K_{2n}[HO(SnF_4{-}O)_{n-1}{\cdots}SnF_4OH] + n-1\ H_2O$$

or by elimination of HF

$$n\ KAsF_5OH \rightarrow K_n[HO(AsF_4{-}O)_{n-1}{\cdots}AsF_4OH] + n-1\ HF$$

The binuclear complexes $(C_2H_5)_4N[F_5Sb\text{-}O\text{-}SbF_5]$, $(C_2H_5)_4N[Sb_2O_2F_8]$ *(2a)*, and $K_2[As_2O_2F_8]$ *(2b)* probably contain oxygen-bridged octahedra.



(2a): X = Sb
(2b): X = As

F. Majdik, Veszprem (Hungary), reported on the products of pyrolysis of alkoxides and aroxides of Al and Ti. Olefins and alcohols are split off and products with oxo bridges are obtained; these sometimes still contain free hydroxyl groups. Thermolysis of compounds of the type $Al(OC_4H_9)_2(OC_6H_5)$ yields polymeric products which contain the phenoxy group. Analogous investigations of $VO(OCH_3)_3$ were reported by *Gy. Pfeiffer*, Veszprem (Hungary). Here methanol and water are eliminated leading *via* $V_4O_7(OH)_4(OCH_3)_2$ to V_2O_5.

Investigations of gold complexes of the type $K[Au(CN)_2X_2]$ by infrared and Raman spectroscopy were carried out by *L. H. Jones*, Los Alamos, Calif. (U.S.A.), who showed that the force constant for the Au-C bonds decreases from 3.16 to 2.92 mdynes/Å in the series X = $CN^{\ominus}$, $Cl^{\ominus}$, $Br^{\ominus}$, $I^{\ominus}$. These values imply a strong σ- but only a weak π-interaction in the Au-C bonds.

Catalytic hydrogenation was studied by *P. J. Halpern*, Chicago, Ill. (U.S.A.), *V. A. Tulupov*, Moscow (U.S.S.R.), *J. C. Bailar*, Chicago, Ill. (U.S.A.), and *L. Simandi*, Budapest (Hungary). Metals, metal ions, and coordination compounds of the d^5-d^{10} elements have catalytic activity. The hydrogen appears to be activated either heterogeneously (*e. g.* by $RuCl_6^{3\ominus}$ or $Cu^{2\oplus}$) or homogeneously (*e. g.* by $Co(CN)_5^{3}$ or $Ag^{\oplus}$) or by addition (*e. g.* with $IrCl(CO)\,[C_6H_5)_3]_2$). During the hydrogenation of olefins, generally a metal-olefin complex is formed first and is then hydrogenated, probably *via* intermediate formation of an olefin-hydrido complex. *Bailar* showed that Pt-Sn compounds can be used for selective hydrogenation, *e. g.* of soya oil. The configuration of dienes is altered in the presence of these catalyst systems above 30 °C. Halogenoalkanes, particularly CCl_4 and $CHCl_3$, can be reduced catalytically by $NaBH_4$ in the presence of $Co^{\oplus}(trispy)_3$; *D. Konrad*, Prague (Czechoslovakia), found that the reaction

$$[Co(trispy)_3]^{\oplus} + CHCl_3 \rightarrow [Co(trispy)_3]^{2\oplus} + CHCl_3^{\ominus}$$

occurs first and that the $CHCl_3^{\ominus}$ reacts further rapidly. The Co(II) complex is reduced again to the Co(I) complex by the $NaBH_4$ (trispy = trispyridyl).

Hydroformylation and hydrogenation using $Co_2(CO)_8$ as a catalyst are inhibited by C_2H_5SH, $(C_2H_5)_2S_2$, and CS_2, but not by thiophene and $(C_2H_5)_2S$, according to *K. Markó*, Veszprem (Hungary). CoS is formed first and then reacts further in the presence of the organosulfur compounds to form $Co_3(CO)_9S$ or $Co_3(CO)_9S(SR)$, so that the reaction comes to a standstill.

W. Langenbeck, Rostock (Germany), observed a structural specificity in the catalytic action of tridentate $Cu^{2\oplus}$, $Co^{2\oplus}$, and $Zn^{2\oplus}$ chelates and of the chelates of these ions with Schiff bases in the oxidative activity of the imidazole/parahematin and benzoyldihydronicotinamide/9-phenylflavin systems. Stereochemical specificity was found with the parahematin of L-histidine and with its Cu complex with D- and L-DOPA as substrates; L-DOPA was oxidized 43% faster than D-DOPA (DOPA = dihydroxyphenylalanine). *E. Thilo*, Berlin (Germany), found that metal ions catalyse the hydrolytic degradation of condensed phosphates and of the $S_2O_7^{2\ominus}$ ion. The catalytic activity is approximately proportional to the stability of the metal-ion EDTA complexes. The concentration dependence of the effect on the reaction with the $S_2O_7^{2\ominus}$ ion indicated that complex formation (chelating) occurs prior to the hydrolysis of the S-O-S bond.

[VB 882/186 IE]
German version: Angew. Chem. 77, 349 (1965)

Theory and Technique of Precipitation Crystallization

From November 10th to 12th, 1964, the Mineralogy Section of the Geological Society of the German Democratic Republic held a symposium on "Theory and Technique of Precipitation Crystallization".

From the lectures:

R. F. Strickland-Constable (London, England) described four methods for increasing the number of nuclei in supersaturated solutions and supercooled melts: (1) On addition of a crystal to a supersaturated solution or melt, the small particles, adhering to the crystal, turn into fresh seeds. This may be prevented by first placing the crystal into a solution slightly below the saturation point. The small particles on the crystal surface are then rapidly dissolved, while the large crystal remains almost undamaged and continues to grow in a supersaturated solution. (2) New seeds are formed when crystalline needles are broken or crushed. (3) The fragments of polycrystals, which frequently show poor cohesion, yield fresh seeds. Cases (2) and (3) commonly occur in mass crystallization. Depending on the type of crystal, the degree of supersaturation and the nature of foreign compounds present in the solution, crystalline needles and polycrystals are formed instead of ideal crystals with plane surfaces. (4) If ideal crystals are required, the number of nuclei can only be increased by disintegration of the crystals already formed on impact with one another or with the stirrer and the wall.

These types of seed increase are the only possible ones on crystallization in the metastable zone (moderately supersaturated solution). Fundamentally, these types of seed increase are to be distinguished from seed formation, the rate of which markedly increases only at higher degrees of supersaturation.

$$I = C\exp[-A_k/kT] = C\cdot\exp[-U\cdot\sigma^3/T^3\,(\ln\alpha)^2]\ \text{seeds/cm}^3\text{sec}$$

I = rate of seed formation
C = frequency factor
A_k = work of seed formation
k = Boltzmann constant
T = temperature [°K]
σ = surface tension
α = degree of supersaturation, *i.e.* effective concentration/saturated concentration
U = constant

J. Myl (Pardubice, Czechoslovakia) discussed the stability of supercooled liquids. Within the metastable zone, *i.e.* within the range between saturation and supersaturation curves in the solubility *vs.* temperature diagram, crystal seeds do not form spontaneously. The width of the metastable zone of aqueous solutions increases with their purity and viscosity, with the duration and degree of superheating, and with the rate of saturation, *i.e.* with the increase in saturation per unit time. This may be proportional to the rate of cooling. Complete degradation of the aggregates of water molecules may be assumed to take place on prolonged and strong heating, while their recombination is retarded on rapid cooling.

According to *U. Steinicke* (Berlin, Germany) aluminum hydroxide may be prepared by a channel process: the solutions of aluminum salt and ammonia are mixed in a jet and directly sprayed into the internal tube (a few cm in diameter) of a double-walled glass tube (the "channel"). The basic idea of this continuous process is to mix the original solutions in the absence of a wall, with subsequent ageing of the precipitate in a channel system. Ageing is controlled by the rate of flow (slope of the channel), the pH-value and the temperature profile. The dried and calcined final product has a high catalytic activity and a sharp maximum in the particle size distribution curve (particle size can be varied from about 10 to 100 μ).

M. J. Koslovski (Tiraspol, U.S.S.R.) examined the influence of spark discharges on the formation of seeds in aqueous electrolyte solutions. The rate of seed formation at the surface of a supersaturated solution is proportional to the square of the field strength and to the degree of supersaturation. The spark flashes over from the electrode to the surface of the solution. Seed formation largely depends on which pole of the power supply the solution is connected to. In the case of KCl, spark discharge with the solution as the negative pole produced a marked crystallization, while crystallization was low with the solution being the positive pole. The crystallization of halides, sulfates, nitrates, phosphates, and carbonates of the alkali metals and alkaline earths was investigated. The rate of seed formation decreases with increasing viscosity and purity of the solution.

According to *H. J. Meyer* (Bonn, Germany) vaterite ($CaCO_3$) is preferentially formed during rapid precipitation from aqueous solutions, especially in the presence of electrolytes. The proportion of the $CaCO_3$-modifications (calcite, aragonite, vaterite) at 50 °C and in the presence of uni-univalent electrolytes (*e.g.* NaCl, NH_4NO_3) depends on the concentration and nature of the latter. Other solutes present and high degrees of supersaturation favor the formation of somatoids [*].

As *R. Boistelle* and *R. Kern* (Nancy, France) showed, clumping of sodium chloride crystals can be prevented by spraying the crystalline powder, *e.g.* with $K_4[Fe(CN)_6]$ solution. On evaporation, the $K_4[Fe(CN)_6]$ forms small sharp points on smooth sodium chloride surfaces. These probably prevent a close fit of the crystal planes and, therefore, the clumping of the crystals. From a more than 23% supersaturated solution, sodium chloride does not crystallize in cubes, but in octahedra. Other solutes present (Cd^{2+}, $CO(NH_2)_2$, $Fe(CN)_6^{4-}$, $Fe(CN)_6^{3-}$) lower the critical concentration and may lead to further changes in form and habit (*e.g.* rhomboid dodecahedra and dendrites are formed).

M. Hille (Berlin, Germany) prepared small NaCl and KCl crystals of definite form and size for flotation studies. Cubes of NaCl and KCl as well as octahedra of NaCl (size about 50 to 60 μ) are formed by precipitation with methanol/ethanol/acetone mixtures from aqueous solutions of these salts, saturated at 20 °C. The organic solvents added must be miscible with the solution. Formamide (20%) is required for precipitating octahedra of NaCl. Octahedra of KCl crystallize from an aqueous solution of KCl, which is saturated at 50 °C, contains urea (50%), and is supercooled down to 30 °C. The flotability of minerals may be improved or made at all possible by a definite crystal form.

Ch. Jentsch (Berlin, Germany) carried out adsorption measurements on alkali halide crystals of different forms. The crystals, 5 to 10 μ in size, were obtained by precipitation with methanol/ethanol/acetone mixtures. The crystal size varies with the ratio of the organic solvents. The solution contained $PbCl_2$ for the precipitation of KCl octahedra, glycine for the precipitation of NaCl rhomboid dodecahedra. No adsorption of the solutes affecting crystal form was noted, but water was adsorbed in several layers.

M. Kahlweit (Göttingen, Germany) dealt with growth studies. A temperature jump was used to produce super- or subsaturation in a saturated solution within about 10^{-5} sec. Growth and dissolution of the crystals were traced by conductivity measurements. It is concluded that growth is controlled by surface reactions (*e.g.* dehydration) at lower degrees of supersaturation, and by diffusion at higher degrees of supersaturation (above 1%).

H. Neels and *S. Aslajan* (Leipzig, Germany) studied the formation of spherolites of sodium hydrogen carbonate from an aqueous solution by addition of methanol. The size of the spherolites decreased from 8 to 4 μ with increasing degree of supersaturation (70–100%). The crystalline needles of the spherolites showed a step-wise growth. *H.* Neels and *A. Felbinger* (Leipzig, Germany) observed that the rate of formation of sodium hydrogen carbonate seeds on carbonization of an ammoniacal sodium chloride solution, is related by an exponential function to the degree of supersaturation. *Todes* (U.S.S.R.) used the rate of seed formation to determine the interfacial energy of $CaSO_4$ in aqueous solution as 12 erg/cm², and *A. E. Nielsen* (Copenhagen, Denmark) determined that of $BaSO_4$ as 130 ± 10 erg/cm². *R. Piwonka*, *H. Ortmann*, and *H. Hartmann* (Lübenwalde, Germany) precipitated cadmium sulfide, in the presence of halide ions, in the stable hexagonal modification, while sulfate ions led to the metastable cubic modification. *St. Zagrodski* and *Z. Niedzielski* (Lodz, Poland) observed increased seed formation on ultrasonic irradiation of supersaturated saccharose solutions, reaching a maximum at a sound frequency of 7.2 kc. [VB 881/212 IE]

German version: Angew. Chem. 77, 351 (1965)

[*] Somatoids are small crystals with uneven planes, which, depending on the conditions of precipitation, are spindle-shaped, spherical, lenticular, sheaf-like, dumbbell-shaped or snow-textured.

Chemical Effects Associated with Nuclear Reactions and Radioactive Transformations

About 130 scientists from 28 countries attended this symposium which was arranged by the International Atomic Energy Agency and the I.U.P.A.C. Joint Commission on Applied Radioactivity and was held in Vienna (Austria) on December 7th–11th, 1964. Some 60 papers, which are to be published soon, were presented.

Investigations Using Mass Spectrometry

The chemical effects of internally converted isomeric transitions with subsequent Auger effect [1] could previously be measured only with compounds of a few nuclides. Due to the occurence of recoil the results were uncertain to an unknown

extent. Molecular disintegrations following the Auger effect were now brought about with non-radioactive molecules, using X-rays to produce an electron deficiency at one of the atoms. The resultant positive charge is rapidly distributed throughout the molecule, which then disintegrates due to internal Coulombic repulsion. The charges and kinetic energies of the fragments were measured about 10^{-5} sec after the energy absorption. After excitation of the L-shell, CH_3I splits into C^{2+}, $3\,H^+$, and I^{5+}, while HI decomposes into H^+ and I^{7+}, and Xe yields Xe^{8+}. Molecular ions and neutral fragments are not formed. The recoil energy measured for the products of the disintegration of CH_3I corresponds to that calculated with the assumption that $C^{2+}H^+{}_3I^{5+}$ with the atomic parameters of CH_3I appears as an intermediate (*R. M. White*, U.S.A.). For the Wilzbach labelling of CH_4, the Pratt-Wolfgang mechanism was confirmed by detection of the $C_2H_4T^+$ ion. The

$$T_2 \xrightarrow{\beta^-} T^3He^+ \xrightarrow[-{}^3He]{+\,CH_4} CH_4T^{+*} \xrightarrow[10^{-11}\,sec]{-H_2} CH_2T^+$$

$$\xrightarrow[-H_2]{+\,CH_4} C_2H_4T^+ \xrightarrow[>10^{-5}\,sec]{+\,e^-,\,-CH_2} CH_2T \xrightarrow{+\,CH_4} CH_3T + CH_3$$

radiochemical portion of the reaction, which is due to β-radiation, was determined separately by addition of D_2 to the CH_4/T_2 mixture; deuterated molecules can only be formed in this way and not *via* T^3He^+ (*S. Wexler*, U.S.A.).

Gases

Radioactive carbon from the reaction $^{12}C(\gamma,n)^{11}C$ reacts mainly as such, or as methine after addition of a hydrogen atom. ^{11}C reacts with hydrocarbons to form $CH\equiv{}^{11}CH$, and ^{11}CH forms $CH_2={}^{11}CH_2$; oxygen reacts only with ^{11}C to yield ^{11}CO. The formation of ^{11}CO is six times more probable than that of a labelled hydrocarbon (*G. Stöcklin*, Germany). The reaction of ^{11}C with hydrocarbons proceeds by insertion into a C–H bond. A primary C–H bond is preferred to a secondary by a factor of 1.26. In hydrocarbon/N_2 mixtures, labelled hydrocarbons and $H^{11}CN$ result, but labelled amines are not observed. The ratio of the cross-sections in these mixtures with reference to the formation of ^{11}CO, $CH\equiv{}^{11}CH$, and $H^{11}CN$ from energy-rich carbon atoms, is 9:4.5:1. Further informations on the reaction mechanisms are to be expected from investigations of the isotopic effect (*A. P. Wolf*, U.S.A.). Isotopic effects of hot T-atoms from the reaction $^3He(n,p)T$ are also being investigated. Recently it has become possible to separate olefines in which only one H is replaced by D. With CH_3CD_3 as starting material, the reaction

$$T^* + C_2H_6 \xrightarrow{-H} C_2H_5T^* \longrightarrow C_2H_3T + H_2 \text{ or } C_2H_4 + HT$$

yields C_2H_2DT and C_2HD_2T in the ratio 1:1.6. Correspondingly, replacement of H in the first stage of the reaction is preferred to the replacement of D by a factor of about 1.3, and disintegration of $CH_2TCD_3{}^*$ is more frequent than that of $CH_3CD_2T^*$ by the same factor (*F. S. Rowland*, U.S.A.). The β-decay of T in $C_2H_4T_2$ *via* $C_2H_4T^3He^+$ as an intermediate yields 11 % HT, 2.5 % CH_3T, 5.5 % C_2H_3T, 1 % C_3H_7T, and 3–4 % C_4H_9T (*F. Cacace*, Italy). This result agrees with mass-spectrometric observations of the ions resulting from $C_2H_4T^3He^+$. Calculations of bond conservation in tritiated alkanes and $^{14}CO_2$ during β-decay gave values of ca. 1 and 80 %, respectively, in agreement with experimental results (*A. A. Gordus*, U.S.A.).

[1] An isomeric transition is called internally converted if the energy of the γ-ray quantum is transferred to an inner-shell electron which is then emitted. Filling of the vacancy by electrons from higher shells may result in further loss of electrons by similar conversion of the X-ray quanta. The latter process is termed the Auger effect and yields multiply positively charged atoms.

Liquids

In organic halides a considerable proportion of activated atoms is found incorporated into the starting material. This is not due to retention, *i.e.* to lack of bond-breaking, (*J. E. Willard*, U.S.A.) but to substitution according to:

$$*X + RX \rightarrow R*X + X$$

To clarify the reaction mechanism, the following reactions were carried out:

1. meso- or (±)-2,3-dichlorobutane$(n,\gamma)^{38}Cl \rightarrow$ dichlorobutanes

2. as 1. but with the addition of $Br_2(n,\gamma)^{80m}Br \rightarrow$ 2-^{80m}Br-3-Cl-butane

3. 2-chlorobutane$(n,\gamma^{38}Cl \rightarrow$ dichlorobutanes.

The isomeric products were separated. It was shown that the replacement of Cl by Cl or Br proceeds partly with retention of configuration and partly with racemization, and that the time of reaction is comparable with the duration of the radical transformation. The replacement of H by Cl is mainly statistical; nevertheless differences due to the different C–H bonds are perceptible. Radicals are not formed (*F. S. Rowland*, U.S.A.). Although frequently investigated, the chemical effects of the nuclear reaction $^{81}Br(n,\gamma)^{82}Br$ in liquids and solids need further discussion, since it has recently become clear that the major part of the 36h-^{82}Br in a strongly internally converted isomeric transition originates from 6 min-^{82m}Br.

Solids

Products from the nuclear reaction $^{14}N(n,p)^{14}C$ in carefully purified NH_4Cl were investigated. After dissolution the radioactivity was found in the form of 75 % CH_3NH_2, 8 % gases ($CO + CO_2 + CH_4$), 3 % HCOOH, 3 % HCHO, and 4 % CH_3OH. While CH_4 and CH_3NH_2 are probably present immediately after irradiation, the oxygen-containing compounds apparently result from precursors on dissolution in water. Surprisingly, the distribution of products is unaltered if, after irradiation, the substance is sublimed in vacuum, or at 1 mm of H_2 or NH_3; thus the precursors survive destruction of the lattice. Two possibly simultaneous mechanisms were discussed in explanation: 1. during sublimation the concentrations of NH_3 and HCl are so small and the contact times so brief, that the precursors do not react; 2. the precursors are less reactive or more stable in the lattice than was so far assumed (*P. E. Yankwich*, U.S.A.). While in normal alkali-metal halides the nuclear reaction $^{35}Cl(n,p)^{35}S$ yields 100 % $^{35}SO_4^{2-}$ after dissolution, ca. 50 % of the activity produced in vacuum-sublimed material or in single crystals can be captured as $^{35}S^{2-}$ after dissolution in sulfide- or sulfite-containing dilute alkali. The precursor may be atomic, neutral sulfur S^0, or perhaps S^- or S^+. Its behavior depends on the structure of its surroundings. From powdered CsCl, ^{35}S can be extracted with carbon disulfide. The lifetime of the fragment in solution must be at least 10^{-6} sec, since, due to the low sulfide concentration, only 1 in 10^6 collisions leads to exchange according to

$$^{35}S^0 + S^{2-} \rightleftharpoons {}^{35}S^{2-} + S^0$$

The numerical values varied within wide limits from experiment to experiment even when using different parts of the same single crystal; they could also be considerably influenced by doping (with Ca^{2+} or Cd^{2+}), γ-irradiation (before or after activation), heating, optical bleaching, or crushing. In pure solvents S^0 is oxidized by water mainly to sulfate (*J. E. Willard*, U.S.A.; *A. G. Maddock*, England).

The change in proportion of the different recoil fragments, caused by heating or irradiation, took up a considerable part of the discussions. It was suggested that migrating electrons

transfer energy to the recoil atoms and thus activate the process or that they alter the environment of the recoil atoms so that a lesser energy of activation is required. Moreover, these electrons interact with defects in the crystal matrix, which explains the complicated annealing behavior. Electrons, as well as defects, can be produced by additional γ-irradiation. The structure of the surroundings of the recoil atom is no longer regarded as controlling the course of annealing (*K. E. Collins*, U.S.A.). The importance of crystal defects is seen from the different annealing behavior of cobalt acetylacetonate/aluminum acetylacetonate mixed crystals, which were prepared by two methods (*J. I. Vargas*, Brazil). For neutron-activated potassium chromate, a parallelism has been found between thermoluminescence, electrical conductivity and isochronous thermal annealing. All these properties or processes show maxima at 160, 250, and 340 °C. The product was found to be predominantly $^{51}Cr^{2+}$ and not Cr^{3+} as previously assumed (*T. Andersen*, Denmark). The old theory by Libby, which explained the recoil behavior of central atoms in complexes in terms of a successive loss of ligands (CrO_3, CrO_2^{2+}, CrO^{4+}, Cr^{6+}) was thereby finally disproved (*G. Harbottle*, U.S.A.). In cobalt nitroammine complexes, annealing proceeds directly from $^{60}Co^{2+}$ to the end product with no intermediate stages. It is not stereospecific (*A. Todesco*, Brazil).

Recoil reactions are accomplished in a small area without greater disturbance of the atomic arrangement and lead to specific changes. The triphosphate fraction isolated from phosphates is preferentially labelled in the middle (P–O–^{32}P–O–P), which can be explained in terms of the insertion of a recoil atom between two PO_4 etrahedra. Triphosphate formed from diphosphates is preferentially labelled at the end (^{32}P–O–P–O–P), the triphosphate resulting from addition and not insertion (*L. Lindner*, Netherlands). Analogous conclusions came from the non-statistical distribution of $ReCl_nBr_{6-n}^{2-}$ ions on activation of K_2ReBr_6–K_2SnCl_6 mixed crystals. Generalization of these conclusions led to a "disorder model" for the mechanism of recoil processes. The region in which the recoil atom originates and in which its fate is decided, includes no more than 20 atoms (*H. Müller*, Germany). Further evidence for the small size of this region was obtained during investigation of alkyl-bromide/bromine mixtures (*R. Hahne*, U.S.A.) and from the annealing behavior of compounds such as $[Rh(NH_3)_5{}^{80m}Br]Br_2$ after the nuclear isomeric transition $^{80m}Br \rightarrow {}^{80}Br$ (*G. B. Schmidt*, Germany).

Considerable isotope effects are found with tetraphenylporphin complexes of Zn, Pd, and Pt (*H. E. Rosenburg*, U.S.A.). Isotope effects of similar magnitude and retentions of less than 1 % were found with ruthenocene. In general, retention seems to be mainly due to reformation (*G. Harbottle*, U.S.A.). In contrast with earlier assumptions, reformation seems also to be possible in complicated organic molecules. Thus, ^{35}S-methionine can be obtained directly from methionine by neutron-irradiation (*B. G. Dzantiev*, U.S.S.R.). Interesting commercial applications can be expected.

Mössbauer Effect

^{129}I and ^{131}I disintegrate with β-radiation into excited ^{129}Xe and ^{131}Xe, respectively, which are converted to the ground state after about 10^{-9} sec. With the aid of the Mössbauer effect information can be obtained about the chemical state of the xenon at the instant of disintegration, *i.e.* 10^{-9} sec after its formation. At this time all changes in the electron shells are completed. The following chemical changes occur due to β-decay:

NaI	→	Xe^0
$NaIO_3$	→	XeO_3
KIO_4	→	XeO_4
$Na_3H_2IO_6$	→	6 O octahedrally around Xe, perhaps XeO_6^{4-}
I_2	→	Xe^0, no Xe^+, no XeI
$KICl_4 \cdot H_2O$	→	$XeCl_4$
$KICl_2 \cdot H_2O$	→	probably $XeCl_2$

These experiments show that the hitherto unknown xenon compounds XeO_4, $XeCl_4$, and $XeCl_2$ are stable at least for a short time (*G. Perlow*, U.S.A.). [VB 892/203 IE]

German version: Angew. Chem. 77, 384 (1965)

Tenth Aniversary of the Institute for Organic Chemistry of the German Academy of Sciences

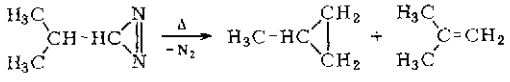
The tenth anniversary of the Institut für Organische Chemie der Deutschen Akademie der Wissenschaften in Berlin-Adlershof (Germany) was celebrated by a Colloquium on November 26th, 1964. Three lectures were delivered: *H. Bredereck* (Stuttgart, Germany) reported on "Complexes of Acid Amides with Acid Chlorides or Dialkyl Sulfates", *J. Rudinger* (Prague, Czechoslovakia) on "Oxytocin: Organic Synthesis as a Means for Investigating the Effects of Hormones", and *H. A. Staab* (Heidelberg, Germany) on: "Investigations on New Aromatic Ring Systems". During the afternoon session, members of the Institute reviewed current work of the Institute in the course of 10 short communications. Abstracts of some of these papers are given below [1].

[1] Other papers, which have in part already been published, were the following: *M. Schulz*, Angew. Chem. *75*, 918 (1963); Angew. Chem. internat. Edit. *2*, 623 (1963); Z. Naturforsch. *19b* 263 (1964); *M. Lorenz*, Mber. dtsch. Akad. Wiss. Berlin *6*, 578 (1964); *H. Dorn*, Angew. Chem. *76*, 920 (1964); Angew. Chem. internat. Edit. *2*, 748 (1964).

Ring Opening of Cyclic Diazo Compounds

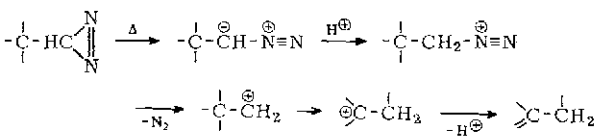
E. Schmitz, R. Ohme, D. Habisch, S. Schramm, A. Stark, and *Ch. Hörig*

Cyclic diazo compounds *(1)* split off nitrogen at temperatures above 150 °C. Cyclopropanes *(2)* and olefines *(3)* are formed *via* intermediary carbenes.

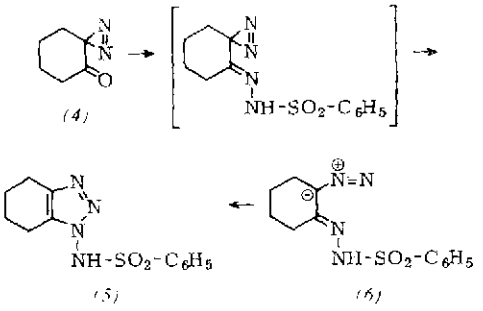


(1) *(2)* *(3)*

The formation of some of the olefines can only be explained by the assumption that a linear diazo compound is formed as an intermediate:



The same is indicated by the fact that the cyclic diazo compound *(4)* of cyclohexanone yields the same triazole *(5)* on reaction with benzenesulfonylhydrazine as is obtained from the linear diazo compound *(6)*.



(4)

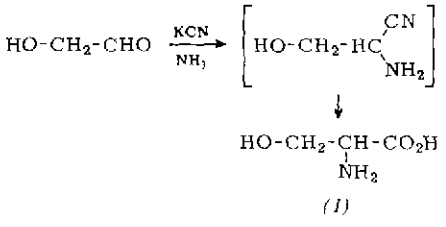
(5) *(6)*

Compound *(5)* is the first derivative which has been obtained from a cyclic as well as from a linear diazo compound.

New Syntheses of β-Hydroxy-α-amino Acids

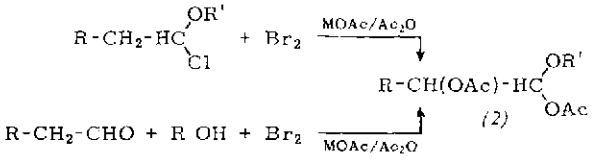
H. Gross, H. Geipel, J. Gloede, and *K.-P. Hilgetag*

In the case of β-hydroxyamino acids the Strecker synthesis has, so far, only been used to prepare serine *(1)*. Glycolaldehyde was the starting material, and the yield was below 10 %.



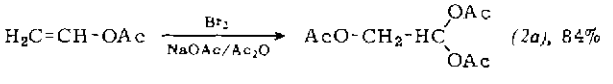
(1)

Higher hydroxy aldehydes have not been used, since they may tautomerize to the hydroxy ketones. Instead of the free hydroxy aldehydes, however, their acylal esters *(2)* can be used for the Strecker synthesis. Compounds of this type are obtained in high yields in the following manner:



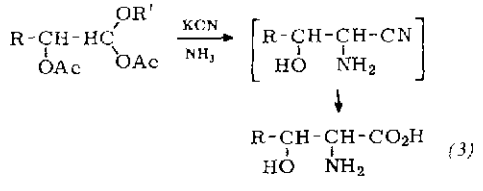
(2)

M = Na up to R = C_3; Ag with R > C_3



(2a), 84%

Strecker syntheses using compounds of type *(2)* afford β-hydroxyamino acids *(3)* in yields of 60 to 80 % with R = CH_3 up to C_4H_9. With R = C_5H_{11} up to $C_{10}H_{21}$, yields of 45 to 60 % are obtained. Thus, yields are generally higher than in the usual Strecker synthesis.



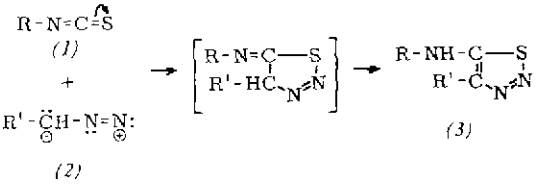
(3)

Compound *(2a)* yields serine in 87 % yield. When using primary amines instead of ammonia, *N*-alkylated serines are obtained, but here yields are lower.

Synthesis of Heterocycles Containing Sulfur and Ring Opening with Formation of Esters of Cyanic Acid

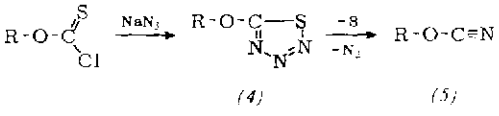
D. Martin and *W. Mucke*

The reaction of isothiocyanates *(1)* with diazo compounds *(2)* yields 5-alkylamino-1,2,3-thiadiazoles *(3)*. According to kinetic studies, this reaction is a 1,3-dipolar cycloaddition proceeding in one step. The rate of addition increases with increasing electrophilic character of the C-atom in *(1)* and is decreased by electron attracting groups R' in *(2)*.



(1) *(2)* *(3)*

The thiadiazoles *(3)* possess considerable thermal stability. On the other hand, the structurally similar 1,2,3,4-thiatriazoles *(4)*, which can be prepared from thiocarbonic ester chlorides and sodium azide, decompose by an exothermic reaction even at 0 °C.



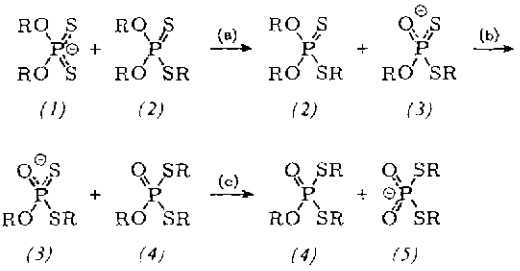
(4) *(5)*

Fractionated distillation of the reaction products yields esters of cyanic acid with about 85 % yield. The aryl esters *(5)*, R = aryl, trimerize on heating at 200 °C to form esters of cyanuric acid. Friedel-Crafts catalysts or sodium alkoxides accelerate this reaction. The alkyl esters of cyanic acid *(5)*, R = alkyl, on the other hand, isomerise on heating to yield alkyl isocyanates [1].

Alkylation and Isomerization Reactions of Dithiophosphates

H. Teichmann

In order to study the side reactions occuring during the technical syntheses of dithiophosphate insecticides, a simple model system was investigated using thin-layer chromatography. Equimolar amounts of *(1)* and *(2)*, R = CH_3, react



(1) *(2)* *(2)* *(3)*

(3) *(4)* *(4)* *(5)*

in methanol at 65 °C within only a few minutes to form *(3)*; after 1.5 h, equal concentrations of *(1)* and *(3)* are present; after about 7 h, *(1)* has completely disappeared. The species *(5)* begins to appear after about 1.5 h and is the only anion left after 25 h. About 50 % of the ester *(2)* has been converted when *(1)* is used up. The alkylation of *(3)* according to Reaction (b) is therefore overlapped by Reaction (c). The final products are *(5)* plus about equal amounts of *(2)* and *(4)*. It follows from the course of reaction that *(4)* is a stronger alkylating reagent than *(2)* and that the nucleophilicity of the anions decreases rapidly in the series *(1)* > *(3)* > *(5)*.

[1] For further reactions of esters of cyanic acid, see *D. Martin*, Angew. Chem. 77, 96 (1965); Angew. Chem. internat. Edit. 4, 73 (1965).

During syntheses of dithiophosphates $(RO)_2P(S)SR'$ from *(1)* and R'Hal, side reactions of types (a)–(c) can be largely suppressed by using low temperatures: the half-life for Reaction (a) at 20 °C is about 6 days.

Catalytic Cleavage and Formation of C—C Bonds in Aromatic Compounds in the Gas Phase

H. Seeboth

Linkages between carbon atoms in aromatic compounds can be split under relatively mild conditions with a nickel catalyst (Ni/NiO on γ-Al_2O_3, Leuna catalyst 6524) which is used for the hydrogenation of phenol. Benzyl alcohol is converted at 200 °C into benzaldehyde and this loses carbon monoxide to form benzene quantitatively.

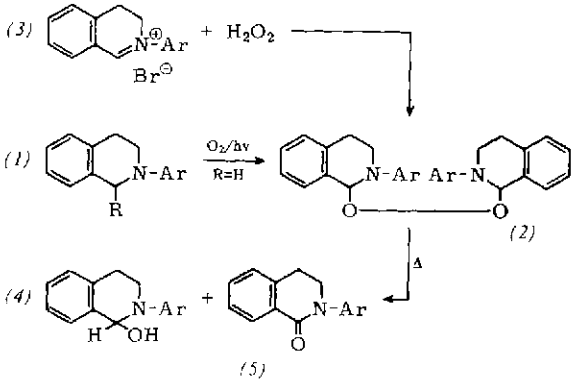
The hydrodemethylation of toluene at normal pressure can be carried out at 300–350 °C. Methane is formed; its amount increases with temperature and with the hydrogen:toluene ratio, but is decreased by the presence of water. Similarly, ethylbenzene and cumene are converted with successive loss of methyl groups into benzene. The demethylation occurs by a radical mechanism. Cycloaliphatic compounds are not formed as intermediates, since methylcyclohexane yields toluene from which benzene is subsequently formed.

Benzene and methane react to form toluene. The yield of toluene increases when the process is carried out in the presence of hydrogen. It is about 10% at 350 °C, a molar ratio of $C_6H_6:CH_4:H_2 = 1:2:2$, and a throughput of benzene of 0.15/hour. Toluene is formed by the reaction of benzene with methyl or methylene radicals which originate from benzene or methane. This is confirmed by the observation that [^{14}C]-toluene is formed when $^{14}CH_4$ and toluene are reacted at 350 °C.

Formation of Peroxides from Heterocyclic Compounds Containing Nitrogen

E. Höft and *H. Schultze*

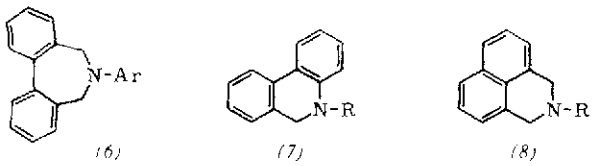
When *N*-aryl-1,2,3,4-tetrahydroisoquinoline *(1)*, R=H, is shaken in benzene with oxygen under ultraviolet irradiation, a peroxide of structure *(2)* is formed which crystallizes on addition of isopropyl alcohol.



It is of interest that a hydrogen peroxide intermediate could not be detected in this reaction.

Peroxides of type *(2)* are colorless stable compounds which revert to the starting material *(1)* on hydrogenation. They can also be prepared from the immonium salts *(3)* and H_2O_2. On heating they decompose into the pseudobases *(4)* and the lactams *(5)*.

In analogy to *(1)*, compounds *(6)* and *(7)* yield peroxides with a structure similar to that of *(2)*. On the other hand, 1,2-disubstituted tetrahydroisoquinolines *(1)*, R = alkyl or aryl, and *N*-aryl-2,3-dihydro-1*H*-benz[*de*]isoquinolines *(8)* do not form peroxides.



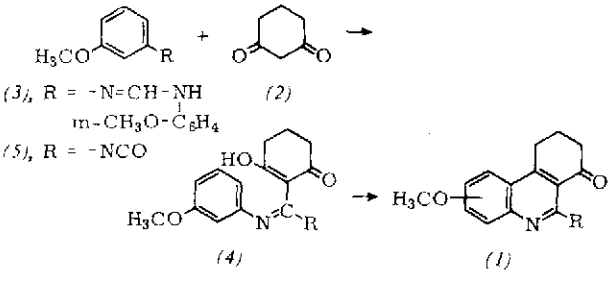
(6) *(7)* *(8)*

Syntheses with Dihydroresorcinol

G. Lehmann

None of the usual quinoline syntheses can be used for the preparation of phenanthridine derivatives *(1)*, R = H. Such syntheses either do not give the desired products or they require starting materials which in turn can only be synthesized in several steps.

A synthesis of *(1)*, R = H, was developed which starts with the addition of dihydroresorcinol *(2)* onto the amidine *(3)*. The Schiff base *(4)* thus formed was cyclized with polyphosphoric acid above 100 °C, to yield a mixture of the 1- and 3-methoxy derivatives *(1)*, R = H.



(3), R = -N=CH-NH *(2)*

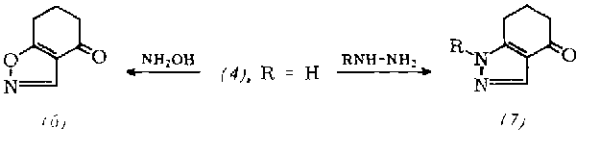
m-CH_3O-C_6H_4

(5), R = -NCO

(4) *(1)*

Starting from dihydroresorcinol and the isocyanate *(5)*, the compounds *(4)*, R = OH, and *(1)*, R = OH, were obtained.

The arylimino group in *(4)*, R = H, can be replaced easily by other amine derivatives. Reaction with hydroxylamine leads to the oxime which is readily cyclized to tetrahydrobenzisoxazolone *(6)*. Reaction with hydrazines, followed by cyclization, yields tetrahydroindazolones *(7)*.



(6) *(4)*, R = H *(7)*

[VB 898/206 IE]
German version: Angew. Chem. 77, 381 (1965)

Complex Acetylides of Transition Metals

R. Nast, Hamburg (Germany)

In liquid ammonia, cadmium and mercury form diamagnetic anionic complexes of the type $Ba[M(C{\equiv}CR)_4]$. Protolytic decomposition of diphenylzinc and diphenylcadmium with phenylacetylene in ether/tetrahydrofuran according to

$$M(C_6H_5)_2 + 2\ HC{\equiv}C{-}C_6H_5 \rightarrow 2\ C_6H_6 + M(C{\equiv}C{-}C_6H_5)_2$$
M = Zn or Cd *(1)*,

leads to the crystalline bisphenylacetylides *(1)*, which are nonelectrolytes and dissolve readily in liquid ammonia. Unsymmetrical phenylacetylides of the type C_6H_5-M-C≡C-C_6H_5, where M = Zn or Hg, were also obtained.

Complex dialkynylmetalates *(2)* of silver and gold are readily obtained in liquid ammonia according to

$$MC{\equiv}CR + KC{\equiv}CR \rightarrow K[M(C{\equiv}CR)_2]$$
(2), M = Ag or Au

These anionic complexes are diamagnetic, sensitive to light, and strong electrolytes in liquid ammonia. Analogous reactions with Ag_2C_2 and Au_2C_2 produced the polynuclear acetylides $[KC{\equiv}CAg]_\infty$ and $K_2[HC{\equiv}C\text{-}Au\text{-}C{\equiv}C\text{-}Au\text{-}C{\equiv}CH]$.

The ligands in $K_2[Pd(CN)_4]$ and $K_2[Pt(SCN)_4]$ can be partly or completely replaced by acetylide ions in liquid ammonia, giving the diamagnetic complexes *cis*-$Ba[Pd(CN)_2(C{\equiv}CR)_2]$ and $K_2[Pt(C{\equiv}CR)_4]$, which are presumably planar.

From theoretical considerations stabilization of the lower oxidation states of central atoms by acetylide ions would be expected. This was confirmed by the preparation of complex acetylides of Cr(0), Mo(0), W(0), Pd(0), Pt(0), and Cu(0). For example the reaction

$$[M(CO)_3(NH_3)_3] + 3\ KC{\equiv}CR \rightarrow 3\ NH_3 + K_3[M(CO)_3(C{\equiv}CR)_3]$$

(3), M = Cr, Mo, or W

in liq. ammonia lead to the tricarbonyltrialkynylmetalates (0) *(3)*. With potassium in liquid ammonia as reducing agent, diamagnetic, pyrophoric, probably polynuclear acetylides*(4)* of Pt(0) and Pd(0) are obtained as follows:

$$K_2[M(CN)_4] + 2\ KC{\equiv}CR + 2\ K \rightarrow 4\ KCN + K_2M(C{\equiv}CR)_2$$

(4), M = Pd or Pt

Finally, an orange-brown, pyrophoric, crystalline phenylacetylide complex *(5)* of formally zero-valent copper is produced by the reaction

$$2\ K_2[\overset{\oplus 1}{Cu}(C{\equiv}C\text{-}C_6H_5)_3] + 2\ Li + 3\ Ba^{2\oplus} \rightarrow \overset{0}{Ba_3}[Cu(C{\equiv}C\text{-}C_6H_5)_3]_2 + 4\ K^{\oplus} + 2\ Li^{\oplus}$$

(5)

The diamagnetism of *(5)* and the position of its C≡C band in the infrared give evidence for a binuclear complex with a Cu-Cu bond.

The infrared spectra of the complex acetylides of metals of the Cr, Ni, Cu, and Zn groups indicate some double-bond character of the carbon-metal bonds, which decreases with increasing electronegativity of the central metal atom of the complex. In the mixed alkynyl complexes of the Pd and Cr groups, the carbonyl and cyano ligands can form much stronger d_π-p_π bonds to the metal than the acetylide ions.

[GDCh-Ortsverband Unterfranken, Würzburg (Germany),
November 6th, 1964] [VB 884/190 IE]
German version: Angew. Chem. 77, 352 (1965)

Association of Isomeric Hydroxyalkane Derivatives

G. Geiseler, Leipzig (Germany)

The tendency of isomeric alcohols, oximes, hydroperoxides, and carboxylic acids derived from n-heptane and n-octane to associate was studied in carbon tetrachloride by infrared spectroscopy and thermodynamic methods. For the alcohols, the degree of association decreases when the hydroxyl group is shifted from a terminal position toward the middle of the molecule. The heats of association for the different associates (maximum multiplicity: 8–10 [1]) indicate that cyclic structures are present (at least for tri- and tetrameric associates) in addition to chains and three-dimensional aggregates.

The oximes are much more strongly associated and behave contrarily. The degree of association increases as the hydroximino group approaches the center of the molecule, but the influence of the position of the NOH group is less marked than that of the OH group in the alcohols. The reason obviously is the bifunctional character of the oxime group. Only two- and three-dimensional associates are formed, and these have probably cyclic structures.

The hydroperoxides are intermediate between the alcohols and oximes. Like primary alcohols, primary hydroperoxides are more strongly associated than the secondary isomers; these, however, are more similar to the corresponding oximes, *i.e.* their degree of association increases as the hydroperoxy group approaches the center of the molecule. Here again only dimers and trimers are formed and hence it can be concluded that hydroperoxides also associate bifunctionally and probably form cyclic structures.

No differences (within the accuracy of the methods) were observed for isomeric carboxylic acids; they form only dimeric associates, which are most stable.

These results suggest that molecules which associate bifunctionally tend to form aggregates of only a few molecules, *i.e.* mainly dimers and trimers; moreover, the dimers are all the more dominant, the stronger the hydrogen bonds. In contrast, molecules which associate monofunctionally form mainly chains and three-dimensional networks containing many molecules. The thermodynamic excess functions for the isomeric alcohols and oximes indicate that the position of the functional group in the chain has a considerable influence on the short-range order. Polar and unsaturated solvents not only suppress the association but also reduce the maximum multiplicity and alter the compositions of the associates.

[GDCh-Ortsverband Aachen (Germany),
November 6th, 1964, and
GDCh-Ortsverband Münster (Germany),
November 9th, 1964] [VB 885/194 IE]
German version: Angew. Chem. 77, 352 (1965)

The Importance of Canal Inclusion Compounds for Polymerization Research

H. Clasen, Frankfurt/Main (Germany)

2,3-Dimethylbutadiene forms a canal inclusion compound with thiourea; the dimethylbutadiene molecules lie head-to-tail in tube-like lattice interstices. Although dimethylbutadiene does not polymerize without a catalyst outside these canals, here it polymerizes spontaneously to form an unbranched, highmelting polymer which gives a crystalline X-ray diffraction pattern. This "canal polymerization" is accelerated by X-rays.

After this and the canal inclusion compound of butadiene became known [1], numerous monomers were examined for their ability to undergo canal polymerization under the influence of high-energy β- and γ-rays [2]. Cyclooctatetraene will not form homopolymers, but will copolymerize with dichlorobutadiene. – So far, stereoregular polymers could be produced by irradiation only via canal inclusion compounds. Following recrystallization, their structures and melting points are the same as those of stereoregular Ziegler-Natta polymers. The yields increase with the duration of irradiation, but it is not yet known for certain whether the decrease in average molecular weight with increasing duration of radiation and with increasing impurities can be explained quantitatively by a monoradical reaction mechanism [3].

[1] The term multiplicity denotes the number of monomers in an associate.

[1] *H. Clasen*, Angew. Chem. *68*, 493 (1956); Z. Elektrochem. Ber. Bunsenges. physik. Chem. *60*, 982 (1956).

[2] *J. F. Brown*, and *D. M. White*, Angew. Chem. *70*, 416 (1958); J. Amer. chem. Soc. *82*, 5671 (1960); *T. F. Yen*, J. Polymer Sci. *38*, 272 (1959); *D. M. White*, J. Amer. chem. Soc. *82*, 5678 (1960); Angew. Chem. *73*, 175 (1961); *I. Sakurada* and *K. Nambu*, Nippon Kagaku Zasshi *80*, 307 (1959); Chem. Abstr. *55*, 4340 (1961); *G. B. Barlow* and *A. C. Clamp*, J. chem. Soc. (London) *1961*, 393; *O. L. Glavati* and *L. S. Polak*, Petroleum Chemistry *2*, 201 (1963).

[3] *A. Ya. Temkin*, Petroleum Chemistry *2*, 210 (1963).

Uniform polymers would be expected in ideal single crystals from purest monomers if the mechanism were a biradical one.

Perhydrotriphenylene functions as host not only for small molecules, but also for unbranched macromolecules, which form highly stable, even fusable canal inclusion compounds [4]. This affords a method of separating branched molecules even in the macromolecular range and provides a means of shielding macromolecular substances in order to prevent undesired reactions. Graft polymerization in canals has not yet been observed. Radioactive host substances which can be regenerated are economically important.

[Lecture at Clausthal (Germany), November 13th, 1964]

[VB 875/179 IE]

German version: Angew. Chem. 77, 353 (1965)

Valence Tautomerism of Unsaturated Ring Systems

R. Huisgen, F. Mietzsch, G. Boche, and *H. Seidl*, München (Germany)

The same kinetic method [5] which was used to prove the presence of 0.01 % bicyclo[4,2,0]octa-2,4,7-triene in equilibrium with cyclooctatetraene by valence tautomerism was applied in the cyclooctatriene series. Kinetic investigations of the Diels-Alder additions of pure cycloocta-1,3,5-triene and of bicyclo[4,2,0]octadiene afforded all the parameters of the free-energy diagram; the free energy of tautomerism is 1.5 kcal/mole, and the activation energy for conversion into the bicyclic compound is 27.1 kcal/mole.

With substituted cycloocta-1,3,5-trienes the equilibrium concentration of the bicyclic tautomer at 20 °C strongly depends on the nature of the substituents: It is 0.007 % for 7,8-epoxycycloocta-1,3,5-triene, 5 % for cycloocta-2,4,6-trien-1-one, 9 % for cycloocta-1,3,5-triene, and 100 % for 7,8-dibromocycloocta-1,3,5-triene.

The kinetics of the Diels-Alder reaction also indicate a valence tautomerism between *trans*-1,2-diphenylbenzocyclobutene and *trans,trans*-5,6-dibenzylidenecyclohexadiene (α,α'-diphenyl-*o*-quinodimethane), activation energy: 20.6 kcal/mole. Analogous ring opening of *cis*-1,2-diphenylbenzocyclobutene at 50 °C to give *trans,cis*-5,6-dibenzylidenecyclohexadiene proceeds seventy times as slow.

[GDCh-Ortsverband Mainz (Germany), November 26th, 1964]

[VB 891/193 IE]

German version: Angew. Chem. 77, 353 (1965)

Fluorosulfonic Acid as a Reaction Medium and a Fluorinating Agent

A. Engelbrecht, Innsbruck (Austria)

Fluorosulfonic acid is probably the most strongly proton-donating solvent. The conductivities observed for solutions of sulfuric acid, perchlorid acid, and hydrogen fluoride in fluorosulfonic acid can best be interpreted by assuming that these substances behave as bases. Only a few fluorides (SbF_5, BF_3, PtF_4, TaF_5, and AuF_3) behave as Lewis acids in fluorosulfonic acid. Correspondingly, many salts, particularly salts of oxyacids, are solvolysed completely in FSO_2OH. In most cases fluorides are subsequently formed, sometimes immediately in strongly exothermic reactions (*e.g.* $FMnO_3$, F_2CrO_2, F_3PO, and F_5TeOH), sometimes only on prolonged heating (*e.g.* $FClO_3$, F_2SeO_2, AsF_5, and AsF_3). In addition to the fluorides, fluorosulfates or fluorosulfate-fluorides may occur as more or less stable intermediates, which in turn undergo thermal decomposition to give either fluoride and SO_3 or mostly oxide and pyrosulfurylfluoride (the anhydride of fluorosulfonic acid).

Characteristic reactions of fluorosulfonic acid are illustrated by its reaction with telluric acid (in the form of BaH_4TeO_6) which leads to new compounds containing the F_5Te group. The most interesting product is undoubtedly F_5TeOH, m.p. 40 °C, b.p. 60 °C, a strong acid which can be used to produce salts with the anion $F_5TeO^{\ominus}$ and other derivatives with the F_5Te group.

[GDCh-Ortsverband Saar, Saarbrücken (Germany), December 11th, 1964]

[VB 890/192 IE]

German version: Angew. Chem. 77, 387 (1965)

Hydrolysis of Metal Alkoxides – a New Method for Studying Polyacids

K. F. Jahr, Berlin (Germany)

If an ester of a metallic acid, *e.g.* $Nb(OC_2H_5)_5$ or $WO(OC_2H_5)_4$, is hydrolysed in an organic solvent with less than the equivalent amount of water in the presence of an anhydro base, a polyanion is formed which precipitates as the salt of the base. The degrees of condensation and protonation of the polyanion are determined mainly by the pK of the base.

Advantages of this new method are:

1. The products are pure salts of the polyacids, without any water of crystallization [1]; in organic solvents, the water only causes hydrolysis and not hydration. Any water contained in the salts is exclusively part of the molecular structure.

2. It is possible to estimate quantitatively the amounts of the metallic acid ester and of the anhydro base which react with a given amount of water to form the salt of a polyacid. The reactions leading to the various anionic species of the polyacid can then be formulated precisely. In particular, the ratio of oxygen to metal atoms (*e.g.* Nb or W) can be determined for each polyanion, a factor which is indispensible for structure determination.

3. Salts of polyacids can be obtained which would be completely hydrolysed in aqueous solution.

4. Salts can be obtained of polyacids which are intermediates in the hydrolysis reaction but which cannot be isolated from aqueous solutions. During the hydrolysis of $WO(OC_2H_5)_4$ in ethanol, the ammonium salt of hexameric "paratungstic acid A" was isolated for the first time [2]. In contrast to the ammonium salt of dodecameric "paratungstic acid Z" (the ammonium paratungstate which crystallizes from aqueous solution in a highly hydrated form) the new salt is readily soluble in water and exhibits all reactions characteristic of the paratungstate A ion, which was hitherto known only in solution; these reactions serve to distinguish it from the paratungstate Z ion.

Oxyacids which condense with metallic acids also react with the esters of metallic acids to give heteropolyacids [3]. Thus, acidolysis of t-butyl orthovanadate $VO(OC_4H_9)_3$ with phosphoric acid in anhydrous organic solvents leads to linear chains of alkoxyvanadatophosphoric acids, $H-(HPO_3-VO_2-OR)_n-PO_4H_2$, in which the vanadate and phosphate groups alternate. The alkoxyl groups are hydrolysed with a little water, giving short-chain vanadatophosphoric acids $H-(HPO_3-HVO_3)_n-PO_4H_2$ *(1)*. The solubilities of *(1)* in organic solvents decrease as the length of the chains increases, and hence the chain extension ceases as soon as the solubility becomes zero. The greater the hydrophilicity of the solvent, the higher is the solu-

[4] *M. Farina, G. Allegra*, and *G. Natta*, J. Amer. chem. Soc. *86*, 516 (1964).

[5] *R. Huisgen* and *F. Mietzsch*, Angew. Chem. *76*, 36 (1964); Angew. Chem. internat. Edit. *3*, 83 (1964).

[1] *K. F. Jahr* and *J. Fuchs*, Chem. Ber. *96*, 2457, 2460 (1963).

[2] *P. Witte*, Ph. D. Thesis, Freie Universität Berlin, 1964.

[3] *U. Skurnia*, Ph. D. Thesis, Freie Universität Berlin, 1964.

bility of the vanadatophosphoric acids, and the degree of polymerization (n) of the products which separate out increases correspondingly. In ethanol and water $n > 100$, so that formula *(1)* becomes practically $(-HPO_3-HVO_3-)_n$ *(2)*. The long-chain polyvanadatophosphoric acids *(2)* produced in water are identical with the "luteophosphorovanadic acids" $P_2O_5 \cdot V_2O_5 \cdot xH_2O$ known since the time of *Berzelius*; like these, *(2)* form polybasic salts $[(-PO_3-HVO_3-)_n]^{n\ominus}M_n^{\oplus}$. The structures of these salts correspond to those of the polyarsenatophosphates which were prepared from molten arsenate/phosphate mixtures and studied extensively by *Thilo* and *Kolditz* [4].

[GDCh-Ortsverband Darmstadt (Germany),
December 15th, 1964] [VB 888/197 IE]
German version: Angew. Chem. 77, 386 (1965)

Thermal Decomposition of Hydrazine

K. W. Michel, Göttingen (Germany) [*]

The thermal decomposition of anhydrous hydrazine was induced by shock waves and was studied using an ultraviolet-absorption method [1]. By increasing the temperature and by diluting the hydrazine/argon mixture (to 0.03 % N_2H_4), bimolecular chain reactions were suppressed to such an extent that the decomposition of hydrazine was virtually determined by the unimolecular dissociation reaction $N_2H_4 \rightarrow 2 \cdot NH_2$. The rate of this reaction is a function of pressure; for a molar density (predominantly argon) of $\varrho_T = 7.5 \times 10^{-5}$ moles/cm³, $k_1 = 10^{12.8} \exp(-\frac{52\ \text{kcal/mole}}{RT})$ sec⁻¹; for $\varrho_T = 2.5 \times 10^{-5}$ moles/cm³, $k_1 = 10^{12.0} \exp(-\frac{48\ \text{kcal/mole}}{RT})$ sec⁻¹. Thus for the rate-determining radical reaction

$$NH_2 + N_2H_4 \rightarrow NH_3 + \cdot N_2H_3,$$

$$k_2 = 10^{13.5} \exp(-\frac{17\ \text{kcal/mole}}{RT})\ \text{cm}^3\ \text{mole}^{-1}\ \text{sec}^{-1}.$$

Quantitative study of the decomposition products was extended to the range from 1100 to 2000 °K. NH_3 was determined from its ultraviolet absorption behind reflected waves. At 1100 °K, about 1 molecule of NH_3 is formed per molecule of N_2H_4. The rate of the unimolecular reaction

$$Ar + NH_3 \rightarrow \cdot NH_2 + \cdot H + Ar$$

is proportional to the molar density of Ar between 10^{-5} and 8×10^{-5} moles of Ar/cm³ and between 2000 and 3000 °K:

$$-d[NH_3]/dt = k[NH_3][Ar]$$

with $k = 10^{15.6} \exp(-\frac{79.5\ \text{kcal/mole}}{RT})\ \text{cm}^3\ \text{mole}^{-1}\ \text{sec}^{-1}$

It follows from this that NH_3 is stable under the conditions of the decomposition of N_2H_4. Nevertheless only $^1/_2$ mole of NH_3 is formed per mole of N_2H_4 at 1600 °K, and less than $^1/_{10}$ mole of NH_3 at 2000 °K.

From these molar ratios, from the fact that only small quantities of NH-radical are formed [2] (in contrast to the decomposition of NH_3), and from the presence of large quantities of N_2H_2 in hydrazine decomposition flames [3], it can be concluded that the reaction

$$2 \cdot NH_2 \rightarrow NH_3 + :NH$$

is less important than the reaction

$$2 \cdot NH_2 \rightarrow N_2H_2 + H_2.$$

[GDCh-Ortsverband Göttingen (Germany),
December 17th, 1964] [VB 897/201 IE]
German version: Angew. Chem. 77, 385 (1965)

Introduction of Tertiary Alkyl Groups into Aliphatic Compounds

P. Boldt and *Lothar Schulz*, Göttingen (Germany)

The direct introduction of tertiary alkyl groups into compounds containing active methylene groups did so far not proceed with good yields. When it was attempted to achieve this reaction by mixing t-butyl bromide, the bromo derivative of a CH-acidic compound (*e.g.* bromomalononitrile), and cyclohexene, only isobutene and malonitrile were obtained in addition to 1,2-dibromocyclohexane. The addition of bromomalononitrile to isobutene also failed to afford compound *(1)*, from which t-butylmalononitrile should have been obtainable, but instead gave the new compound *(2)* in good yield.

(1) $(CH_3)_2C(CH_2Br)-CH(CN)_2$ $\qquad$ $(CH_3)_2C(CH_2CH(CN)_2)-Br$ *(2)*

The first experiment showed that reaction conditions must be observed, under which t-alkylcarbonium ions are stable until alkylation has taken place; an attempt was therefore made to alkylate CH-acidic compounds under the conditions of the Friedel-Crafts reaction. It had been demonstrated in the case of acetoacetic ester [1], that only low yields of products containing the t-alkyl group are obtainable, and that CH-acidic compounds decompose readily [2]. We found, however, that these difficulties can be circumvented.

t-Butyl-malononitrile and -malonic ester [3], as well as t-amylmalononitrile were accessible in good yields using Lewis acids as catalysts. CH-Acidic compounds containing activating keto groups were particularly readily alkylated by employing silver cations or protonic acids as catalysts. The previously unknown ethyl t-butylacetoacetate is formed on treatment of t-butyl bromide and ethyl acetoacetate with equivalent quantities of silver perchlorate, or on passing isobutene into a solution of ethyl acetoacetate in nitromethane containing catalytic quantities of perchloric acid. In both cases, the yield did not exceed 60 %, because the formation of ethyl t-butylacetoacetate is reversible.

[GDCh-Ortsverband Göttingen (Germany),
December 17th, 1964] [VB 895/200 IE]
German version: Angew. Chem. 77, 386 (1965)

The Steric Course of Catalytic Hydrogenations

F. Zymalkowski, Bonn (Germany)

The widespread opinion that catalytic hydrogenations always yield the stereoisomer of highest energy which is stable under the conditions used is at variance with the following findings:

1) Hydrogenation of *o*-, *m*-, or *p*-cresol with Rh/Al_2O_3 in aqueous NaOH at 20 °C and 1 atm of hydrogen always leads to the *cis*-methylcyclohexanols as the major products, *i.e.* *m*-cresol yields the isomer of lower energy under the same conditions as *o*- and *p*-cresol yield the isomer of higher energy. Here the relative positions of two substitutents is there-

[4] *E. Thilo* and *L. Kolditz*, Z. anorg. allg. Chem. *278*, 122 (1955).

[*] Present address: Esso AG., Hamburg (Germany).

[1] *K. W. Michel* and *H. G. Wagner*, Z. physik. Chem. NF *35*, 392 (1962); *K. W. Michel*, Angew. Chem. *74*, 721 (1962).

[2] *K. W. Michel* and *H. G. Wagner*, Paper No. 48, Xth International Symposium on Combustion, Cambridge, 1964.

[3] *D. McLean* and *H. G. Wagner*, Naturwissenschaften *52* (1965), in the press.

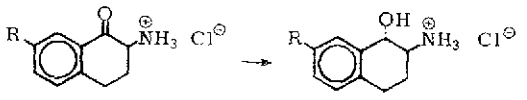
[1] *J. T. Adams, B. Abramovitch*, and *C. R. Hauser*, J. Amer. chem. Soc. *65*, 552 (1943).

[2] *W. J. Monacelli* and *G. F. Hennion*, J. Amer. chem. Soc. *63*, 1722 (1941).

[3] *P. Boldt* and *L. Schulz*, Naturwissenschaften *51*, 288 (1964).

fore more important for the steric course of the reaction than the energy content of the hydrogenation products.

2) Hydrogenation as above with Pt instead of Rh/Al_2O_3 gives rise to the *trans*-methylcyclohexanols as the major products [1]. The catalyst, too, can therefore influence the steric course of the hydrogenation more decisively than the energy content of the hydrogenation products.

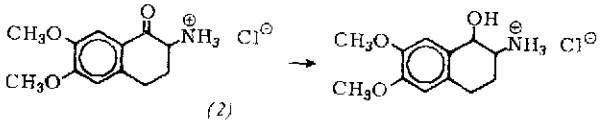


(1a): R = H

(1b): R = OCH_3

(1c): R = OH

3) Hydrogenation of *(1a)*, *(1b)*, or *(1c)* in aqueous-ethanolic hydrochloric acid produces a *trans*-aminotetralol from each. However, under the same conditions, *(2)* gives rise to the *cis*-aminotetralol. Here the nature of the substituent determines the steric results.

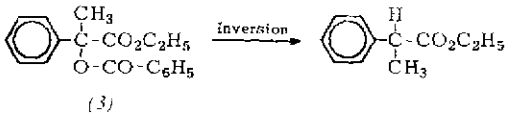


(2)

4) When *m*-cresol is hydrogenated in acetic acid at room temperature with Pt/Rh [2], 55–60% *trans*-3-methylcyclohexanol is obtained at atmospheric pressure, but 60% of the *cis*-isomer is obtained at 5 atm pressure. Similar results are found for resorcinol. This means that a relatively slight alteration in pressure can influence the steric course of a hydrogenation.

Since isomerization of the products certainly does not occur under the conditions used for these hydrogenations, it appears that the energy content of the stereoisomers formed is only one of the factors – and by no means always the dominating one – which influence the steric course of catalytic hydrogenations.

Hydrogenolysis of ethyl D-benzoylatrolactate *(3)* over Pd/$BaSO_4$ in 10% ethanolic triethylamine causes inversion of the configuration to give ethyl L-α-phenylpropionate in 70% optical purity.



(3)

Since the reaction occurs only in this strongly polar solvent, it can be concluded that a polar mechanism and not a radical mechanism is involved, and that a benzoyloxy group is displaced in an S_N reaction by a hydride anion.

[GDCh-Ortsverband Wuppertal/Hagen (Germany), January 6th, 1965] [VB 889/191 IE]

German version: Angew. Chem. 77, 387 (1965)

[1] *A. Skita*, Ber. dtsch. chem. Ges. *53*, 1792 (1920); *55*, 144 (1922).

[2] *S. Nishimura*, Bull. chem. Soc. Japan *33*, 566 (1960).

The Photolysis of Ammonia in the Vacuum-Ultraviolet

W. Groth, Bonn (Germany)

The photolysis of ammonia was studied at 1849 Å (Hg), 1470 Å (Xe), 1236 Å and 1165 Å (Kr), both in stationary and flowing systems. At 1849 Å, the primary process is

(a) $NH_3 + h\nu \rightarrow NH_2 + H$;

at 1470 Å, 12 to 13% of the NH_3 molecules decompose according to

(b) $NH_3 + h\nu \rightarrow NH + H_2$,

87 to 88% according to (a), while at 1236 Å and 1165 Å, 14% of the NH_3 molecules decompose according to (b), 86% according to (a) and/or according to

(c) $NH_3 + h\nu \rightarrow NH + H + H$.

Addition of molecular hydrogen has no influence on the quantum yield of the NH_3 decomposition. The stationary H-atom concentration is about 3.5 times higher at 1236 Å and 1165 Å than at 1470 Å.

The pressure dependence of the quantum yield was measured in all three cases. The quantum yield is the larger, the shorter the wavelengths used. Reaction mechanisms were derived, which, in the case of (b) and (c) correctly describe the nature and the ratio of the products if reactions of the NH radicals are taken into account.

The photochemical transformation of flowing ammonia to hydrazine is achieved at 1849 Å with a relative yield of up to 86%. It is much smaller at shorter wavelengths, due to the primary formation of NH radicals.

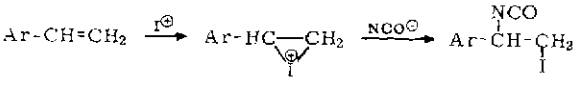
[GDCh-Ortsverband Karlsruhe (Germany), January 7th, 1965] [VB 901/205 IE]

German version: Angew. Chem. 77, 387 (1965)

SELECTED ABSTRACTS

High-melting metal oxides were obtained in crystalline form by *K.-Th. Wilke* from solutions in melts of metal compounds which decompose at high temperatures (*e.g.* oxalates, nitrates, or sulfates). Suitable media for the decomposition include alkali salts which can be dissolved away with water after the reaction. The oxides are obtained mainly as dendritic or skeleton-like crystal clusters. Platelets with a maximum diameter of 5 mm and needles up to 15 mm long were produced. Thus, CeO_2 was prepared from $Ce(SO_4)_2$ in NaCl as glistening white crystals in the form of hairs or needles, Fe_2O_3 from $FeSO_4$ in Na_2SO_4 as dark red platelets or from $FeSO_4$ in LiCl as green-black platelets, and TiO_2 from $TiOSO_4$ as a yellowish crystalline powder. / Z. anorg. allg. Chem. *330*, 164 (1964) / –Kr. [Rd 125/312 IE]

New syntheses of aziridines, carbamates, oxazolidones, and cis- or trans-2-amino alcohols were achieved by *A. Hassner* by addition of pseudohalogens such as INCO and INO_2 onto olefins. INCO adds on exclusively *trans* to open-chain and cyclic olefins and *trans*-diaxially to steroid olefins.



This permits steroespecific introduction of nitrogen functions into organic compounds. The additions proceed *via* an iodonium ion as intermediate. / 148th Meeting Amer. chem. Soc. 1964, Abstracts p. 29S / –Ma. [Rd 129/316 IE]

The synthesis of FSO_2NF_2 and $(FSO_2)_2NF$ has been carried out by *W. Lustig, C. L. Bumgardner* et al. Thus two further N–F compounds containing S–N single bonds have become known in addition to F_5S-NF_2. FSO_2NF_2 is formed from SO_2 and N_2F_4 either by heating at 100 °C at 100 atm pressure or by irradiation with ultraviolet light ($\lambda = 2537$ Å); the yield is 60 % (based on the SO_2). It is a colorless gas, m.p. −110 °C, b.p. −18 °C, with a Trouton constant of 21.29. $(FSO_2)_2NF$ is formed by fluorination of imidodisulfuryl fluoride $(FSO_2)_2NH$ at 25 °C with a 1:9 mixture of fluorine and helium. It is a colorless gas, m.p. −79.9 °C, b.p. −60.8 °C, and has a Trouton constant of 23.3. / Inorg. Chem. *3*, 1165 1964) / −La. [Rd 185/394 IE]

The synthesis of alkali fluoroxenates(VI) has been carried out by *R. D. Peacock, H. Selig,* and *I. Scheft*. Molten XeF_6 (m.p. 46 °C) reacts with MF (where M = Cs or Rb) to give $MXeF_7$; these heptafluoroxenates(VI) decompose above 50 °C (M = Cs) and above 20 °C (M = Rb), respectively, to yield XeF_6 and octafluoroxenates(VI) M_2XeF_8, which are stable up to 400 °C. KF and NaF are also absorbed by XeF_6, but here there are probably no compounds formed that are stable at room temperature apart from the octafluoroxenates(VI). The sodium derivative decomposes below 100 °C and can be used to purify XeF_6. LiF does not react with XeF_6. $CsXeF_7$ and molten XeF_6 are both yellow; the other fluoroxenates(VI) and solid XeF_6 are colorless. The infrared spectra of XeF_6, $MXeF_7$, and M'_2XeF_8 (M' = Cs, Rb, K, or Na) are quite different. $CsXeF_7$ is pseudotetragonal; Cs_2XeF_8 and Rb_2XeF_8 are considered to be the most stable compounds of Xe. / Proc. chem. Soc. (London) *1964*, 285 / −Gn. [Rd 195/404 IE]

Charge-transfer complexes of biochemically important substances have been investigated by *L. D. Wright* and *D. B. McCormick*. L-Tryptophan, *p*-aminobenzoic acid, flavianic acid, and picric acid, for example, form strong π-complexes with a twofold amount of D-riboflavin, as indicated by the 56 % reduction in the extinction of these substances on addition of riboflavin. 1,1,3-Tricyano-2-aminoprop-1-ene forms stronger complexes with D-riboflavin, flavin mononucleotide, flavin adenine dinucleotide, and diphosphopyridine nucleotide than with pyrimidine compounds. It is probably complexes between pyrimidine and flavin coenzymes which are involved in hydrogen and electron transport in biological systems, for 1,1,3-tricyano-2-aminoprop-1-ene is a strong inhibitor of oxidative phosphorylation. / Experientia *20*, 501 (1964) / −Re. [Rd 167/376 IE]

A synthesis of lactones by hydroformylation of unsaturated esters is reported by *J. Falbe, N. Huppes,* and *F. Korte*. Aliphatic and alicyclic α,β- or β,γ-unsaturated carboxylic esters react with CO/H_2 (synthesis gas) at 200–300 atm pressure and 200–250 °C in the presence of 1–2 % $Co_2(CO)_8$ as catalyst to give mono- or bicyclic lactones. Long-chain α,β-unsaturated esters yield both γ- and δ-lactones owing to isomerizations which occur during the reaction. The lactone formation proceeds in three steps:

$$RHC{=}CR\text{-}CO_2R + CO/H_2 \rightarrow OHC\text{-}CHR\text{-}CHR\text{-}CO_2R$$

$$\xrightarrow{CO/H_2} HOH_2C\text{-}CHR\text{-}CHR\text{-}CO_2R$$

$$\rightarrow \text{(lactone)} + ROH$$

Thus, for example, ethyl acrylate gives 88 % γ-butyrolactone, ethyl crotonate gives 67 % δ-valerolactone plus 23 % β-methyl-γ-butyrolactone, ethyl β,β-dimethylacrylate gives 88 % β-methyl-δ-valerolactone, ethyl sorbate gives 33 % 3-propyl-γ-butyrolactone and 49 % γ-ethyl-δ-valerolactone. / Chem. Ber. *97*, 863 (1964) / −Ma. [Rd 130/317 IE]

A filter solution for the mercury resonance line at 1849 Å is described by *C. M. Wolff* and *R. Pertel*. This spectral line can normally be disregarded in photochemical experiments for both ordinary quartz and atmospheric oxygen absorb strongly at this wavelength. (In order to work at this wavelength, a specially purified quartz, *e.g.* Suprasil, must be used for all optical parts, and the light beam must pass through a vacuum or a nitrogen atmosphere.) A 3.2×10^{-4} M solution of 9,10-dimethylanthracene in cyclohexane with a light path of 1 mm absorbs 99.9 % of the next Hg resonance line at 2537 Å but transmits about 20 % of the intensity at 1849 Å. / J. opt. Soc. America *54*, 1168 (1964) / −Hz. [Rd 168/377 IE]

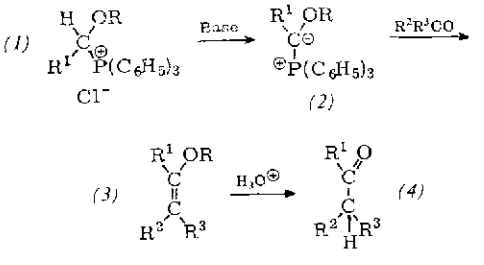
Potentiometric "acid-base" titrations in fused salts were carried out by *A. M. Shams el Din* and *A. A. El Hosary*. Following a proposal by *H. Lux*, acids and bases in fused salts are defined by the equation:

$$\text{acid} + O^{2-} \rightarrow \text{base},$$

i.e. the O^{2-} activity must be measured. Electrodes made of silver, nickel, copper, iron, or tungsten are suitable for this purpose. These electrodes differ in their standard potentials, and thus the determination of the equivalence point during titrations becomes possible by measuring the potential difference (maximum ΔE at the equivalence point) between any two of the above indicator electrodes. In this way, the difficult task of preparing reference electrodes of constant potential is avoided. The titration of the "acids" $NaPO_3$, NaH_2PO_4, and $K_2Cr_2O_7$, for example, with the "base" Na_2O_2 in molten $NaNO_3$ is described. / J. electroanalyt. Chem. *8*, 139 (1964) / −Hz. [Rd 170/379 IE]

***N*-Fluoro compounds of the types RNF_2, HNF–COOR, and RFN–CO–NHR** have been synthesized from amides, urethanes, and *N*-substituted ureas by *R. E. Banks, R. N. Haszeldine,* and *J. P. Lalu* by passing a stream of fluorine diluted with nitrogen through 5–16 % aqueous solutions of the organic compounds at 0–5 °C. The reactions carried out included: $H_3C-CO-NH-CH_3 \rightarrow H_3CNF_2$ (7 % yield); $H_2N-CO-OC_2H_5 \rightarrow FHN-CO-OC_2H_5$ (30 % yield, b.p. 56 °C/5 mm) + $H_3C-NF-CO-NH-CH_3$ (27 % yield, b.p. 74 °C/19mm) + H_3CNF_2(4 % yield); $H_5C_2-NH-CO-NH-C_2H_5 \rightarrow H_5C_2-NF-CO-NH-C_2H_5$ (9 % yield, b.p. 56 °C/1 mm) + $H_5C_2-NF_2$ (5 % yield, b.p. 15 °C). Disubstituted compounds RNF–CO–NFR were not isolated. The *N*-fluoro compounds are strong oxidizing agents. / Chem. and Ind. *1964*, 1803 / −Ma. [Rd 171/380 IE]

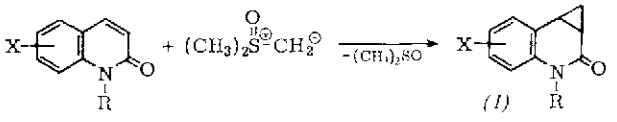
A new synthesis of methyl ketones applying the Wittig olefin synthesis is described by *D. R. Coulson*. α-Halogenoethyl methyl ether reacts with triphenylphosphine to give the phosphonium salt *(1)*, which on treatment with potassium t-butoxide in glycol monomethyl ether yields the unstable ylide *(2)*. This ylide reacts with aldehydes and ketones to form the enol ethers *(3)*, which are separated off by distillation and hydrolysed with aqueous methanolic HCl to give



the ketones *(4)*. Thus, for example, benzaldehyde → 3-phenylpropan-2-one in 88 % yield, cinnamaldehyde → 3-styrylpropan-2-one in 82 % yield, n-heptanal → 2-nonanone (57 %), pelargonaldehyde → 2-undecanone (51 %), cyclohexanone → cyclohexyl methyl ketone (45 %), and 2-octanone → 3-methylnonan-2-one (15 %). / Tetrahedron Letters *1964*, 3323; cf. Angew. Chem. *71*, 260 (1959) / −Ma. [Rd 175/384 IE]

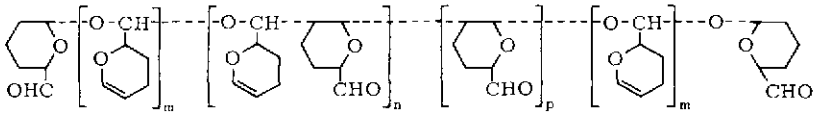
Aliphatic carboxylic acids formed by a Friedel-Crafts synthesis from pentane and carbon dioxide in the presence of $AlCl_3$ were detected for the first time by gas chromatography by *H. Hopff* and *Th. Zimmermann*. At 90–100 °C and a CO_2 pressure of 100–144 atm, a 1 % yield (based on $AlCl_3$) of the following acids is obtained: $C_nH_{2n-1}COOH$ (n = 2, 4, or 5), α-methylbutyric acid, and an isomeric acid $H_5H_{11}COOH$. – The synthesis of a small amount of benzoic acid using this method was achieved by *Friedel* and *Crafts* in 1888; later *Meyer* and *Hopff* obtained much higher yields of benzoic acid (German patent 524186). / Helv. chim. Acta *47*, 1293 (1964) / –Re. [Rd 166/375 IE]

***N*-Alkyl-3,4-dihydro-3,4-methylenequinol-2-ones, derivatives of a new ring system,** were obtained by *B. Loev, M. F. Kormendy*, and *K. M. Snader* from dimethylsulfoxonium methylide and *N*-alkylquinol-2-ones. For example, the reaction of *N*-methylquinol-2-one in dry dimethyl sulfoxide with excess ylide (prepared from trimethylsulfoxonium iodide and NaH) followed by hydrolysis and distillation leads to the derivative



(1), R = CH_3, b.p. 100–104 °C/0.005 mm, n_D^{25} = 1.6100, in 43 % yield. Further derivatives prepared include *(1)*, X = 6-CF_3, R = CH_3, m.p. 82.5–84 °C (78 % yield); *(1)*, X = 6-CF_3, R = C_2H_5, m.p. 60.5–62 °C (56 % yield); and *(1)*, X = 7-CF_3, R = CH_3, m.p. 50 °C (66 % yield). / Chem. and Ind. *1964*, 1710 / –Ma. [Rd 172/381 IE]

High molecular-weight soluble polymers were made from 2*H*-3,4-dihydropyran-2-carboxaldehyde *(1)* ["dimeric acrolein"] by *H. Ohse, H. Cherdron*, and *F. Korte* by polymerization with diethylaluminum chloride at 25 °C/760 mm. The polymers formed by working below 0 °C are insoluble. The average conversion was 67 %. In solvents with high dielectric constants, the products have significantly higher molecular weights, *e.g.* in dichloroethane (ε = 10.65, 69.4 % conversion), $\eta_{sp}/c \cdot 10^2$ = 3.0; in chloroform (ε = 4.81, 61.8 % conversion), $\eta_{sp}/c \cdot 10^2$ = 1.8 (c = 10 g/l in pyridine). The polymers dissolve in pyridine, and some in $CHCl_3$, tetrahydrofuran, or aromatic hydrocarbons. When the solutions of the polymers are not stabilized by addition of a basic substance, *e.g.* β-naphthylamine, the polymers soon precipitate out quantitatively. From the results of infrared spectroscopic examination, the authors propose the following structure for the polymers:



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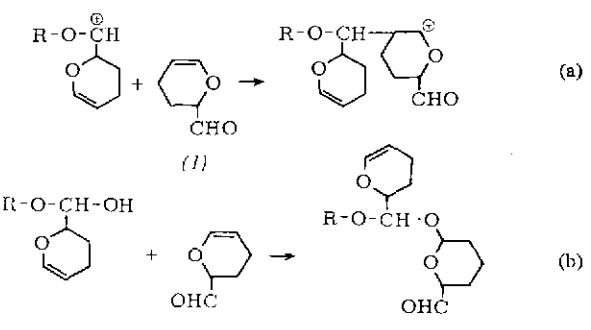
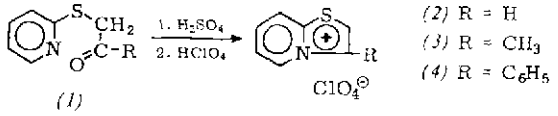


which are formed by steps (a) and (b). / Makromolekulare Chem. *76*, 147 (1964) / –Hl. [Rd 183/392 IE]

The thiazolo[3,2-*a*]pyridinium ion, a new aromatic heterocyclic system, has been prepared by *C. K. Bradsher* and *D. F. Lohr*. Its salts are readily obtained by dehydration of pyridyl sulfides *(1)* containing a carbonyl group in β-position to the sulfide bridge. The sulfides are prepared from the sodium salt of 2-mercaptopyridine and an α-acylalkyl halide. The parent ion *(2)* is obtained from the dimethylacetal of chloro-

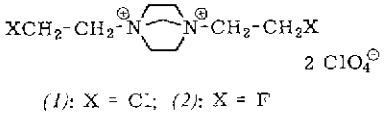


(1)

(2) R = H
(3) R = CH_3
(4) R = C_6H_5

acetaldehyde *via* an acetal of b.p. 100–103 °C/0.2 mm (32 % yield), which is hydrolysed with concentrated sulfuric acid and isolated as its perchlorate, m.p. 281–283 °C (85 % yield). Bromoacetone affords the analogous compound *(3)*, m.p. 177–178.5 °C, and phenacyl bromide yields *(4)*, m.p. 201–202 °C. / Chem. and Ind. *1964*, 1801 / –Ma. [Rd 173/382 IE]

The condensation of formaldehyde with bis-(2-halogenoethyl)-amines in alcohol at room temperature was investigated by *G. R. Pettit* and *J. A. Settepani*. The derivative *(1)* of a new ring system 1,4-diazabicyclo[2,2,1]heptane is obtained from bis-(2-chloroethyl)amine in 76 % yield as its diperchlorate, m.p. 222–223 °C (decomp.). A dose of 23 mg/kg completely inhibits the growth of Walker 256 carcinoma in rats. An ethanolic solution of bis[di-(2-fluoroethyl)amino]methane,

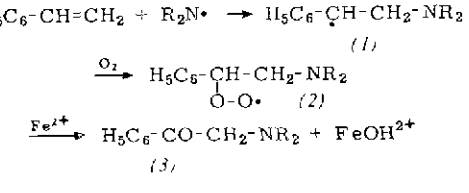


(1): X = Cl; *(2)*: X = F

$CH_2[N(CH_2CH_2F)_2]_2$, obtained from formaldehyde and bis-(2-fluoroethyl)amine, gave the same quaternary ammonium salt *(2)*, m.p. 223.5–225 °C (decomp.), as an ethanolic solution of bis-(2-fluoroethyl)amine and formaline. The results of NMR studies and the chemical properties of the products are in agreement with the structures assumed. / Chem and Ind. *1964*, 1805 / –Ma. [Rd 174/383 IE]

A new synthesis of α-amino ketones from olefins has been reported by *F. Minisci* and *R. Galli*. Amino radicals are generated by the redox system *N*-chloroamine/Fe^{2+} or Cu^+ salt. They add onto olefinic double bonds. The alkyl radical *(1)* thus formed reacts with oxygen to give a peroxy radical *(2)*, which is then reduced to the α-amino ketone.

The reactivity of the amino radical depends on its charge distribution and on steric factors. Products prepared include the amino ketones from styrene and dibutylamine (76 % yield); from styrene and morpholine (41.5 %); from *trans*-stilbene and dibutylamine (21.7 %); from *trans*-stilbene and



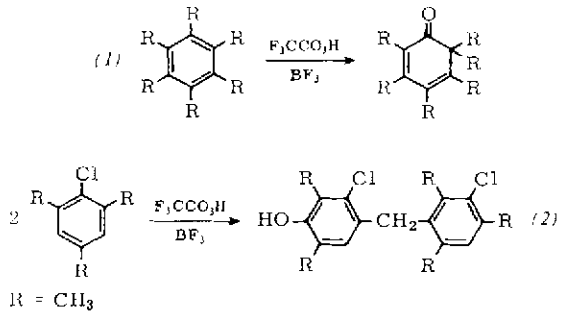
(1)

(2)

(3)

piperidine (73 %); and from 2-vinylpyridine and piperidine (traces). / Tetrahedron Letters *1964*, 3197 / –Ma. [Rd 151/338 IE]

The system trifluoroperoxyacetic acid/boron trifluoride is a strong oxidizing agent, according to *C. A. Buehler* and *A. J. Waring*, and is especially suitable for attacking aromatic compounds. It probably generates $OH^{\oplus}$ ions. These convert aromatic hydrocarbons into phenols by direct electrophilic substitution. Positions already bearing substituents can also be attacked; Wagner-Meerwein-rearrangements were also observed. Completely substituted aromatic hydrocarbons, *e.g.*



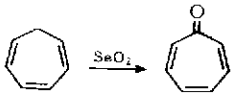
(1)

(2)

R = CH_3

hexamethylbenzene *(1)*, yield cyclohexadienones. The reagent is capable of removing hydrogen from reactive methylene groups in the form of hydride ion, so that diphenylmethane derivatives *(2)* result. / Abstracts, 148th Meeting Amer. chem. Soc. *1964*, 20U / –Ma. [Rd 152/339 IE]

A one-stage synthesis of tropone *(1)* has been discovered by *P. Radlick*. A mixture of 0.1 mole of KH_2PO_4 in 33 ml of water, 330 ml of dioxane, 0.46 mole of 1,3,5-cycloheptatriene *(2)*, and 0.48 mole of selenium dioxide are heated at 90 °C for 15 h.



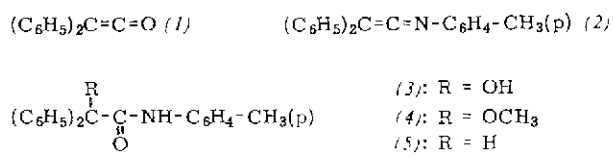
(2) *(1)*

After cooling, the mixture is filtered and poured into 750 ml of ice water; the aqueous solution is extracted thrice with 250 ml of methylene chloride each. The extract is washed with 10 % $NaHCO_3$ solution, dried over magnesium sulfate, filtered, and concentrated *in vacuo*. Vacuum distillation of the liquid residue affords about a 25 % yield of tropone, b. p. 91–92 °C/4 mm, $n_D^{23} = 1.6152$. / J. org. Chemistry *29*, 960 (1964) / –Bi. [Rd 153/340 IE]

Organic solvents alter the coding properties of synthetic messenger RNA. This was observed by *A. G. So* and *E. W. Davie* when they added alcohols, acetone, dioxane, or ethylene glycol to protein-synthesizing cell-free systems of *Escherichia coli*. For example, ethanol suppresses the incorporation of phenylalanine into acid-insoluble material normally observed in the presence of polyuridylic acid but stimulates the incorporation of leucine and isoleucine. The incorporation of proline into acid-insoluble protein in the presence of polycytidylic acid is increased twentyfold by ethanol, but the amino acids leucine and threonine are also incorporated, although they are normally not coded by polycytidylic acid. The dependence of the incorporation on the presence of organic solvents and on the magnesium ion concentration, and the striking parallel between these phenomena and the effects of streptomycin [1] will probably make it necessary to revise the code assignments made to date. It is possible that the keto-enol tautomerism equilibria in the bases of the transfer RNAs become displaced because of the lower polarity of the organic solvents and that this alters their coding properties. / Biochemistry *3*, 1165 (1964) / –Sch. [Rd 181/390 IE]

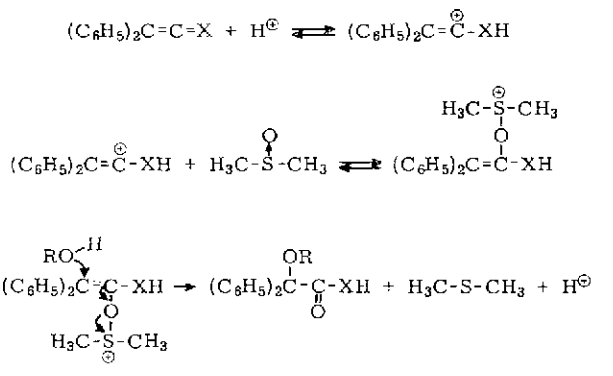
[1] *J. Davies, W. Gilbert*, and *L. Gorini*, Proc. nat. Acad. Sci. U.S.A. *51*, 883 (1964).

The acid-catalysed oxidative solvolysis of diphenyl ketene *(1)* and its *N*-(*p*-tolyl)imine *(2)* in dimethyl sulfoxide (DMSO) is described by *I. Lillien*. Benzilic acid is formed in 88 % yield from *(1)* in DMSO containing a few drops of concentrated HCl or $HClO_4$, while *(2)* gives rise to 91.5 *N*-(*p*-tolyl)-α-hydroxydiphenylacetamide *(3)*. When a solution of *(2)* in DMSO is mixed with an equal volume of methanol and acidified with a few drops of conc. HCl, 71 % *N*-(*p*-tolyl)-α-methoxydiphenylacetamide *(4)* can be isolated. In the absence of water (gaseous HCl in ether/DMSO), *(2)* affords only 66 % *N*-(*p*-tolyl)diphenylacetamide *(5)*, which arises by hydrolysis of the primary keteneimine/HCl adduct during work-up. All the reactions proceed at room temperature.



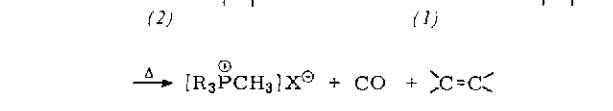
(3): R = OH
(4): R = OCH_3
(5): R = H

The following course of reaction is probable (X = $-N-C_6H_4-CH_3(p)$ or $=O$; R = H or CH_3):

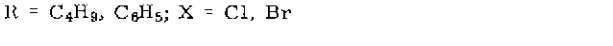


/ J. org. Chemistry *29*, 1631 (1964) / –Bi. [Rd 154/341 IE]

A new synthesis of olefins has been discovered by *D. B. Denney, C. J. Rossi*, and *J. J. Vill*. Pyrolysis of the phosphonium salts *(1)* at 130–225 °C produces high yields of olefins derived from the alcoholic component of the ester *(2)*.



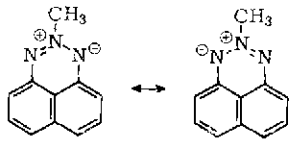
(2) *(1)*



R = C_4H_9, C_6H_5; X = Cl, Br

The salts *(1)* are prepared by mixing α-halogeno esters *(2)* with tributyl- or triphenylphosphine and can be used without previous isolation. Thus, for example, pyrolysis of the salt obtained from n-octyl bromoacetate and tributylphosphine at 170 °C/14 mm for 4 h afforded 72 % pure 1-octene (based on salt). Secondary butyl esters pyrolysed at 160 °C gave 33 % 1-butene, 48 % *trans*-2-butene, and 19 % *cis*-2-butene (overall yield: "excellent"). Cyclohexyl esters give 57 % cyclohexene; *cis*-2-phenylcyclohexyl esters give (at 195 °C/0.5 mm) 83 % 1- and 17 % 3-phenylcyclohexene; the *trans*-isomer gives 65 % 1- and 35 % 3-phenylcyclohexene. t-Amyl esters give rise to 32 % 2-methyl-1-butene and 68 % 2-methyl-2-butene (total yield 60 %). In general, primary alcohols yield terminal olefins, secondary and tertiary alcohols yield approximately thermodynamic equilibrium mixtures of isomeric olefins (in contrast to the pyrolysis of the esters or xanthates of the alcohols). Sometimes rearrangements occur; for example, cyclopropylmethanol yields butadiene instead of methylenecyclopropane. / J. org. Chemistry *29*, 1003 (1964) / –Bi. [Rd 155/342 IE]

2-Methyl-2 *H*-naphtho[1,8-*de*]triazine, a blue triazine, has now been recognized to be the first representative of a new class of heterocyclic compounds. Although the compound *(I)* was first obtained by *Sachs* [1] in 1909, its structure has only now been elucidated by *M.J.Perkins*. It is produced by methylation of 1*H*-naphtho[1,8-*de*]triazine (prepared by diazotization of



(I)

1,8-diaminonaphthalene in acetic acid) using dimethyl sulfate in caustic soda and crystallizes from petroleum ether as blue-black needles, m.p. 132 °C; the yield is 30 %. The isomeric 1-methyl derivative is also obtained in 30 % yield as a by-product; it forms red prisms, m.p. 91–92 °C from CCl_4. The unusual triazine *(I)* forms a 1:1 adduct with 1,3,5-trinitrobenzene of m.p. 154 °C, and can be converted into a tetrabromo derivative, m.p. 212–213 °C. Its methyl group reacts with aromatic aldehydes to give 2-(β-styryl)-2*H*-naphtho-[1,8-*de*]triazines. / J. chem. Soc. (London) *1964*, 3005 / –De.
[Rd 180/389 IE]

Two molecular-weight ranges in poly-(4-vinylpyridine) were found by *P. P. Spiegelman* and *G. Parravano*, who polymerized 4-vinylpyridine by initiation with butyl-lithium in toluene or heptane at temperatures between –30 and + 30 °C. The polyvinylpyridine precipitates out. The conversion to polymer was measured by dilatometry and was found to be proportional to the monomer concentration, *i.e.* to $[H_2C{-}C{-}C_5H_4N]^1$, and to $[n\text{-}C_4H_9Li]^{1/2}$; the activation energy is 12.7 kcal/mole. These results suggest the formation of an equilibrium complex by the growing polymer anions. It was concluded from the conversion data that one chain end is activated by each molecule of initiator and that no chain transfer occurs. Fractionation of the polymer by elution chromatography divided it into two quite sharp molecular-weight ranges (3.2×10^4 and $1.0–3.0\times10^6$). When the limit of solubility of the growing polymer is exceeded, the precipitating polymer apparently encloses active chain ends which then cannot grow further. Active ends that lie exposed, however, continue to grow to higher molecular-weight polymers. / J. Polymer Sci. *A 2*, 2245 (1964) / –Hl.
[Rd 182/391 IE]

The amino-acid sequence around the active site in liver alcohol dehydrogenase from horses has been elucidated by *T. K. Li* and *B. L. Vallee*. Of the 28 molecules of cystein in the enzyme, only two can be carboxymethylated with [^{14}C]iodoacetate at pH 7.5 and 22 °C within 165 min. This reaction completely inactivates the enzyme. The labelled protein was then hydrolysed with succinyltrypsin yielding 36–38 different peptides, although from its content of 80 lysine and arginine residues about twice this number was to be expected. Two-dimensional electrophoresis and chromatographic purification of the peptides showed that only one was radioactive. This peptide contained the sequence Met–Val–Ala–Thr–Gly–Ileu–Cys–Arg. These results suggest that the enzyme consists of two similar or identical peptide chains. / Biochemistry *3*, 869 (1964) / –Hö.
[Rd 189/398 IE]

The diphenylphosphide anion, $(C_6H_5)_2P^{\ominus}$, can be prepared from diphenylphosphine using either lithium aluminum hydride or butyl-lithium, and according to studies by *F. G. Mann* and *M. J. Pragnell* has the ability to cleave not only anisole, but also benzyl phenyl ether (88 % phenol, 82 % benzyldiphenylphosphine), allyl phenyl ether (78 % phenol, 76 % allyldiphenylphosphine), and benzyl *p*-hydroxyphenyl ether (46 % hydroquinone, 43 % benzyldiphenylphosphine). The cleavage occurs in boiling tetrahydrofuran. When $(C_6H_5)_2P^{\ominus}$ is heated alone in tetrahydrofuran, 22 % 4-hydroxybutyldiphenylphosphine is formed after 7 h. *O,O'*-Methylenecatechol affords 18 % catechol and 31 % *o*-hydroxymethyldiphenylphosphine after 10 h under these conditions. Ethyl ethers such as phenetole are hardly attacked, so that demethylation of ethoxymethoxy compounds can be effected without appreciable de-ethylation. / Chem. and Ind. *1964*, 1386 / –Ma.
[Rd 127/314 IE]

An adduct of triphenylphosphine and hydrogen peroxide has been discovered by *D. B. Copley*, *F. Fairbrother*, *J. R. Miller*, and *A. Thompson*. During the preparation of $(C_6H_5)_3PO$ from triphenylphosphine and H_2O_2 in methanol, the solvent was distilled off *in vacuo* at room temperature and the adduct $[(C_6H_5)_3PO]_2{\cdot}H_2O_2$ was obtained as a white solid, m.p. 131 °C, which dissolves in chloroform, methanol, and acetone. The adduct decomposes *in vacuo* at 160 °C but is reformed from its components in methanol. The infrared spectrum of the adduct contains a band at 1180 cm^{-1} which is not due to an H–O deformation vibration, for it is also present in the same position in the spectrum of $[(C_6H_5)_3PO]_2{\cdot}H_2O_2$. This band was assigned to a P=O vibration which is also observed in the spectrum of $(C_6H_5)_3PO$, where it lies 15 cm^{-1} higher. The shift in wave numbers indicates that the H_2O_2 links pairs of $(C_6H_5)_3PO$ molecules together via hydrogen bridges. The absence of absorptions between 1600 and 1700 cm^{-1} proves that the adduct is not a hydrate. / Proc. chem. Soc. (London) *1964*, 300 / –Gn.
[Rd 196/405 IE]

[1] Liebigs Ann. Chem. *365*, 53 (1909).

BOOK REVIEWS

Massenspektrometrie (Mass Spectrometry). By *C. Brunnée* and *H. Voshage*. Part I: Physikalische und apparative Grundlagen (Physical Fundamentals and Basic Equipment); Part II: Anwendungen (Applications). Karl Thiemig KG., Munich 1964. 1st Edit., XII + 316 pp., numerous illustrations, several tables, linen, DM 54.– (about $ 13.75).

It is about ten years since the book by *H. Ewald* and *H. Hintenberger* on the methods and applications of mass spectroscopy was published. Since then, no monograph on mass spectroscopy has appeared in the German language. The book by *Brunnée* and *Voshage* is written by two first-class capacities in this field and reports on the theoretical fundamentals, the instrumentation and equipment, and the practical applications of mass spectrometry. Following an introductory section, chapters are devoted to mass separation, sample introduction, and ion detection. A rigorous but thoroughly comprehensible treatment is given to the physical fundamentals of the subject, and the apparatus required are well explained; the text is clear and goes into sufficient detail. The second part of the book deals with the applications of mass spectrometry, with the determination of the relative abundances of isotopes, precision mass determinations, quantitative analyses, qualitative analyses, physicochemical investigations, and studies of the interactions of ions with materials.

It is understandable and excusable that the authors have given a preferential treatment to their own field of research. For this reason, the section on the determination of the relative abundances of isotopes seems to be overaccentuated in comparison

with the other chapters, and the Atlas-Werke in Bremen is given too strong preference by frequent mention in the text and in the figures compared with other instrument manufacturers.

However, on the whole, this book can be recommended as an introduction to and a review of the complete field of mass spectrometry for a broad range of readers, including physicists, chemists, and engineers, as well as geologists and mineralogists, and even clinical physicians and biologists.

H. Kienitz [NB 335/193 IE]

Anleitung zum Messen von Absorptionsspektren im Ultraviolett und Sichtbaren (Directions for Measuring Absorption Spectra in the Ultraviolet and Visible Regions). By *M. Pestemer*. Georg Thieme Verlag, Stuttgart 1964. 1st edit., viii + 78 pp., 7 figs., paperback DM 7.80 (about $ 2.00).

This little pocketbook attempts to give foolproof instructions for the measurement of absorption curves for purposes of structural investigations or for determining concentrations. In the first section (26 pages), the fundamental aspects of optical absorption are introduced, and the most important structural elements of spectral photometers are described. This is followed by a discussion of sources of errors (14 pages), including information on the measurement of fluorescence spectra and on the determination of the direction of transition moments. There follow some practical procedures for the purification of samples and solvents, and then several tables are given containing a variety of data.

The book contains a number of useful tips, but for more detailed information and discussions, recourse will still have to be made to more comprehensive works. More precise specifications are desirable occasionally, *e.g.* in the description of the prerequisites for the validity of Beer's law (p. 10). In the discussion of methods for determining the direction of transition moments (p. 38), the expressions "direction of photoexcitation" or "orientation of electronic excitation" are used, but the correct term "transition moment" does not appear. Moreover, magnetically induced dichroism of molecules in solution has probably never been used to evaluate the direction of transition moments (p. 39). The concept of the transition moment or transition probability is also not utilized in the discussion of the Beer-Lambert equation; instead, an absorption equation is derived on the basis of the absorption cross-section – a concept no longer used in molecular spectroscopy (p. 8). *W. Liptay* [NB 265/123 IE]

Biochemie der Mineral- und Spurenelemente (Biochemistry of Mineral and Trace Elements). By *Th. Bersin*. Akademische Verlagsgesellschaft, Frankfurt/Main 1963. 1st Edit., XVI + 695 pp., 99 figures, 1 color plate, linen, DM 68.– (about $ 17.25).

The importance of trace elements (*i. e.* elements required in only minute concentrations by living organisms) in both biochemistry and medicine has become more and more apparent within recent years. Since no monograph had hitherto been published on this rapidly developing field, the attempt to give a comprehensive survey is worthy of recognition. *Bersin* has divided his book into three main sections, which can be characterized as follows: theoretical fundamentals and general importance; descriptions of individual trace elements; practical applications.

The second part of the book is the longest and completest (pp. 238–554); here the importance of the individual trace elements is recorded, almost in the form of a handbook. The value of this compilation is evident from the fact that, in the reviewer's estimation, over 90% of the numerous publications cited appeared within the past ten years. A list of references as complete as this is hard to find anywhere else. Probably due to the compactness of this review of a field which is still in rapid development, important papers with well-founded results are often given just as little space as work of poorer quality. Critical appraisal of the contents of the book is thus left to the reader.

Before the individual trace elements are discussed, the ligands with which they are associated are dealt with. It would have been better to have coupled this discussion with that of the individual elements in order to avoid frequent repetition of the same data in various parts of the book. Thus, for example, relatively long descriptions of transferrin are found on pp. 178–180. and again on pp, 320–321. The same applies to ferritin, chlorophyll, vitamin B_{12}, and most of the other naturally occurring metal chelates whose structures are known. It is particularly redundant to repeat complicated structural formulae, when a cross-reference would have sufficed.

The applications of chelates recounted in the final section (pp. 555–631) impressive by demonstrate how deeply coordination chemistry has penetrated into biology, medicine, therapy, and agronomy.

The introductory section (pp. 5–136) must be criticized more strongly. The fundamentals required for an understanding of the subject are to be disclosed here, but the arrangement of the material is didactically inadequate. For example, the reader is confronted with the concept of hybridization on p. 11, whereas the discussion of the chemical bond only starts on p. 36. The gap between is filled with such variegated topics as chelates, polynuclear complexes, inclusion compounds, association colloids, and exchange reactions. Obviously such an array of different themes condensed into such little space must occasionally fall short of a correct deductive treatment. Experimental methods should have been discussed more fully.

Despite these reservations, the book ought to prove useful for research workers in this field. It provides a key to the literature on the subject and serves as an introduction to special problems. The book is intended for use by chemists, physicians, biologists, and agronomists.

Ernst Bayer [NB 339/197 IE]

Schmelzpunkttabellen organischer Verbindungen (Tables of the Melting Points of Organic Compounds). By *W. Utermark* and *W. Schicke*. Friedrich Vieweg & Sohn, Braunschweig 1963. 2nd Edit., XXXII + 715 pp., linen DM 75.– (about $ 19.–).

In this second edition, in accordance with the title of the book, the melting point – as the essential criterion for identifying organic compounds – has been maintained as the ordering principle. Over 3200 of the most important organic compounds with melting points between −189.9 °C and +500 °C are tabulated for rapid checking by analysts for purposes of identification or purity control.

The good formula and trivial name indices given provide helpful keys to the use of the complete tables. An important plus for this book is its inclusion – contrary to the usage of handbooks and pocketbooks, which often list more substances – of not only columns for the molecular weight, density, refractive index, melting point, boiling point, solubilities, color, crystal form, and a reference of each compound, but also of columns for "structural formula", "physical constants and properties", and "typical reactions and derivatives".

It is unfortunate that the authors have not succeeded in finding specific reactions for every compound, and it would be profitable if they could fill up the space allotted to "physical constants and properties", for this is sometimes yawningly vacant. For most of the substances, it is a very old reference to the original volumes of Beilsteins Handbuch that is given, and for 10 or 20% of the compounds there is no literature reference at all (*e.g.* for lupolone, p. 238, 7-dehydrocholesterol, p. 362, or sulfathiourea, p. 436). Current usage in nomenclature has not been applied throughout; for example, tetraethyltin would have been better than tin tetraethyl (p. 12), and the names of substituents in compounds should have been placed in alphabetical order. However, these and other

minor errors such as the diazirine structure given for diazomethane (p. 2) have little effect upon the prime purpose of the tables.

The introductions, indices of technical terms, and interchangeable table headings are in four languages (German, English, French, and Russian) and increase the value of the book. These features ought to contribute to its broad dissemination among chemists, and its success is confirmed by the appearance of an English edition.

W. Jung [NB 317/176 IE]

Fachwörterbuch der Chemie (einschließlich Verfahrenstechnik und den Grundlagen der verwandten Wissenschaften) / Dictionary of Chemistry (Including Chemical Engineering and Fundamentals of Allied Sciences), Vol. II: English-German. By *Richard Ernst* and *Ingeborg Ernst-von Morgenstern*. Brandstätter Verlag, Wiesbaden 1963. 1st Edit., 1056 pp., linen DM 48.– (about $ 12.00).

It is a remarkable phenomenon that the present generation, which is by no means inexperienced in scientific exchange – in particular with the Anglo-American countries – seems to be incapable of producing a German-English chemical dictionary which is at least free from drastic language or chemical errors. The present volume too does not completely satisfy all the demands which must be placed upon a dictionary of this kind. Although it does explain that "allenolic acid" is 2-hydroxy-6-naphthylpropionic acid and does contain a lot of interesting information on the German meanings of English trivial names – an aid which should not be underestimated when it comes to doing translations – the experienced bilingual chemist cannot suppress a feeling of pity when he sets the book a less severe test, and places himself in the position of a foreigner, for example, who wants to know what the German is for "alumium (!) potassium sulphate", for the book recommends the translation "Alumen[ustum]", whatever that may be. The results are not much better for "aluminium sulphate", for which the only German translation given is "schwefelsaure Tonerde". Carbenes are only known in the plural – and here the explicatory remark "(Asphaltteile)" is appended! And for a "carbethoxyl group", in German one is supposed to say "Cathylgruppe" and nothing else. These examples can be multiplied.

The complete title of the book reads "Dictionary of Chemistry Including Chemical Engineering and Fundamentals of Allied Sciences". Even when applying a rather free interpretation of the fundamentals of allied sciences, the reviewer is still unable to see any justification for the inclusion of entries such as "ammi visnaga" (= Zahnstocherdolde), "blank-cartridge fire" (indicated as a verb (!) and translated accordingly as "mit Platzpatronen schießen"), "eleven marker drill" (= elfreihige Drillmaschine), or "psilosis" (= weiße Diarrhöe) in a chemical technical dictionary. Even the term "Panzerfaust" – an anti-tank gun – is included.

Some of the omissions are "electrophilic", "thin-layer chromatography", and "exocyclic", but fortunately the number of these lapses is few. The word "fragmentation" appears with the abbreviated description "(biol.)". Paper chromatography is called "paper strip chromatography" in the English section, and "enzymatical" is found instead of enzymic or enzymatic; antiquated key-words such as d-[pri-act]amyl bromide (= optically active amyl bromide) are also encountered. In addition, the spelling of German terms, *e.g.* Zyklohexan, Zystin, Karbonat, does not correspond to modern practice.

If the reviewer may be allowed to give a word of advice, it is: if a second edition of this dictionary should become necessary, the services of a competent chemist should be engaged in order to effect drastic modernization of the English and German vocabulary and to reduce it to such terms as really belong to chemistry.

H. Grünewald [NB 316/175 IE]

Einführung in die Elektronentheorie organisch-chemischer Reaktionen (Introduction to the Electronic Theory of Organic Reactions). By *Heinz Becker*. VEB Deutscher Verlag der Wissenschaften, Berlin 1964. 2nd edit., 501 pp., numerous illustrations and tables, linen DM 56.– (about $14.25).

This is the second edition of this book by *H. Becker*; the first edition appeared in 1961. The earlier chapters are devoted to the theory of the chemical bond, the distribution of electrons in organic molecules, and general discussion on the course of chemical reactions. The following chapters contain descriptions of nucleophilic substitution at saturated carbon atoms, eliminations, nucleophilic reactions at polarized double bonds and electrophilic reactions at olefinic and aromatic double bonds. The two concluding sections deal with electronsextet rearrangements and freeradical reactions. Each chapter includes references to important monographs or to surveys in manuals or review journals. In parts the literature has been reviewed up to 1962. The author's intention has not been to give as exhaustive a treatment as possible of all chemical reactions. Instead he has attempted to give an intelligible presentation of the mechanisms of the most important reaction types both by considering the interaction between substrate and reagent and by discussing the factors which influence the course of the reaction. He has thereby tried to draw attention to general principles in order to make it easier to understand and survey the entire subject. *Becker*'s book is not only very suitable as an introduction to the theory of organic reactions, but also it offers a great deal of inspiration to the practical organic chemist by showing him how to apply his theory usefully to the selection of suitable reaction conditions. It can therefore be heartily recommended to every student who wishes to acquire deeper insight into the theory of organic reactions.

H. Zimmermann [NB 271/128 IE]

Fortschritte der Arzneimittelforschung (Progress in Drug Research), Vol. 7. Edited by *E. Jucker*. Birkhäuser Verlag, Basel-Stuttgart 1964. 1st Edit., 477 pp., numerous illustrs. and tables, linen DM 96.– (about $ 24.00).

This most recent volume of the series again brings a number of monographs on current problems of pharmaceutical research.

D. R. H. Gourlay deals with the "Basic Mechanisms of Drug Action" (44 pp.) and attempts with data from 157 references to summarize modern concepts concerning the point of attack and mode of action of pharmaceutical preparations. Although most of these ideas are purely hypothetical, they nevertheless provide incentives for further research. – "The Application of Radioactive Isotopes in Pharmaceutical Research" is discussed in 68 pp. (in German) by *K. E. Schulte* and *I. Mleinek*. First they deal with the use of radioactive isotopes in research related to the various modes of application of drugs and then with their use as an analytical tool; finally they report on the sterilization of pharmaceutical products with high-energy radiation (100 references). The essay by *H. Jackson* on "The Development of Antifertility Substances" evaluates information from 231 publications and gives a lucid 53-page review of this subject. *F. Trendelenburg* reports (in German) on "Antibacterial Chemotherapy of Tuberculosis" on 100 pp. After an introduction to the definition of the concept and to the methods for evaluating an antituberculous chemotherapy, he describes individual tuberculostatics, summarizing the characteristic features of each preparation. Following a discussion of the biological basis of tuberculosis chemotherapy, his article closes with a practical clinical section and a list of 380 references – all in all an excellent contribution. – A review of "The Pharmacology of Homologous Series" is given on 32 pp. with 55 references by *H. R. Ing*, who again calls attention to the problems involved in correlating structure and activity. – A monograph (in German) on "Amino Nucleoside Nephrosis", in which *U. C. Dubach* has made an exhaustive appraisal of the pertinent literature, concludes the volume.

"Amino nucleoside" is the designation given to the basic nucleoside obtained from the antibiotic puromycin after the elimination of *p*-methoxyphenylalanine; in it, 6-dimethylaminopurine is attached by a glycosidic linkage to 3-aminoribose. A typical nephrotic syndrome can be produced experimentally in rats by this amino nucleoside, and the present article (112 pp., 245 references) is intended to contribute to an understanding of nephrotic syndromes in humans.

A subject index for this volume and an author index and article index for Vols. 1–7 of the series close the book, whose outlay and appearance are excellent.

O. Schaumann [NB 308/167 IE]

Analytical Methods for Pesticides, Plant Growth Regulators, and Food Additives (in 4 Vols.). Edited by *G. Zweig*. Vol. I: Principles, Methods, and General Applications. Academic Press, New York-London 1963. 1st edit., xiv + 637 pp., numerous illustrations and tables, linen $24.00.

The current nutritional laws have caused an ever increasing demand for reliable methods for routine control of agricultural products and foodstuffs for their content of residues of pesticides, growth regulators, and other similar chemicals which are added to perishable nutritional goods during their commercial and industrial production and handling.

In this first volume of the series, edited by *G. Zweig*, on the analyses of such residues, twenty-seven notable American authors from universities, and from industrial and government laboratories have combined to give numerous practical examples illustrating the methods of formulation analysis, residue analysis, analysis of food additives, extraction and purification procedures, and toxicological tests. Further sections are allotted to the fitting-out of laboratories for residue analysis, to special procedures, *e.g.* spectrophotometry, gas and paper chromatography, total halogen analysis, isotopic methods and bioassays, to the statistical evaluation of results, and to special problems of interest in individual branches of food industry.

The forthcoming volumes will contain discussion of the analysis of residues of insecticides (Vol. II), of fungicides, nematicides, soil fumigants, rodenticides, and food and feed additives (Vol. III), and of herbicides (Vol. IV). There has long been a pressing need for a reliable modern laboratory manual of toxic residue analysis, and hence each of these volumes will undoubtedly be eagerly awaited and welcomed by workers in this field.

H. Maier-Bode [NB 273/130 IE]

Chemical Applications of Infrared Spectroscopy. By *C.N.R. Rao*. Academic Press, New York-London 1963. 1st edit., xiii + 683 pp., numerous illustrations and tables, linen $19.50.

It is amazing that, with the exception of the world-renowned book by *Bellamy*, it has taken so long for monographs on infrared spectroscopy to appear in English, although the British and Americans have had undoubtedly the greatest share in the development and application of this subject. For about two years now a glut of books in English on this theme has appeared on the market; the book by *Rao* holds a spezial position among them. It deals mainly with the chemical applications of infrared spectroscopy. It is only in the first chapter that a very brief survey of the theory of spectra, some experimental influences on the appearance of spectra, instrumentation and sample preparation, and the fundamental applications of infrared spectroscopy are given. Chapters 2–7 contain discussions of the spectra of individual classes of compounds. Frequently, despite the brevity of the text, the treatment goes into considerable detail. The next three chapters – two of them by collaborators – are devoted to special applications of infrared spectroscopy in organic chemistry and biochemistry and in the field of high polymers. In conclusion, there are chapters on quantitative analysis and other subjects which do not fit well into the general scheme of presentation selected. An appendix is given which includes a short proposal for a course of instruction in infrared spectroscopy, tables for band assignments, and commendably extensive author and subject indexes.

It is only natural to compare this volume with *Bellamy*'s book. The scope of the topics dealt with is the same, and the arrangement of material is largely the same. However, the presentation in *Rao*'s book seems to be more fluent. The inclusion of numerous illustrations and tables provides an aid to simple comprehension and speedy orientation. The abundance of references given for each chapter are also collected together here and are more readily surveyed and easier to use. The reviewer does not agree with *Rao* on one point, *viz.* the divison between the "middle" and "far" infrared at 650 cm^{-1}. The so-called KBr region at least – because of the techniques required for measurement therein and because of the information it conveys – and perhaps even the whole of the spectral region that can be measured with prism instruments belongs to the middle infrared, so that the division should be drawn at 200–250 cm^{-1}.

W. Brügel [NB 280/137 IE]

Behavior of Electrons in Atoms. Structure, Spectra, and Photochemistry of Atoms. By *R. M. Hochstrasser*. The General Chemistry Monograph Series, edited by *R. Johnson*. W. A. Benjamin, Inc., New York-Amsterdam 1964, 1st edit., xi + 162 pp., numerous illustrations, linen $4.50. paperback $2.15.

The electronic theory of the atom forms the basis of all modern instruction in chemistry. It is therefore desirable to familiarize the student of chemistry as early as possible with the most important concepts of quantum mechanics. In this book, *R. M. Hochstrasser* attempts to give a simple presentation of the theory of the atom for the beginner in chemistry. The author strives to explain the fundamentals of the theory without recourse to the mathematical formalism of quantum mechanics. The starting point for his discussion takes the form of experimental phenomena which can be easily interpreted.

In the earlier chapters atomic spectra, the interaction between atoms and electrons (the Franck-Hertz experiment), the wave nature of particles, the electron shells of atoms, electron spin, the Pauli principle, and the periodic system of the elements are considered. Finally, the Zeeman effect, interatomic transfer of excitation energy (sensitized fluorescence), and the formation and properties of excimers are discussed. However, the material covered does include the theory of the chemical bond.

In accordance with its purpose, the book is written in a rather elementary way and does not demand any specialized knowledge on the part of its readers. An understanding of the text is made quite easy by numerous explanatory diagrams. Thus the book seems ideal for giving the beginner in chemistry a first impression of the electronic structure of the atom.

H. Zimmermann [NB 270/127 IE]

The Inorganic Chemistry of Nitrogen. By *W. L. Jolly*. The Physical Inorganic Chemistry Series. Edited by *R. A. Plane* and *M. J. Sienko*. W. A. Benjamin, Inc., New York-Amsterdam 1964. 1st edit., xi + 124 pp., numerous illustrations and tables, linen $5.75.

The present volume in this series is intended to give a survey of nitrogen and its inorganic compounds with particular emphasis on their physical and physico-chemical properties. Following a comparison of nitrogen with the elements carbon phosphorus, and oxygen, elemental nitrogen as such is discussed, with particular attention to the nature of the bonding in the N_2 molecule. This is followed by a chapter on ammonia, including the use of liquid NH_3 as a medium for reactions,

on metal amides, imides, and nitrides and ammonium salts, and on metal amine complexes (metal-salt ammoniates). In the next seven chapters a systematic survey is given of data on nitrogen-halogen compounds, on further H–N and HO–N compounds, on *N*-oxides and the corresponding acids, and on S–N, P–N, C–N, and B–N compounds. In conclusion, a chapter on the thermodynamics of nitrogen compounds is given.

It is naturally a gigantic task to try to reproduce even only the essential aspects of this expansive field on 124 pages with an acceptable degree of coverage without creating the impression of only a very superficial treatment. It is therefore not surprising that on reading through the book, one notices a number of unfortunate omissions. For example, it is not enough to characterize the nitrides of the transition metals simply by the expression "interstitial or metallic nitrides". Again in the treatment of the synthesis of NaN_3, the reader misses even a short discussion of the reaction mechanism (use of ^{15}N to elucidate it). Furthermore, although many physical properties have been gathered together into tables, some of these are absolutely without explanation. This applies, for example, to the table of successive formation constants for metal amine complexes in aqueous solution. Without some discussion, such a table is of little value, especially since the book is not intended to be simply a work of reference. However, it must be emphasized that there are many interesting new results to be found in the book which is characterized by its lucidity in the presentation of the material and in the mode of expression in the text. Nevertheless, in the reviewer's opinion, the present volume falls somewhat short of its aim in filling an existing gap in the literature in this field.

O. Schmitz-Du Mont [NB 275/132 IE]

Steroid Chromatography. By *R. Neher*. Elsevier Publishing Company, Amsterdam-London-New York 1964. 2nd revised and extended edition, xiii + 389 pp., 31 figs., 78 tables, linen DM 33.50 (about $8.50).

In this second considerably enlarged edition of his monograph, *Neher* surveys column chromatography (77 pp.), paper chromatography (152 pp.), thin-layer chromatography (41 pp.), and gas chromatography (36 pp.) of steroids. Following a short introduction to the individual methods, the conventional adsorbents, solvents for elution, and spray reagents, *etc.* are described, and then the chromatographic behavior of the various classes of steroids is described, frequently in readily surveyable tabular form. The examples taken from the extensive literature in this field have been critically chosen – no attempt has been made to reproduce a comprehensive collection of references – and in the appendix more important publications which have appeared this year are given, by title at least. The book provides, particularly in the first two sections, so many facts that it is a pity that not all are to be found by using the extensive subject index. Thanks to its detailed description of representative separations and the many practical hints that it includes, derived from the experience of its competent author, this book should be of value even to the experimental worker who is already well versed in this field.

The layout of the book is excellent, printing errors and incorrect references are few (the solvent systems from Table 63 and the table on page 210 are confused in the text). The formulation of digoxigenin with a 3α-hydroxyl group and the use of ζ instead of ξ to indicate unknown configurations are in error throughout; the general remarks made on pages 56 and 57 contradict in part the data given in the tables.

Neher's book can be highly recommended to all (chemists, biologists, and medical practitioners) who are concerned with the separation or detection of steroids. The time spent in careful scrutiny of this monograph will soon be repaid many times by following the instructions given by its author when running chromatograms.

G. Snatzke [NB 276/133 IE]

Physical Methods in Organic Chemistry. Edited by *J. C. P. Schwarz*. Oliver & Boyd, Edinburgh-London 1964. 1st edit., xi + 350 pp., several illustrations and tables, linen £2.10.0 (about $7.00).

This book is intended to appeal principally to students and to those chemists who did not have the good fortune to come into contact with the latest physical methods for determining structures during their student days. After an introductory section (*J. C. P. Schwarz*, 21 pages) which includes *inter alia* extensive tables indicating various problems and their methods of solution, there follows a review of the principles common to both ultraviolet and infrared spectroscopy (*P. Bladon* and *G. Eglinton*, 13 pages). Next come chapters on infrared and Raman spectroscopy (*G. Eglinton*, 91 pages), electron-jump spectroscopy (*P. Bladon*, 42 pages), nuclear and electron spin resonance spectroscopy (*L. M. Jackman*, 42 pages), optical rotation [optical rotatory dispersion, circular dichroism, and the correlation of $[\alpha]_D$ values] (*J. C. P. Schwarz*, 34 pages), molecular-weight estimations (*C. T. Greenwood*, 32 pages), X-ray diffraction methods (*G. A. Sim*, 30 pages), mass spectrometry (*R. I. Reed*, 17 pages), and dipole moments (*B. L. Shaw*, 15 pages). The best chapters are those on infrared and ultraviolet spectroscopy in which the positions of the bands are explained in detail by recourse to effects that are completely familiar to every organic chemist. The results summarized in the tables here represent a valuable supplement to larger monographs on the subject for those familiar with the uses of infrared spectroscopy. Numerous examples are used to demonstrate its applications, particular attention being paid to the possibilities of erroneous interpretations. The section on NMR spectroscopy is also excellent, apart from the fact that the difference between the coupling constant J and spin-spin splitting – a point that is especially difficult for the beginner – is unfortunately not made clear enough. A review of the methods of ORD and CD, which are constantly finding more and more applications, especially in the field of natural products, such as that given in the chapter on "optical rotation" has so far never appeared in a monograph in German. On the other hand, in the chapter on mass spectrometry by *Reed*, it is astonishing that no mention is made of the present rapid trend towards application of this technique to the elucidation of the structures of even the most complex molecules.

This book can be warmly recommended not only to every student, but also to every older practitioner; this is one of the monographs that the reviewer would have liked to have available during his graduate research work.

G. Snatzke [NB 277/134 IE]

Encyclopedia of Chemical Technology. Edited by *R. E. Kirk* and *D. F. Othmer*. New edition edited by *A. Standen*. Interscience Publishers, a division of John Wiley & Sons, New-York-London-Sydney 1963. 2nd revised edit., Vol. 2: Aluminum Compounds – Azo Dyes. xv + 910 pp., numerous illustrations and tables, price for the single volume $45.–. Vol. 3: B – Calcium. xvi + 927 pp., numerous illustrations and tables, price for the single volume $45.–.

The two new volumes contain a total of 82 articles each with an average length of 22.5 pages arranged under alphabetical key-words. The longer articles include "Boron compounds" (131 pp.), "Batteries and electric cells, primary" (161 pp.), "Aluminum compounds" (66 pp.), "Anthraquinone derivatives" (63 pp.), "Amines" (57 pp.), "Amino acids" (57 pp.), "Ammonia" (55 pp.), "Antiseptics and disinfectants" (45 pp.), "Asphalt" (44 pp.), "Ammonolysis" (42 pp.), "Azo dyes" (42 pp.), "Beer and brewing" (42 pp.), "Bacterial, ricketsial, and mycotis infections, chemotherapy" (35 pp.), "Butylenes" (35 pp.), "Amino resins and plastics" (35 pp.), and "Bioassay" (29 pp.).

The authors of the two volumes comprise 116 collaborators, 32 from technical colleges and 84 from the chemical industry. In contrast to the first edition, here the results of efforts to secure non-American authors as contributors can be seen: 6

of the experts come from Switzerland, 5 from France, 2 from the Netherlands, and one each from England, Denmark, and Israel. This new edition has really been completely revised, as can be seen, for example, from the fact that only 20 of its 116 coauthors participated in the first edition 15 years ago, but principally from the significant increase in size of the new edition. The material covered in 1091 pages in the first edition requires 1836 pages in the new edition. In order to maintain the usefulness and handiness of the book, it is to be hoped that it will not try to cover new material through an increase in length but rather through abridgement by clever editorial organization.

The new edition contains many valuable improvements on its predecessor. A 15-page section on organo-aluminum compounds has been added under the heading of aluminum compounds. One innovation is the instructive article (25 pp.) which reports the facts about automobile exhaust and offers measures for controlling and avoiding it. The technology of azeotropic distillation has increased so much that entirely new article written by *D. F. Othmer* is devoted to it; this covers 20 pages in contrast to the mere 4 pages allocated previously to the whole subject of distillation. An important section on antistatic agents (24 pp.) gives reliable information about both the theoretical and practical aspects of this problem, which is of such great significance to the textile industry. In the section on "Aquametry", all the methods for estimating water contents are given in summary – an interesting review of modern analytical technique collected together under the common denominator of one special estimation. The section on "Bioassay" (29 pp.) indicates the general regularities of biological assay methods and explains the mathematical manipulations required for carrying out biological tests quantitatively. The treatment of "Boron compounds" (131 pp.) has been extended and now includes the contributions from the first edition (34 pp.), from the first supplement (26 pp.), and from the second supplement (35 pp.). The U.S. Borax Research Corporation is largely responsible for compiling this article, which has been completely rewritten, which is excellently composed, and which presents a first-class survey of this new field which is of equally great importance for inorganic and organic chemistry and for atomic energy technology. The articles on the production of electrical current in galvanic elements (primary batteries or cells) and on the storage of current in accumulators (secondary batteries) have also been considerably lengthened. These cells have acquired immense importance in the U.S.A. in information and rocket technology, so that this review is highly welcome.

With regard to the other sections, the question arises whether the progressive development could not have been adequately discussed without an increase in the number of pages. The extensions of the sections on "Ammonia" (from 38 to 55 pp.), "Ammonolysis" (from 18 to 42 pp.), "Asphalt" (from 34 to 44 pp.), and "Beer and brewing" (from 30 to 42 pp.) could perhaps have been avoided. In contrast, the sections on "Analgetics and antipyretics" (14 pp.) and on "Anaesthetics" (18 pp.) do not contain enough information. However, these paragraphs might have been omitted altogether, since the encyclopaedia includes the key phrase "Stimulants and depressants of the nervous system" under which the same facts about these pharmaceuticals are considered in a broader connection. It also appears somewhat irregular when analgetics, antipyretics, and anaesthetics are allocated individual key-word articles, whereas analeptics, antidiabetics, and antiphlogistics, *etc.* are not. In the condensed form that is required in a reference book of this kind, it is unnecessary to include an alphabetically arranged article for every individual technical concept; instead, this calls for systematic, intensively edited collective articles. The encyclopedia would be more valuable if the editor tried to divide up the material better among his collaborators and to achieve more active coordination among them.

The encyclopaedia has the advantage of being backed by the greatest and most highly differentiated chemical industry in the world, and the American chemical industry is renowned for its liberal policy in revealing the results of its development work for general publication. The work is of particular interest to German readers because they can find in it information on technical fields which are sadly neglected in Germany. The extensive reviews of the literature given at the end of each section are also an admirable feature. Every contributor to these volumes is to be congratulated, and it is to be hoped that the publication will have much success in the future.

H. Sachsse [NB 283/141 IE]

Comprehensive Biochemistry. Edited by *H. Florkin* and *E. H. Stotz*. Volume 13: Report of the Commission on Enzymes of the International Union of Biochemistry. Elsevier Publishing Co., Amsterdam-London-New York 1964. 1st Edit., XII + 164 pp., price of single volume DM 22.80 (about $ 5.75).

Section III of this handbook, which is appearing in the form of numerous small volumes, has as its general theme "Biochemical Reaction Mechanisms" and is to deal mainly with enzymes. It may at first appear surprising that a whole volume of this section, which is to consist of only five volumes in all, is devoted to the reproduction of the new proposals of the International Union of Biochemistry for the nomenclature of enzymes. However, perusal of this volume soon places its usefulness beyond doubt. The editors have not restricted the text to the 1961 nomenclature report, but have worked in amendments and corrections which have become necessary in the meantime. Enzyme units, symbols for describing enzyme kinetics, a list of enzymes almost one hundred pages long which gives information on the systematic names, the trivial names, the reaction catalysed, and the specificity of each enzyme, and a long subject index form the main sections of the book, which can be recommended as a work of reference. The orderly arrangement of the text and the particularly clean print deserve special mention.

H. Grünewald [NB 345/202 IE]

A History of Chemistry. By *J. R. Partington*. Vol IV. McMillan & Co. Ltd., London; St. Martin's Press, New York 1964. 1st Edit., XXXI + 1007 pp., 91 illustrs., linen £10.10.0 (about $ 29.00).

This volume of "A History of Chemistry" deals with the development of chemistry in the 19th and partly in the 20th century. Volumes II and III have already appeared, and volume I will be published last.

Although it appears to be relatively easy from our present-day perspective to appraise the value of results from earlier centuries with regard to their importance for the progress of chemical science, any such evaluation becomes more and more difficult, the closer one approaches to the present. For this reason, the order of presentation used in the previous volumes (*i. e.* arranging the material mainly according to the personality of prominent historical figures) is maintained only for the time up to about 1865. In the present volume the period from *Davy* (first electrochemical investigations) up to the time of *Kekulé* (theoretical considerations on the structures of organic compounds which culminated in the cyclic formula for benzene) is presented in this fashion. Thereafter, like *Paul Walden* in his "Geschichte der Organischen Chemie seit 1880" (History of OrganicChemistry since 1880), *Partington* switches over to a non-personalized presentation of the general trends in the fields of physical, organic, and inorganic chemistry; here, for example, thermochemistry and thermodynamics are described up to the time of *Nernst* and *Haber*, organic chemistry up to *Willstätter*, *H. Wieland*, *Diels*, and *Wallach*, and inorganic chemistry up to *Ruff*, *Stock*, and *K. A. Hofmann*. The final chapter deals with radioactivity and atomic structure and ends with a description of the preparation of the transuranic elements, thus leading right into the present.

The reader is amazed at the author's exquisite command of the data on the evolution of chemistry. Anyone who has ever taken the trouble to trace back the development of an idea or the repercussions of an original discovery by recourse to the original publications will appreciate the vast effort that has been expended by a single author here in order to produce this excellent "History of Chemistry".

W. Ruske [NB 321/179 IE]

Crystallographic Data on Metal and Alloy Structures. Compiled by *A. Taylor* and *B. J. Kagle*. Dover Publications Inc., New York; Constable & Co. Ltd., London 1963. 1st Edit., 263 pp., paperback $ 2.25.

This book of tables was prepared, according to statements by the authors, from original literature, the ASTM data file, Pearson's Handbook of Lattice Spacings and Structures of Metals and Alloys, Structure Reports, Strukturberichte, and "Landolt-Börnstein". The columns in the tables contain in series: chemical formula (in alphabetical order), occasionally the mineral name/crystal system, indications of the structural type, and, if known, ASTM index data/space group/lattice constants/number of formula units per unit cell. The contents are arranged in three parts: Table 1 contains about 2300 "Alloys and Intermetallic Compounds" – where, however, a large number of halides (!), sulfides, and selenides are included; Table 2 contains borides (about 95), carbides (about 105), hydrides (about 45), nitrides (about 110), and oxides (about 350) together with a number of silicates and a few carbonates; Table 3 contains data on elements.

Judging from the title, more detailed and more comprehensive data on the crystal structures proper might have been expected; partly it would be sufficient to include an additional column of "references" and to reduce, for example, the abundant space allotted to lattice constants. It is difficult to understand – in view of the title – why the authors have augmented their data by an apparently random selection of information on non-metallic compounds, *e.g.* halides and oxides. It is also not clear why the data given for silicates are so incomplete, why (occasionally erroneous) mineral names are given for oxides but mostly none for sulfides, arsenides, *etc.* Moreover, the ASTM index data, *i.e.* d-values and relative intensities of the three strongest X-ray reflexes, can only seldom be used for purposes of identification, when recourse cannot be had to the complete X-ray diffraction diagram.

The booklet may occasionally be of value as a supplement to other literature, especially for getting a first information. Its low price is attractive.

H. J. Meyer [NB 306/165 IE]

Oxidation Mechanisms. Applications to Organic Chemistry. By *R. Stewart*. Frontiers in Chemistry, edited by *R. Breslow* and *M. Karplus*. W. A. Benjamin, Inc., New York-Amsterdam 1964. 1st edit., xi + 179 pp., 2 figs., several tables, linen $ 7.50.

Mechanisms of Oxydation of Organic Compounds. By *W. A. Waters*. Methuen's Monographs on Chemical Subjects. Series edited by *H. J. Emeléus*, *D. W. G. Style*, and *R. P. Bell*. Methuen & Co., Ltd., London; John Wiley & Sons, Inc., New York 1964. 1st. edit., vii + 152 pp., 2 figs., linen £1.5.0 (about $ 3.50).

Most mechanistic investigations carried out during the past thirty years were concerned with substitution, addition, elimination, and rearrangement reactions, and only these were dealt with in textbooks. However, the simultaneous appearance of these two monographs shows that there is also a wide interest in oxidation (and reduction) reactions and their mechanisms. Both books cover the material to an extent that would fill out a course of a one-hour lecture per week for a semester. *Stewart* arranges his presentation mainly according to oxidizing reagents, whereas the arrangement by *Waters* is based (albeit none too strictly) on the type of substrate being oxidized. Neither book attempts to achieve exhaustive coverage; in *Stewart*'s treatment some aspects (*e.g.* ozonolysis) are omitted altogether, because they have been reviewed within recent years. Instead, he gives a detailed discussion particularly of chromic acid and permanganate oxidations. *Waters* emphasis mainly oxidations which involve a one-electron transfer, for he himself has participated significantly in the elucidation of the course of these reactions. His book is intended principally for students, and hence he gives only a few references to original publications and does not include an author index. *Stewart*, on the other hand, cites about 400 articles, which will help his readers to find easier access to more specialized aspects of the subject. Biochemical oxidations are discussed in a separate chapter by *Stewart*, but *Waters* only touches upon this subject.

The reviewer is reluctant to recommend either book more than the other, for both are stimulating and are critically written. Organic chemistry institutions should acquire both of them, for they complement each other to a certain degree.

R. Criegee [NB 293/151 IE]

Azeotropy and Polyazeotropy. By *W. Swietoslawski*. A translation from the Polish edited by *K. Ridgway*. Pergamon Press, Oxford-London-New York-Paris 1963. 1st edit., 226 pp., numerous illustrs. and tables, linen £3.10.0 (about $ 9.75).

This monograph is a new edition of the book which appeared in 1957 in Polish.

In part I (pp. 13–146), individual azeotropic mixtures and series of azeotropic mixtures are dealt with, with particular attention to the azeotropic boiling range even for ternary and quaternary mixtures. An especially long chapter is devoted to interesting azeotropic mixtures with a saddle-like temperature profile. The concept of polyazeotropy is introduced in the second part (pp. 147–160) and illustrated with the example of coal-tar distillation. Part III (pp. 161–192) deals with special polyazeotropic systems, with the dehydration of ethanol, and with experimental methods for determining azeotropic distillation ranges. In part IV (pp. 193–205), a short discussion is given of the methods for thermochemical investigation of azeotropic mixtures, particularly the estimation of enthalpies of evaporation and of mixing.

The book contains numerous illustrations and is intended primarily for the use of the practical experimenter. The author's highly condensed description of ebulliometry and its use in practice for examining azeotropic mixtures is excellent. Experimental difficulties are not passed over without comment.

The monograph makes no demands on the theoretical knowledge of the reader, and is thus readily understandable even for beginners, although the overall clarity suffers somewhat because of the vast amount of experimental material included. It should also be mentioned that a clear distinction is not always drawn between rules that have been derived empirically and regularities that have been derived by calculation from thermodynamics.

The layout of the book is satisfactory, although the print is sometimes smudged or broken and although there are several misprints. The book contains numerous references to literature sources (312 in all) and can be recommended to anyone who wishes to be come acquainted with the problems and applications of azeotropic distillation. Moreover, the book will go a long way to alleviate the lack of coordination that is frequently extant between research and applied work. This intention of the author has been well achieved in the reviewer's opinion, for the book offers interesting incentives to workers in both fields.

M. Rehse [NB 296/154 IE]

Technique of Organic Chemistry. Edited by *A. Weissberger*. Vol. XI: Elucidation of Structures by Physical and Chemical Methods. Part I. Edited by *K. W. Bentley*. Interscience Publishers, a Division of John Wiley & Sons, New York-London 1963. 1st edit., ix + 642, 23 pp., numerous illustrations and tables, linen £6.5.0 (about $17.50).

Methods for the elucidation of structures are of interest not only to the natural-products chemist, but also to the organic chemist engaged in synthetic work, for he often encounters new and unexpected reaction products. The present volume of this series will therefore appeal to a wide variety of readers. A chapter on "Isolation, purification and preliminary observations" by *K. H. Overton* forms the introduction here; this includes very valuable tables of data on color and precipitation reactions for use in determining roughly what class of compound is being examined. This is followed by contributions on ultraviolet spectroscopy (*J. C. D. Brand* and *A. I. Scott*), infrared spectroscopy (*A. R. H. Cole*), nuclear magnetic resonance spectroscopy (*J. B. Stothers*), mass spectrometry (*K. Biemann*), and dissociation constants and optical activity (*J. F. King*). These topics are discussed in greater detail in Vol. I of the same series (Physical Methods of Organic Chemistry, four parts). In this book, descriptions of the appropriate practical procedures and theoretical fundamentals have been almost completely disregarded; instead, only an appraisal of the value of the methods for purposes of elucidating structures is given. In each section a description of the general principles involved is followed by illustrations with examples from the chemistry of natural produtes. These chapters are wonderfully adapted to the needs of the organic chemist engaged in empirical evaluation of physical measurements conducted with commercial instruments.

Working hypotheses on the structures of certain natural products are often developed using biogenetic principles. The general background for such an approach is given by *E. Leete* in chapter VII, who reminds readers to consider theories before applying them. An essay by *G. A. Swan* on the "Detection and protection of functional groups" introduces chemical methods. Of the latter, Part I contains discussion on "Reduction and hydrogenation" by *F. J. McQuillin* and on "Dehydrogenation" by *Z. Valenta*. The material collected together in this volume can be obtained only with considerable effort from other sources, and it gives terse but reliable information on the applicability and drawbacks of the reactions discussed. We can look forward to the forthcoming "chemical" chapters with great interest.

The whole volume has been very carefully edited; errors are seldom found (the position of the $\rangle C-H$ nuclear resonance in Fig. 4, page 212 is incorrect, an equation on page 460 is printed upside down). The layout, *e.g.* the appearance of the steric formulae, is excellent. However, this has been attained at the expense of the time required for publication: the literature reviewed in the individual contributions does not go beyond 1960 (copyright 1963).

This small book contains so much information that it can be recommended to even those who are undecided about buying the complete series.

W. Kirmse [NB 266/124 IE]

Noble Gases and their Compounds. By *G. J. Moody* and *J. D. R. Thomas*. Pergamon Press, Oxford-London-Edinburgh-New York-Paris-Frankfurt 1964. 1st edit., vii + 62 pp., 11 tables, linen 12s. 6d. (about $1.75).

This little book gives on the whole an excellent survey of the title subject. In the first chapter, the history of the discovery of the noble gases is recounted briefly. The second chapter is devoted to early attempts to produce inert gas compounds and deals with helides, MHe_2, clathrates, and the particularly interesting older studies on the preparation of inert gas halides. In the third chapter, the authors give a reasonably detailed report on the "present" status of the chemistry of the noble gases; this begins with *Bartlett*'s compound $XePtF_6$, the discovery of which initiated numerous investigations in the U.S.A., and then describes the xenon fluorides XeF_2, XeF_4, and XeF_6, together with their properties, crystal structure, and the nature of their bonds, and finally the oxyfluorides XeO_xF_y. The discussion then proceeds to XeO_3 and the salts of the acids H_6XeO_6 and H_4XeO_6, the krypton fluorides KrF_2 and KrF_4, and attempts to prepare compounds of radon. The compound $BaKrO_4$ recently obtained by *von Grosse* and the recent determination of the structure of $Na_4XeO_6 \cdot 8H_2O$, for instance, could not yet be fully considered. In the fourth chapter a survey of future prospects for developments in this field is given. The cursory reader will miss the presence of tables summarizing the most important physical properties of the compounds.

The book is well arranged, and is easy to read; the latter stattement applies especially the discussion of the chemical bonds of these compounds. As in almost every account in English of the discovery of the first genuine valence compounds of the noble gases in 1962, here too there is no mention, of the fact that the first binary noble gas fluorides were prepared independently and almost simultaneously in Germany (XeF_2, July 1962) and in the U.S.A. (XeF_4, early August 1962). Purchase of this little volume can be recommended without reservation.

R. Hoppe [NB 278/135 IE]

Treatise on Analytical Chemistry. Edited by *I. M. Kolthoff* and *P. J. Elving*. Part I: Theory and Practice. Vol. 5: Section D.3: Optical Methods of Analysis. Interscience Publishers, a Division of John Wiley & Sons, New York-London-Sidney 1964. 1st edit., xx + 639 pp., numerous illustrations and tables, linen £6.0.0 (about $16.75).

The constantly increasing number of publications appearing nowadays in every field of science lends increasing importance to the various multivolume series which contain comprehensive surveys of extensive, but specialized, topics. This series edited by *Kolthoff* and *Elving* is intended to give a complete appraisal of the entire field of analytical chemistry. Volumes 5 and 6 of Part I are devoted to optical analytical methods. The concept "optical methods" is assumed to be very wide in scope, and hence includes all techniques employing absorption or emmison, optical rotation, or diffraction or scattering over the whole range of the electromagnetic spectrum, from X-rays up to microwaves. Diffraction and absorption of electrons and neutrons are also discussed in these volumes.

In Vol. 5, *E. J. Meehan* reviews the general principles pertaining to all optical investigations in the first three introductory chapters of Volume I (optical methods, the fundamentals of spectrophotometry, spectroscopic apparatus and measurements). Detailed discussions are given by *F. W. Billmeyer* of the fundamentals of light scattering, by *D. B. Judd* and *I. Nimeroff* of the specification and designation of color, by *A. A. Schilt* and *B. Jaselskis* of ultraviolet and visible spectrophotometry, by *A. L. Conrad* of fluorescence methods, by *H. A. Liebhafsky*, *H. G. Pfeiffer*, and *E. H. Winslow* of the absorption, emission, and diffraction of X-rays, by *D. B. Wittry* of X-ray microanalysis, by *J. H. Goldstein* of microwave spectrophotometry, and by *F. P. Hochgesang* of light scattering and turbidity measurements.

In every chapter the theoretical basis of the phenomenon in question is first discussed to an extent required for a complete understanding of its analytical applications. Instrumentation and measurement problems are considered by using simple illustrations, and the most important properties of commercial or even "home-made" apparatus are reviewed. Practical examples are used to give a critical survey of methods of evaluation; a detailed treatment of possible sources of errors is also always given. Each chapter closes with a list of references which, however, seldom contains mention of continental European monographs.

Despite the large number of contributors, the volume conveys an impression of completeness; in the more specialized

chapters the fundamentals discussed in the introductory chapters are considered in more detail; repetitions have largely been avoided, and the symbols used have all been standardized throughout the text.

This volume makes it possible to secure rapid familiarity with the methods of optical analysis and to obtain reliable information on the scope and limitations of their application. The complete work promises to become the standard handbook of analytical chemistry, and probably will be soon found in every chemical library.

W. Liptay [NB 264/122 IE]

Structure Elucidation of Natural Products by Mass Spectrometry. Vol. I: Alkaloids. By *H. Budzikiewicz, C. Djerassi,* and *D. H. Williams.* Holden-Day Series in Physical Techniques in Chemistry. Holden-Day Inc., San Francisco-London-Amsterdam 1964. 1st edit., xi + 233 pp., numerous illustrations, linen $10.50.

The present volume contains a detailed discussion of the mass spectrometry of alkaloids, especially of those of the indole and isoquinoline series. Although the book has therefore a highly specialized character, it is of general significance since it contains a chapter on deuteration procedures. In this remarkable section, a comprehensive collection of methods for marking organic compounds with deuterium is given with numerous examples. In their later discussion on the mass-spectrometric degradation of alkaloids, the authors presume that the charge on the molecule ion – *e.g.* on a nitrogen atom – is localized. All the degradation mechanisms are formulated according to this principle in the present volume, although this approach sometimes leads to structural formulae for the degradation products, which are unacceptable from the energy standpoint. Thus, for example, the fragment p from a pyrrolizidine alkaloid shown on p. 223 is formulated as a diradical cation, and the energetically much more favorable, and thus more probable simple cation is not even considered.

A few careless errors probably result from the rapid appearance of the book (only three months after completion of the general first part), but these will be certainly corrected in any future edition.

Despite these faults, the book can be recommended as being the first detailed review of the mass-spectroscopy of the alkaloids, and it well deserves a place in every laboratory devoted to mass-spectroscopic investigations of these compounds.

G. Spiteller [NB 289/147 IE]

The Mitochondrion. Molecular Basis of its Structure and Function. By *A. L. Lehninger.* W. A. Benjamin, Inc., New York-Amsterdam 1964. 1st edit., xx + 263 pp., numerous illustrations, and some tables, linen $9.90.

Although classical cell research was in a position to define mitochondria both morphologically and functionally at the beginning of this century, research proper on these subcellular particles which are responsible for energy metabolism in the cell only began with the development of modern biochemical and biophysical methods after the Second World War. Today the beginnings of the elucidation of the molecular function and structure of mitochondria are recognizable. A decisive contribution to this development was made by *A. L. Lehninger* with his discovery of the participation of mitochondria in the oxidation of fats and in oxidative phosphorylation. In the present volume he presents the first summary of the current state of research and of the molecular basis of mitochondrial structure and function. The subject matter is discussed in detail, and comprises mitochondria in the intact cell, the oxidative cycles and the respiratory chain, the components of the oxidative system and of oxidative phosphorylation, problems of control, compartmentation, and integration, as well as further questions related to active ion-transport, water balance, and biogenesis. The book is well illustrated and contains much unabridged material taken directly from representative authors in this field, and abundant references to review articles and important journal publications are also included. It forms an excellent introduction for those who wish to acquaint themselves with the problems involved in this field, and should also be welcome as a work of reference for the expert on this subject.

B. Hess [NB 291/149 IE]

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Relationships between Structures and Mass Spectra of Organic Compounds [*]

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Our knowledge concerning the relationships between the structure and mass spectra of organic compounds has widened immensely during the past few years. It has become possible to alter the course of fragmentation in the mass spectrometer by changing certain substituents using simple chemical reactions. The fragmentation products formed are then entirely different from those of the starting material. A combination of controlled mass-spectrometric decomposition with chemical microreactions often permits the solution of complicated structural problems with a minimum expenditure of time and material. One example for the alteration of the fragmentation pattern by a simple chemical reaction is discussed in connection with the elucidation of the structure of pleiocarpamine.

I. Introduction

The qualitative analysis of organic compounds by means of mass spectrometry is a method of very recent origin. During the initial period between 1950 and 1959, *Beynon* [1], *Stenhagen* and *Ryhage* [2, 3], *Meyerson* [4] and particularly *McLafferty* [5] investigated the characteristic fragmentation reactions of simple classes of compounds. The general laws of fragmentation determined in this way then allowed the elucidation of the structures of unknown compounds, mainly natural products. This second stage of development was initiated by the elucidation of the structure of phthiocerol, a wax-like constituent of the capsule of the tubercle bacillus [6]. The tremendous possibilities opened up by the new method were demonstrated by *Biemann* [7] and also by *Djerassi* and *Budzikiewicz* [8] by solving complicated structural problems in the fields of amino acids and alkaloids.

II. Mass-Spectrometric Investigations of Organic Compounds

In the ionization chamber of the mass spectrometer, the molecules of the gaseous sample are bombarded with electrons, generally with an energy of 70 eV. On collision the electron transfers energy to the molecule. The quantity of energy transferred is not exactly known and probably depends on whether the impact is central or glancing. The energy is generally sufficient to eject an electron from the molecule, and is also sufficient to split the molecular ion formed into fragments. In this way an organic compound is cleaved by the reagent

[*] Compiled from lectures given by the authors during the past three years in Vienna, Linz, Heidelberg, Elberfeld, Mülheim/Ruhr Munich, Ingelheim, Erlangen, Würzburg, Mainz, Frankfurt, Darmstadt, Marburg, Berlin, Amsterdam, Liège, Zurich, Basel, and Prague; cf. also *G. Spiteller*, Chem. Weekblad *59*, 205 (1963); Z. analyt. Chemie *197*, 1 (1963); *G. Spiteller* and *M. Spiteller-Friedmann*, Ind. chim. belge *29*, 357 (1964).

[**] Present address: Institut für Organische Chemie der Universität Göttingen (Germany).

[1] *J. H. Beynon*, Nature (London) *174*, 735 (1954); Mikrochim. Acta *1956*, 437; Mass Spectrometry and Its Application to Organic Chemistry. Elsevier, Amsterdam 1960.

[2] Review: *R. Ryhage* and *E. Stenhagen*, J. Lipid Res. *1*, 361 (1960).

[3] Review: *R. Ryhage* and *E. Stenhagen* in *F. W. McLafferty*: Mass Spectrometry of Organic Ions. Academic Press, New York 1963, pp. 399–452.

[4] Review: *H. M. Grubb* and *S. Meyerson* in [3], pp. 453–528.

[5] *F. W. McLafferty*, Analytic. Chem. *28*, 306 (1956); Appl. Spectroscopy *11*, 148 (1957); in [3], pp. 309–342.

[6] *L. Ahlquist*, *R. Ryhage*, *E. Stenhagen*, and *E. v. Sydow*, Arkiv Kemi *14*, 211 (1959); *R. Ryhage*, *S. Ställberg-Stenhagen*, and *E. Stenhagen*, ibid. *14*, 247, 259 (1959).

[7] a) *K. Biemann*, Angew. Chem. *74*, 102 (1962); Angew. Chem. internat. Edit. *1*, 98 (1962); b) Mass Spectrometry. Organic Chemical Applications. McGraw Hill, New York 1962; c) in [3], pp. 529–556.

[8] a) *C. Djerassi*, Pure appl. Chem. *6*, 575 (1963); b) *H. Budzikiewicz*, *C. Djerassi*, and *D. H. Williams*: Interpretation of Mass Spectra of Organic Compounds. Holden-Day, San Francisco 1964; c) Structure Elucidation of Natural Products by Mass Spectrometry. Vol. 1, Alkaloids. Holden-Day, San Francisco 1964.

"electron" inside the ionization chamber, and is irrecoverably destroyed.

In the course of degradation, positively and negatively charged ions, neutral molecules, and radicals are formed. The charged particles can be separated by physical means, *i.e.* by electrical and magnetic fields (according to their mass and charge), and their mass spectrum can be determined photographically or with the aid of a recording device (Fig. 1). In general, only the positively charged ions, whose formation is more probable than that of the negative ions by a factor of 10^4, are measured. The spectra of negative ions, which are more difficult to record and which have mainly been studied by *von Ardenne* [9], can supplement the spectra of positive ions, especially in the case of compounds of higher molecular weight containing hydroxy groups [10].

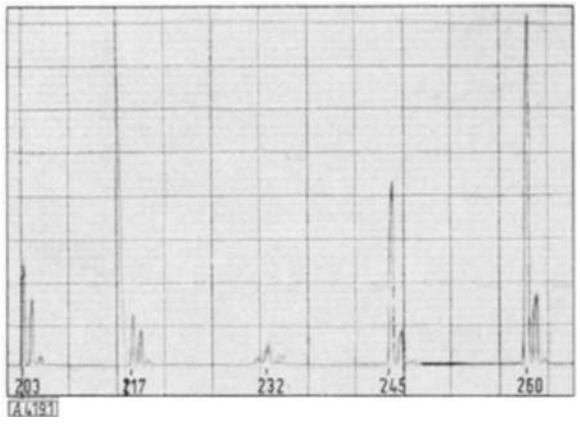


Fig. 1. Section from the mass spectrum of androstane, $C_{19}H_{32}$, reduced to half-size, taken with an Atlas Model CH-4 Mass Spectrometer; temperature of the TO-4 ion source approximately 60 °C. The mass/charge ratios m/e were inserted to facilitate interpretation. The molecular-ion peak is at 260. The entire spectrum from m/e = 29 to m/e = 262 is 79.5 cm long.

Except for compounds which contain numerous π-electrons, electrons of the energy normally used (70 eV) form singly charged particles almost exclusively, so that the peaks of a mass spectrum indicate the mass numbers (molecular weights) of the decomposition products. The quantity of ions having the same mass number is proportional to the height of the peak.

In this sense, mass spectrometry differs fundamentally from other techniques such as infrared or ultraviolet spectroscopy; in the latter two methods a molecule is excited by electromagnetic waves but is not altered chemically, so that the sample used can be recovered unchanged. In contrast, a molecule hit by an electron in the ionization chamber of the mass spectrometer generally undergoes cleavage. In infrared and ultraviolet spectroscopy, wavelengths are measured, *i.e.* the quantities of energy absorbed which are characteristic for certain structural elements. In the mass spectrometer, the quantity of energy transferred on collision with the electron varies (when electrons are used whose energy lies above the ionization potential of the compound investigated) and can therefore be neither measured nor related to the structure of the investigated compound. On the other hand, the quantity and molecular weight of the fragmentation products can be derived from the mass spectrum. Chemical and mass-spectrometric decomposition processes exhibit many parallel characteristics.

[9] *M. v. Ardenne, K. Steinfelder,* and *R. Tümmler,* Angew. Chem. *73,* 136 (1961).

[10] *M. v. Ardenne, K. Steinfelder,* and *R. Tümmler,* Z. physik. Chem. *220,* 105 (1962); *M. v. Ardenne, R. Tümmler, E. K. Weiss,* and *T. Reichstein,* Helv. chim. Acta *47,* 1032 (1964).

A. Prerequisites for the Investigation of Organic Compounds by Mass Spectrometry

1. *Volatility*

In contrast to ultraviolet and infrared spectroscopy, where a substance is generally investigated in solution or as a solid, mass spectra can be obtained from substances only if these are present as a gas. This does not mean that gases or easily volatile liquids and solids alone are appropriate. Rather, the minimum vapor pressure required (about 10^{-6} mm Hg) is so small that even compounds such as amino acids can be investigated [11]. Difficultly volatile substances cannot, however, be evaporated into the gas reservoir of the mass spectrometer in the normal manner, and introduced through a nozzle into the ion source [7a], but must be carefully volatilized in the ion source itself [12–14]. With the exception of a few classes of compounds, nearly all organic substances can be studied by mass spectrometry in this way. Admittedly, strongly polar compounds which contain numerous OH or NH groups must be converted into more volatile derivatives, *e.g.* by acetylation, in order to make them suitable for mass spectrometric investigation [7b].

2. *Resolving Power of the Instruments*

The applicability of mass spectrometry is also limited by the resolving power of the instrument, *i.e.* by its ability to record ions of different masses as two separate peaks. The maximum resolving power of currently available single-focusing instruments is between 1000 and 1500. A resolving power of 1000 means that ions with a mass of 999 and 1000 can just be separated.

Double-focusing instruments achieve a resolving power which is approximately twentyfold. However, this increase in resolving power to 20000 does not necessarily mean that it is possible to obtain spectra of compounds with molecular weights up to 20000, since most substances with molecular weights above 1000 do not possess the required vapor pressure.

The advantage of using double-focusing mass spectrometers is mainly that the empirical formula of an ion can be determined by an accurate measurement of its

[11] *K. Heyns* and *H. F. Grützmacher,* Liebigs Ann. Chem. *667,* 194 (1963).

[12] *P. A. Finan* and *R. I. Reed,* Nature (London) *184,* 1866 (1959). *R. I. Reed, W. K. Reid,* and *J. M. Wilson* in *R. M. Elliot*: Advances in Mass Spectrometry. Pergamon Press, London 1963, pp. 416–417.

[13] *G. Spiteller, C. Brunnée, K. Heyns,* and *H. F. Grützmacher,* Z. Naturforsch. *17b,* 856 (1962); *G. Spiteller* and *M. Spiteller-Friedmann,* Mh. Chem. *94,* 742 (1963).

[14] *J. F. Lynch, J. M. Wilson, H. Budzikiewicz,* and *C. Djerassi,* Experientia *19,* 211 (1963).

mass [15]. For example, it is possible to decide whether an ion with a mass of 44 has the empirical formula C_2H_4O (exact molecular weight 44.0403) or C_3H_8 (exact molecular weight 44.0767) simply by comparison with a standard sample (peak-matching). However, this method is still very expensive, so that single-focusing instruments are preferable for routine measurements.

3. *Amount of Sample*

The quantity of sample required to record a mass spectrum depends on the method of introduction and on the type of recording device used. With photographic recording and direct evaporation of the sample inside the ion source, approximately 10^{-3} mg is sufficient, while 1 mg may be required if the compound is introduced into the ion source *via* the gas reservoir.

4. *Purity*

In general, the interpretation of a mass spectrum is not seriously affected by small quantities of impurities. Since a mass spectrum is composed additively of the contributions of the individual components, it is often possible to recognize impurities in the sample from the appearance of additional or more intense peaks. However, it is very difficult to detect a compound which is stereoisomeric with the main component, as in general such isomers afford similar mass spectra.

[15] Review: *R. A. Saunders* and *A. E. Williams* in [3], pp. 343 to 398.

B. Reproducibility of the Mass Spectra

The ratio of the intensities of the fragment peaks to the intensity of the molecular-ion peak is strongly influenced by instrumental factors; when mass scanning is achieved by altering the electric field, the focusing quality decreases with increasing molecular weight of the ions, so that the intensity ratio recorded in the spectrum is displaced in favor of particles having a low molecular weight (massdiscrimination effect).

In addition, as in chemical processes, the experimental conditions are of considerable importance; with increasing electron energy the intensity ratios of fragment to molecular-ion peaks increases appreciably, but reaches a limiting value at about 30 eV. Between 50 and 100 eV the spectra are more or less independent of the electron energy. For this reason, an energy of 70 eV is generally selected.

A decisive factor affecting the relative abundance of fragments and the molecular ion produced, is the temperature of the substance undergoing cleavage in the mass spectrometer [16]. Molecules which possess more kinetic energy require less energy for decomposition, as they are already thermally excited and more easily cleaved than "cold" ones [17]. In the spectra of compounds which have been evaporated in cold ion sources at relatively low temperatures, the peaks of the molecular ions are more intense than those of the fragments. This is less so when the same compounds are evaporated in hot ion sources.

The upper part of Figure 2 shows the mass spectrum of n-triacontane, taken with a CEC instrument (scanned by variation of the electric field) at an ion-source temperature of 340 °C. The lower part of the figure shows the spectrum of the same compound taken with an Atlas CH-4 instrument (scanned by variation of the magnetic field) at an ion-source temperature of approximately 70 °C. The differences in the inten-

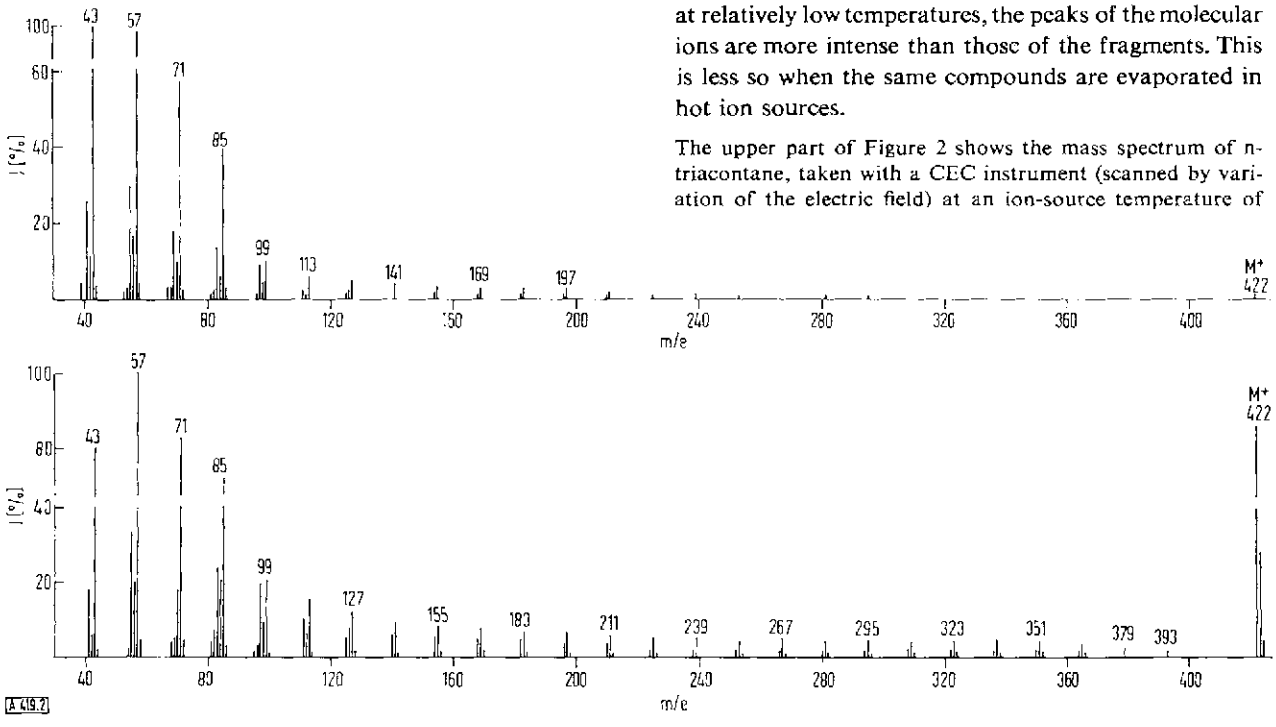


Fig. 2. Top: mass spectrum of n-triacontane $H_3C-(CH_2)_{28}-CH_3$ (A.P.I. no. 1316 [*]) taken with a CEC instrument; ion source at 340 °C. Bottom: mass spectrum of the same substance taken with an Atlas CH-4 instrument; TO-4 ion source at about 70 °C.
Ordinate: Intensity I [%].
Abscissa: m/e.

[16] *M. Spiteller-Friedmann, S. Eggers,* and *G. Spiteller,* Mh. Chem. *95,* 1740 (1964).

[17] *D. P. Stevenson,* J. chem. Physics *17,* 101 (1949).

[*] The A.P.I. number refers to the "Catalogue of Mass Spectral Data", issued by the American Petroleum Institute (A.P.I.) as Research Project 44.

sity ratios of the ions can be ascribed principally to the difference in temperature. (These and all following diagrams are line spectra derived from original spectra.)

The reaction conditions and the type of instrument influence the intensity ratio of the ions, but have no effect on the main fragmentation reactions. The same fragments are therefore formed from a particular substance irrespective of the nature of the instrument and conditions, and a qualitative analysis of the spectrum becomes possible. Using identical reaction conditions and the same instrument, the mass spectra are exactly reproducible and perfectly suitable for quantitative analysis (*e.g.* hydrocarbon mixtures in the petroleum industry).

C. The Course of Decomposition Reactions in the Mass Spectrometer

While in a chemical reaction the reagent attacks a particular group or bond, the electronic attack in the mass spectrometer is directed towards no particular site of the molecule. Whereas a chemical reaction owing to the relative sizes of the reaction partners takes place only on the surface of the molecules, it must be assumed that the much smaller electron can penetrate a molecule at any point, transferring part of its energy to the bonding and non-bonding electrons of the molecular orbitals penetrated and leading to the excitation of different centers. Within about 10^{-13} seconds [18], an electron is ejected from the excited molecule leaving behind a positively charged molecular ion. According to the "statistical theory of mass spectra" [18], the energy in excess of the ionization potential is assumed to distribute itself uniformly over all bonds, and fragmentation of the molecular ion then occurs. Numerous examples have shown that, with a few exceptions, this theory is at least qualitatively valid; in larger molecules, however, only partial distribution of the transferred energy takes place before fragmentation occurs [19].

D. Fragment Formation

Fragments are formed preferentially with a minimum expenditure of energy. It follows that the intensity of an ion peak will be the greater the less energy is required for ion formation and the more is needed for its further cleavage. The intensity of an ion peak therefore depends on both the probability of formation and the probability of decomposition of the ion.

The ionization of an unsubstituted aromatic hydrocarbon requires a relatively small amount of energy owing to the abundance of π-electrons, while cleavage of the resultant molecular ion, in which the positive charge is stabilized by the residual π-electrons, requires a considerable amount of additional energy. For this reason, fragment formation is not very probable and the molecular-ion peaks of such compounds exhibit a very high intensity (Fig. 3).

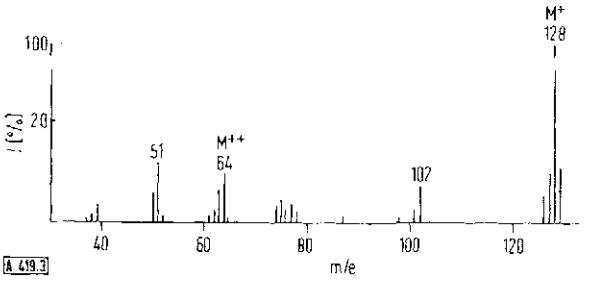


Fig. 3. Mass spectrum of naphthalene (A.P.I. no. 41).
Ordinate: intensity I [%].
Abscissa: m/e.

In a saturated aliphatic hydrocarbon, electrons can be removed only from σ-bonds. Since these are more stable than π-bonds, appreciably more energy is necessary to bring about ionization. Stabilization of the charge in the molecular ion is not possible. The latter must contain a single-electron bond, so that the difference between the energy required to form the ion and that required to decompose it is relatively small. This means that the fragment peaks have a very high intensity compared to the molecular-ion peak (Fig. 2).

It was frequently attempted to solve stereochemical problems with the aid of mass spectrometry. Normally, however, stereoisomeric compounds have similar mass spectra, due to the fact that the main fragmentation reactions do not involve the center of stereoisomerism. Thus, stereoisomeric differences lead to only slight variations in peak intensity, particularly when the center of stereoisomerism is remote from the bonds which are preferentially cleaved. It is only when bonds participating in the center of stereoisomerism are broken in the main fragmentation reactions that the mass spectra differ sufficiently for stereochemical conclusions to be drawn.

1. *Single Bond Cleavage*

Since fragmentation occurs preferentially with minimum energy expenditure, weaker bonds are ruptured rather than stronger ones, and cleavage reactions in which stable fragments are formed are preferred, because here the energy required for rupture is at least partially balanced by the gain in stabilization energy.

In saturated aliphatic hydrocarbons, for example, the weaker C–C bonds are therefore split more readily than the stronger C–H bonds, the main fragments being ions with the general formula C_nH_{2n+1} and masses 15, 29, 43, 57, *etc.*

By cleavage of a C–C bond in a straight-chain saturated hydrocarbon, primary carbonium ions of approximately equal stability are formed (subsequent rearrangement leading to secondary and tertiary carbonium ions may then occur). All C–C bonds in such a hydrocarbon therefore have an equal probability of being ruptured. The continuous decrease in peak intensity with increasing molecular weight of the fragments (Fig. 2) is due to the fact, that ions of higher molecular weight undergo secondary cleavage reactions more readily (see Section II.D.2a), which lead to the accumulation of low molecular-weight ions as final degradation products.

[18] *H. M. Rosenstock* and *M. Krauss* in [3], p. 2.

[19] *V. Hanuš* and *Z. Dolejšek*, Collect. czechoslov. chem. Commun. *28*, 653 (1964).

[19a] *R. A. Friedel, J. L. Shultz*, and *A. G. Sharkey*, Analytic. Chem. *28*, 926 (1956).

a) Influence of an Alkyl Substituent on the Course of Fragmentation

The C–C bonds in a branched saturated hydrocarbon are likewise approximately equal in strength. By fission of bonds at branching points, however, secondary and tertiary carbonium ions are formed. Because of the inductive electron donor effect of alkyl groups, a positive charge is better stabilized in such intermediates than in primary carbonium ions. For this reason, less energy is required to split branched saturated hydrocarbons than their straight-chain isomers. The molecular-ion peaks of branched hydrocarbons therefore exhibit a lower intensity than those of their straight-chain isomers (Fig. 4). The preferential splitting of bonds at branching points is demonstrated by the relatively high intensities of the peaks of ions formed by such reactions. However, it must be remembered that secondary decomposition reactions are less favored because of the greater stability of secondary and tertiary

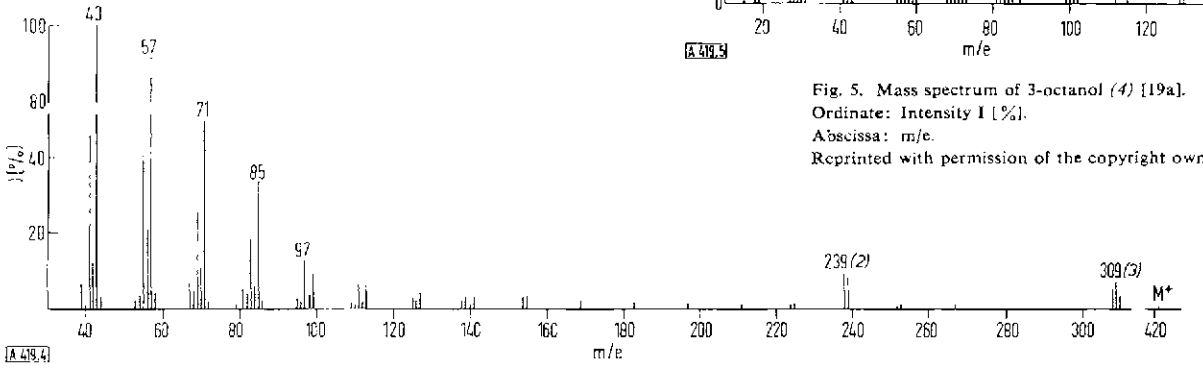


Fig. 4. Mass spectrum of 9-octyldocosane *(1)* (A.P.I. no. 866).
Ordinate: Intensity I [%].
Abscissa: m/e.

carbonium ions. It is therefore possible, in the absence of functional groups, to deduce the position of branching from the mass spectrum (Fig. 4). For example, 9-octyldocosane *(1)* is decomposed into the carbonium ions *(2)* and *(3)*.

$H_3C-(CH_2)_7-\overset{\oplus}{C}H-(CH_2)_{12}-CH_3$ *(3)*, mass number 309

$\overset{1}{\uparrow}\,{}^{-e}_{-H_3C-(CH_2)_7\cdot}$

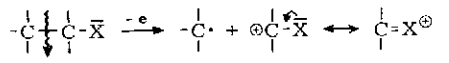
$H_3C-(CH_2)_7-\overset{1}{C}H-(CH_2)_{12}-CH_3$ *(1)*

$\overset{2}{\downarrow}\,{}^{-e}_{-H_3C-(CH_2)_{12}\cdot}$

$H_3C-(CH_2)_7-\overset{\oplus}{C}H-(CH_2)_7-CH_3$ *(2)*, mass number 239

b) The Influence of a Substituent Containing a Singly Bonded Hetero-Atom with a Lone Electron Pair

Functional groups containing a singly bonded hetero-atom with a lone pair of electrons (first-order substituents) have a much stronger effect on fragmentation than alkyl groups. Such compounds are cleaved with high probability at one of the C–C bonds adjacent to the hetero-atom, since in this way stabilized ions can be formed.



X = NH_2, NHR, NR_2, OH, OR, SH, SR, Halogen

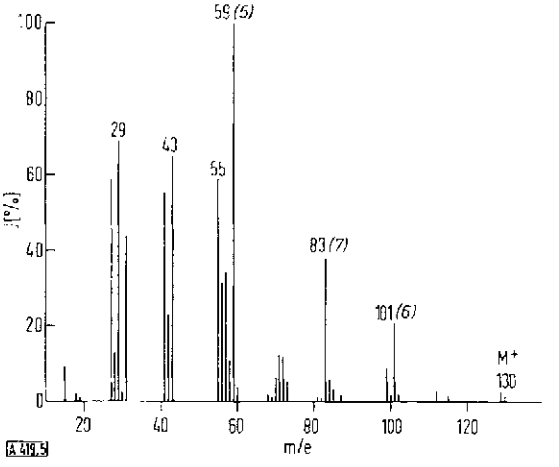


Fig. 5. Mass spectrum of 3-octanol *(4)* [19a].
Ordinate: Intensity I [%].
Abscissa: m/e.
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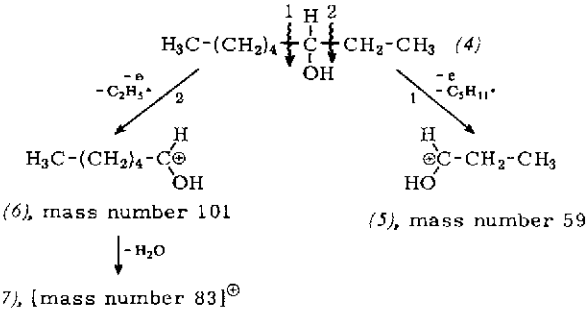
For example, the mass spectrum of 3-octanol *(4)* (Fig. 5) contains two characteristic fragments with mass numbers 59 *(5)* and 101 *(6)*, formed by cleavage of a C–C bond on either side of the functional group.



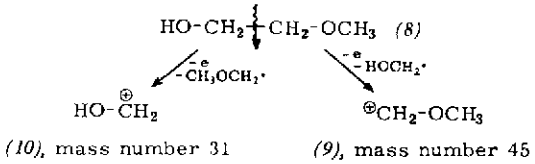
The low intensity of the peak of fragment *(6)* compared to that of fragment *(5)* can be attributed at least in part to the greater tendency of heavier ions to undergo further decomposition reactions. For example, *(6)* decomposes very readily to form *(7)* with the elimination of one molecule of water.

In general, molecular ions of alcohols and amines show a lower intensity than those of straight-chain saturated hydrocarbons with the same number of carbon atoms, in spite of the fact that ionization occurs more readily due to the lone pair of electrons at the hetero-atom. The reason is that the probability of decomposition of the molecular ions is greater (because of the high stability of the fragments $[>\overset{\oplus}{C}-X:]$) than their probability of

formation, so that the energy required to form the fragments is smaller than in the case of hydrocarbons.

An increase in the tendency of the hetero-atom to supply a negative charge to stabilize a positive charge on an adjacent carbon atom leads to increased fragmentation probability. The fragments of amines formed in such reactions therefore produce a much higher intensity in the mass spectrum than those of alcohols of comparable constitution. The ability of halogens to supply a negative charge is so small that such fissions are hardly ever observed, especially since the lower bond strength of the carbon-halogen bond (compared to that of the C–C bond) strongly favors release of the halogen over other possible decomposition reactions.

The ability to stabilize charges decreases from nitrogen to the halogens *via* sulfur and oxygen. It does not run parallel to the electronegativity [20] (which refers to the ease of displacement of the electrons of a σ-bond) but is a measure of nucleophilic properties (*i.e* of the availability of a lone π- or p-electron pair). Although bimolecular nucleophilic reactions in solution and monomolecular decomposition reactions in the gas phase (such as take place in the mass spectrometer) cannot be directly compared, it is in some cases possible to carry out comparative basicity measurements by mass spectrometry; for example in methoxyethanol *(8)* the negative charge density and hence the basicity of the ether oxygen is greater than that of the alcoholic hydroxy group because of the inductive electron-donating effect of the methyl group. When the compound is decomposed in the mass spectrometer, formation of fragment *(9)* is much more likely than that of *(10)* (Figure 6).



(10), mass number 31 *(9)*, mass number 45

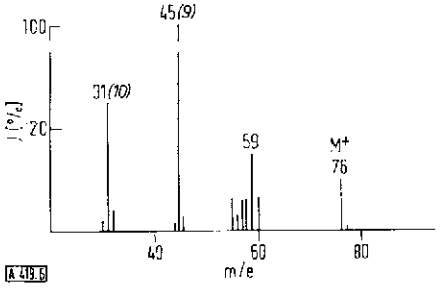


Fig. 6. Mass spectrum of methoxyethanol *(8)* taken with an Atlas CH-4 instrument; temperature of the TO-4 ion source approximately 50 °C.
Ordinate: Intensity I [%].
Abscissa: m/e.

A comparative determination of basicity by mass spectrometry has the advantage over wet chemical processes that interfering effects of the solvent are eliminated. For example, tertiary amines in aqueous solution exhibit a lower basicity than secondary ones, although an increase could be expected from the additional alkyl group and the consequent increase of electron density on the nitrogen [21]. The decrease actually observed is due entirely to the water, since with chloroform as solvent the basicity rises on passing from secondary to tertiary amines. Similarly, mass-spectrometric studies show that tertiary amines [$>\overset{\oplus}{C}-\ddot{N}R_2$] form fragments much more frequently than secondary [$>C-\overset{\oplus}{\ddot{N}}HR$] or primary [$>\overset{\oplus}{C}-\ddot{N}H_2$] ones [22].

[20] Cf. [7b], p. 88.

2. *Multiple Bond Cleavage*

So far we have considered only the stability of positively charged fragments. No allowance has been made for the simultaneously formation of uncharged particles. Since however the total energy balance determines the course of a decomposition reaction, this consideration is valid only when fissions are compared in which particles of roughly equal stability are formed, *e.g.* alkyl radicals. Very often, neutral molecules may be split off during decomposition reactions. They are much more stable than radicals and therefore can no longer be disregarded.

Uncharged particles, *i.e.* neutral molecules and radicals, cannot be observed directly in the mass spectrum, but their mass can be obtained from the mass difference between peaks of positively charged ions. For example, a mass difference of 28 could be due to the loss of a molecule of carbon monoxide or one of ethylene.

A decision whether a neutral molecule or a radical has been eliminated can readily be made in many cases; compounds which consist only of C, H and O must have an even-numbered molecular weight. If a radical is eliminated from such a compound by single bond cleavage, an ion of odd mass number is formed, and the difference in mass between the molecular ion and the fragment must likewise be an odd number. In contrast, release of a neutral molecule from such a compound can be recognized by an even difference in mass. The formation of a neutral molecule from nitrogen-containing compounds, which do not necessarily possess an even-numbered molecular weight, cannot be so easily recognized from their mass spectra, since nitrogen-containing neutral molecules of uneven mass as well as nitrogen-free neutral molecules of even mass or with an even number of nitrogen atoms can be eliminated.

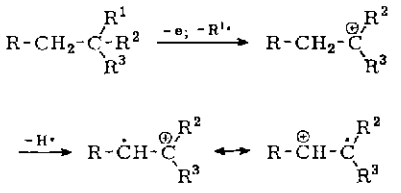
a) Multistage Decomposition Reactions

Uncharged particles, *e.g.* H_2O, CH_3, and CO, are generally eliminated in stages. Normally, almost any number of stable neutral molecules but only a single radical can be eliminated. Multiple homolytic bond cleavage would lead to radical-ions of low stability, so that such processes do not occur for energetic reasons if other fissions can take place. Although this rule is not always valid, its application may frequently help to exclude erroneous interpretations of fission mechanisms. For example, a mass difference of 30 might be interpreted as the loss of two methyl groups, but much more likely represents the release of one molecule of CH_2O or NO.

[21] *H. A. Staab*: Einführung in die theoretische organische Chemie. 2nd Edit., Verlag Chemie, Weinheim, 1960, p. 631, where further references are given.

[22] *L. Dolejš, V. Hanuš, V. Černý*, and *F. Šorm*, Collect. czechoslov. chem. Commun. *28*, 1586 (1963); *N. Neuner-Jehle, H. Nesvadba*, and *G. Spiteller*, Mh. Chem. *95*, 687 (1964); Cf. [8b], p. 77; [8c], p. 167.

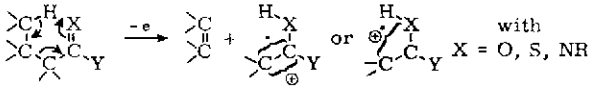
An exception to this rule is, for example, the decomposition of an ion which is formed by the homolytic fission of a saturated, branched hydrocarbon at the branching point.



This ion decomposes with the elimination of a hydrogen radical from one of the CH groups adjacent to the positive charge center, as the radical cation formed is more stable than the primary ion (see Figure 4).

b) Rearrangement Reactions

McLafferty [23] was the first to show that neutral molecules are frequently split off during rearrangement reactions, *via* a six-centered intermediate. For example, the elimination of an olefin is characteristic for compounds containing a double bond and a γ-CH group. If X = O, S, or NR, the free p-electrons may contribute considerably to the stabilization of the rearranged fragment.



X = CH_2, CHR, O, S, NR
Y = H, R, OR, OH, NH_2

The positive charge may reside in the olefin or in the rearranged fragment, depending on the degree of stabilization. In the mass spectra of aliphatic carboxylic acids (X = O, Y = OH), for example n-butyric acid [23a], the rearranged fragment has a mass number of 60. The intensity of the peak of the rearranged fragment is particularly marked in the case of low-molecular compounds

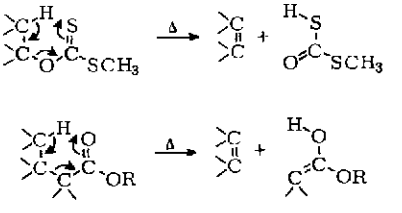
The exclusive participation of γ-hydrogen atoms in the rearrangement reaction was demonstrated by using a carboxylic acid in which the CH_2 groups had been successively replaced by CD_2 groups. While in the mass spectrum of the α-labelled compound the rearranged fragment had the mass number 62, a fragment of mass number 60 occurred in the case of the β-labelled compound, and the spectrum of the γ-labelled compound showed the rearrangement peak at mass number 61. It was concluded that the rearranged fragment contains the α-CH_2 group and one γ-H atom [24], in agreement with *McLafferty*'s postulate [23].

The labelling of carbon atoms in a molecule by hydrogen-deuterium exchange [25] is frequently used in mass spectrometry to explore decomposition mechanisms. However, a particular hydrogen atom is not always shifted to a precisely defined site in the molecule, as in the above-mentioned McLafferty rearrangement (which, for this reason, is designated as a "specific" rearrangement [23]). It is frequently observed that labelled atoms are more or less uniformly distributed over all the fission fragments. Such "random rearrangements", which occur predominantly in hydrocarbons, generally lead to fragments of low peak intensities and are often only of secondary importance in the interpretation of a spectrum.

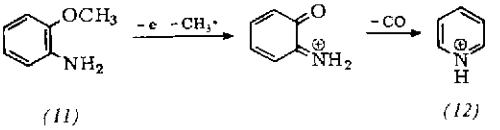
While the origin of the hydrogen atom in the McLafferty rearrangement has been clarified, there is still no agreement as to whether the hydrogen migrates in the form of a radical [8b, 8c] or as a proton [26]. A proton migration is supported by the fact that an increase in electron density at the atom X facilitates the reaction. The rearrangement probability decreases in the order X = NR > O > CH_2.

The main argument for a radical migration comes from measurements of the ionization potentials of simple molecules, which indicate that the positive charge of the molecule-ion is located at the atom X. This argument, however, does not appear to be conclusive, since no allowance has been made for the fact that in recording mass spectra of organic compounds the electron energy is not maintained in the region of the ionizing potential but at 70 eV, so that initially any electron can be eliminated from the molecule. In addition, it has been demonstrated that the course of the rearrangement is independent of the site of the positive charge [26].

The "McLafferty rearragement", which in many cases strongly influences the decomposition of compounds with second-order substituents, finds parallels in certain chemical decomposition reactions, for example in the preparation of olefins by *Tschugaeff*'s method or in the thermal decomposition of esters.



Other decomposition processes occurring in the mass spectrometer cannot be compared with chemical reactions and cannot be interpreted by a simple displacement of pairs of electrons. One example is the decomposition of *o*-anisidine *(11)*. Here the mass spectrum shows that the molecular ion releases a methyl group and then decomposes to form a pyridinium ion *(12)* with the elimination of one molecule of CO [27]. These fission products have a particularly low energy content, so that alternative fragmentation routes



(11) *(12)*

[23] *F. W. McLafferty*, Analytic. Chem. *31*, 82 (1959).
[23a] *G. P. Happ* and *D. W. Stewart*, J. Amer. chem. Soc. *74*, 4404 (1952).
[24] *Ng. Dinh-Nguyen, R. Ryhage, S. Ställberg-Stenhagen*, and *E. Stenhagen*, Arkiv Kemi *18*, 393 (1961).
[25] For a review, see [8c], Chapter 2.
[26] *G. Spiteller* and *M. Spiteller-Friedmann*, Mh. Chem. *95*, 257 (1964).
[27] *G. Spiteller* and *M. Spiteller-Friedmann*, Mh. Chem. *93*, 1395 (1962).

are not available in this and similar decomposition reactions [28] because of the stability of the original compound.

c) Decomposition Reactions which Proceed via Radical Ions

The interpretation of the cleavage of alicyclic compounds is appreciably more difficult. Except when fragments are formed by hydrogen abstraction, at least two carbon-carbon bonds must be broken, and naturally more energy is required for this purpose than for the rupture of a single bond. Therefore, the molecular-ion peaks of unsubstituted alicyclic compounds are much more intense than those of open-chain saturated compounds with the same number of carbon atoms (Fig. 7).

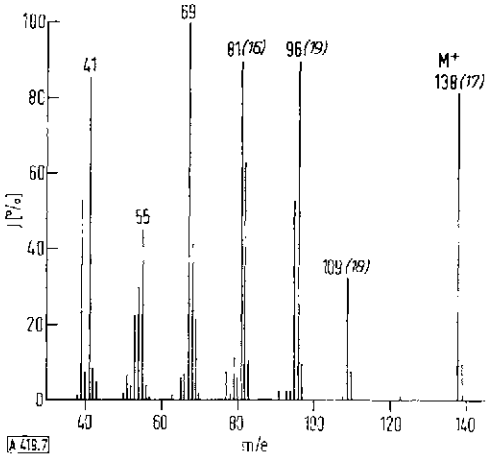


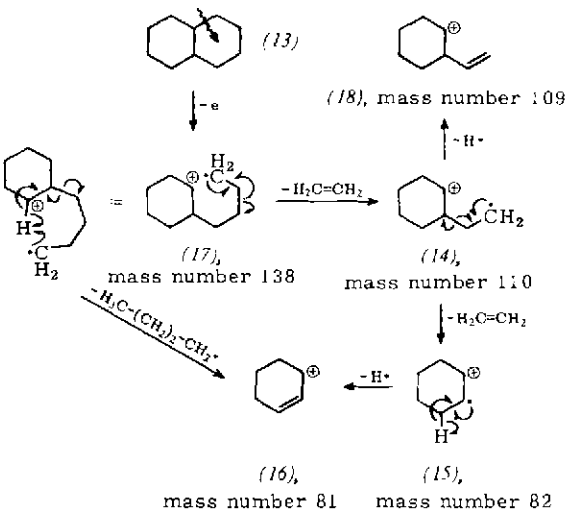
Fig. 7. Mass spectrum of *cis*-decalin *(13)* (A.P.I. no. 992).
Ordinate: Intensity I [%].
Abscissa: m/e.

As the mass spectrum of *cis*-decalin *(13)* shows, alicyclic hydrocarbons decompose to give numerous fragments which are, however, not particularly characteristic. Their formation can proceed along various routes, so that relationships between structure and mass spectrum are not readily apparent. The primary cleavage occurs preferentially at a ring junction; in this way relatively stable carbonium ions can be formed. The primary decomposition product is a radical ion *(17)* in which the center of positive charge is separated from the radical site by several saturated carbon atoms; stabilization of the decomposition product is therefore insignificant. Formation of such radical ions makes the decomposition of alicyclic hydrocarbons fundamentally different from that of aliphatic hydrocarbons, which form simple ions.

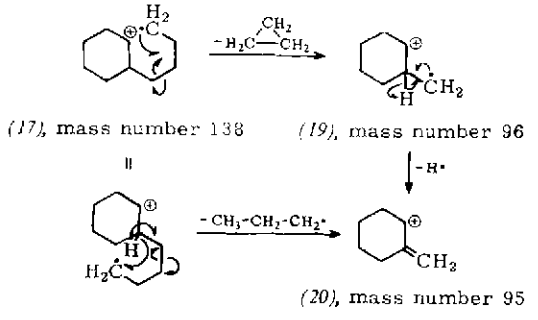
For the decomposition of such radical ions, the radical character of the particles appears to be of decisive significance. The elimination of one molecule of ethylene from *(17)* [29] leads to the formation of the radical ion *(14)* with mass 110, which can decompose further with the elimination of a hydrogen atom or a molecule of ethylene. The fragment *(15)* formed by the twofold elimination of ethylene can be stabilized by the loss of a hydrogen radical to form an allyl cation *(16)* with mass 81.

[28] *J. H. Beynon, G. R. Lester*, and *A. E. Williams*, J. physic. Chem. *31*, 1861 (1959).

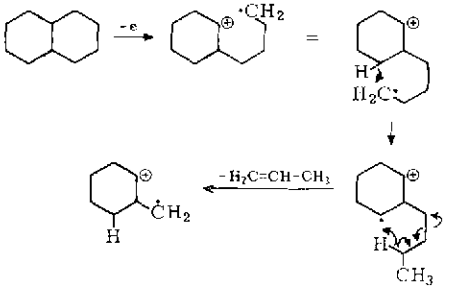
[29] Following a suggestion of *Budzikiewicz, Djerassi*, and *Williams* [8b], the displacement of a pair of electrons is symbolized by an arrow and that of a single electron by a small hook. However, unlike these authors, we are indicating each electron to avoid errors.



The decomposition of the primary fission product *(17)* by elimination of a butyl radical in the course of rearrangement may explain the formation of *(16)* in a different manner. Probably, both reactions occur simultaneously. The loss of one molecule of cyclopropane from *(17)* leads to an ion *(19)* from which, once again, a hydrogen atom can be eliminated. However, fragment *(20)* can also be formed in a single step from *(17)* by rearrangement.



In analogy with observations by *N. Neuner-Jehle* with quinolizidines, it seems that C_3H_6 can also be eliminated as propylene in the course of a twofold hydrogen shift:



Although the formation of only a small proportion of the fragments appearing in the spectrum of *cis*-decalin has thus been interpreted, and only a few ways of formation of the individual ions have been discussed, this example does show the many possible decomposition reactions of cyclic compounds and hence the difficulties encountered in the interpretation of their spectra. If functional groups are present, however, they may exert a specific influence on the mode of fragmentation.

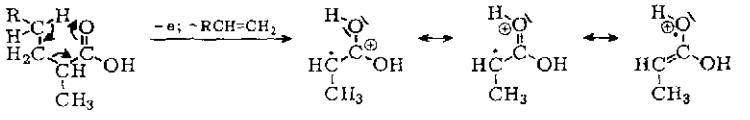
III. General Rules for the Interpretation of Mass Spectra

A. The Formation of Key Fragments

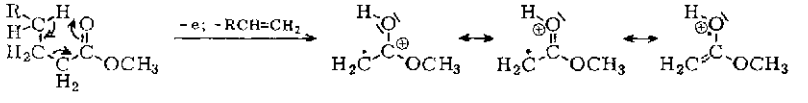
The rules derived so far for the decomposition of organic molecules in the mass spectrometer allow us to formulate some principles governing the interpretation of mass spectra.

A relationship between the structure and the mass spectrum of a compound will be apparent if some decomposition reactions require much less energy than all others, so that spectra are formed which contain few, but intense peaks. Such characteristic peaks frequently represent the key to the elucidation of the structure of an unknown compound, and may be designated as peaks of "key fragments".

Key fragments differ from others which occur in nearly every spectrum by their particularly high intensity and/or their unusual mass number. For example, an ion of mass number 41, in general an allyl cation, cannot be designated as a key fragment since, owing to its great stability, it arises from many organic compounds with different structures. The same is true for other hydrocarbon fragments unless their peaks are distinguished by abnormally high intensities (see Fig. 4).



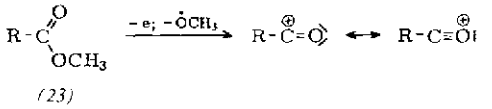
(21) mass number 74



(22) mass number 74

It is self-evident that a single key fragment is not sufficient to postulate the existence of a certain group in the compound studied, since ions of the same empirical formula may have different structures. For example, the spectra of α-methylcarboxylic acids *(21)* and of unbranched methyl esters *(22)* show a key fragment with mass number 74, which in both cases is formed in the course of a McLafferty rearrangement.

However, in simple methyl esters *(23)*, release of an $\cdot OCH_3$ radical is also favored, since a stable ion can be formed in this manner, too. Consequently, the spectra of simple methyl esters exhibit a fragment with mass number M minus 31 (M = molecular ion) corresponding to the loss of a methoxyl radical, in addition to the rearrangement fragment with mass number 74. On the other hand, carboxylic acids cannot yield fragments of 31 mass units (M.U.), provided that substituents



(23)

such as CH_2OH are absent, since to achieve this both an OH group and a CH_2 group (in the form of a carbene) must be eliminated, which is impossible for energetic reasons. The simultaneous presence of peaks at mass numbers 74 and M minus 31 therefore indicates a methyl ester rather than an α-methylcarboxylic acid.

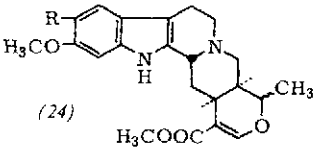
While individual key fragments normally indicate only the group to which a compound belongs, they may provide conclusive evidence of the presence of certain structural elements when taken together. Hence they can make a substantial contribution to the elucidation of the structure of an unknown compound.

Key fragments are formed above all from compounds containing basic nitrogen atoms or aromatic ring systems, since stabilized ions can be derived from these with particular ease. It is therefore not surprising to find, for example, that in alkaloid chemistry mass spectrometry has been widely employed to determine structures.

B. Spectrum-Comparison Technique

The use of mass spectrometry in the elucidation of alkaloid structures depends to a significant extent on the ability of many plants to produce several alkaloids which differ only by the presence or absence of functional groups but contain the same carbon skeleton. If these functional groups do not substantially influence the course of fragmentation, then the same main cleavage reactions ensue on decomposition of all these alkaloids in the mass spectrometer. According to the masses and positions of the substituents, the positions of the key-fragment peaks differ merely by a certain number of mass units, so that the carbon skeleton can be identified simply by comparison of the spectra (Figure 8). For example, the positions of the key-fragment peaks of isoreserpinine *(24a)* and reserpiline *(24b)* differ by 30 mass units (1 CH_3O minus 1 H).

This spectrum-comparison technique was initially used by *Biemann* [30]. It permits a structure determination only when spectra of compounds with known structure



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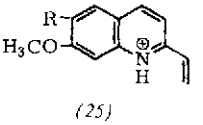

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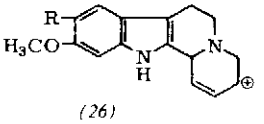
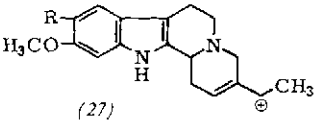


(26)



(27)

(a): R = H; *(b)*: R = OCH_3

are available for comparison, or when the key fragments give some indication of the groups present so that reference compounds can be selected.

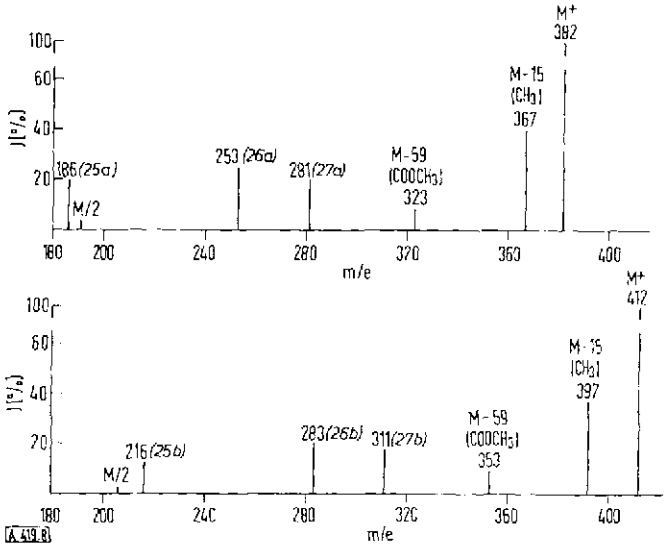


Fig. 8. Mass spectra of isoreserpinine *(24a)* (top) and reserpiline *(24b)* (bottom), both taken with the Atlas CH-4 mass spectrometer; temperature of the ion source approximately 120 °C. Only key fragments are shown.

Ordinate: Intensity I [%].

Abscissa: m/e.

IV. Combination of Chemical and Mass-Spectrometric Decomposition Reactions

Even when a structure cannot be derived directly, *e.g.* for lack of reference material, the mass spectrum almost invariably gives some indication of the structural elements present. These indications can be confirmed or disproved by chemical degradation reactions. Samples of 2–5 mg are sufficient when the reaction products are also studied by mass spectrometry. Their purification is generally unnecessary, since impurities do not adversely affect the recognition of the usually intense key-fragment peaks, although they do increase the number of low-intensity peaks. In addition, volatile constituents originating from impurities can be removed within the ion source by gradual heating.

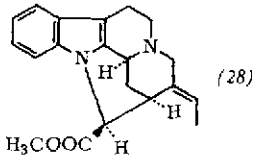
Frequently, the course of a reaction can be deduced merely from the change in molecular weight. Simple chemical reactions frequently alter the basicity of key atoms and thus influence the course of fragment formation in such a way that the spectra exhibit characteristic cleavage products first for one and then for the other part of the molecule.

A. Elucidation of the Structure of Pleiocarpamine

The structure of the alkaloid pleiocarpamine *(28)* was determined by combining small-scale chemical reactions with mass spectrometry and NMR measurements [31]. Elementary analysis gave the empirical formula $C_{21}H_{24}O_2N_2$ and showed the presence of OCH_3 and $C{-}CH_3$ groups as well as the absence of an $N{-}CH_3$ group [32]. Its ultraviolet spectrum indicated the presence of a methoxyindole chromophore and the infrared spectrum the absence of NH and OH groups as well as the presence (possibly) of a five-membered cyclic ketone [32]. The NMR spectrum showed an ethylidene side-chain, and methylation revealed that the second nitrogen atom also was tertiary [32].

The small amount of substance available made the elucidation of structure by chemical means very difficult, and resort was made to mass spectrometry.

The mass spectrum of pleiocarpamine *(28)* (Fig. 9) contained the molecular-ion peak at mass number 322. This led to a correction of the empirical formula from $C_{21}H_{24}O_2N_2$ to $C_{20}H_{22}O_2N_2$ [31]. A key fragment at mass number 263 corresponded to the loss of a particle with mass 59, presumably a methoxycarbonyl group.



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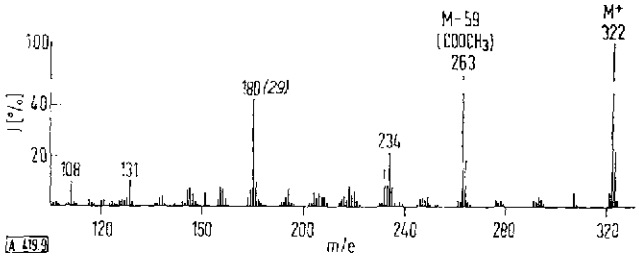


Fig. 9. Mass spectrum of pleiocarpamine *(28)* [31].

Ordinate: Intensity I [%].

Abscissa: m/e.

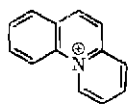
This finding was in contradiction to previous results [32] but could be confirmed by a reinterpretation of the infrared and ultraviolet spectra. In order to fully clarify this point, pleiocarpamine was reduced with $LiAlH_4$, giving a product with a molecular weight of 294 (determined by mass spectrometry). This corresponds to the loss in mass accompanying the reduction of a $COOCH_3$ group to a CH_2OH group (28 M.U.). At the same time, the unchanged position of the key fragment at mass number 263 demonstrated that a CH_2OH group had been eliminated in place of a $COOCH_3$ group. In this way the presence not only of a methoxycarbonyl group in pleiocarpamine was demonstrated, but also that of an unsubstituted indole chromophore, since the molecule could not contain more than two oxygen atoms.

The structure of the important key fragment with mass number 180 in the spectrum of pleiocarpamine was elucidated in the following manner. Since this ion is formed not only from pleiocarpamine but also from the product of reduction with $LiAlH_4$, it could not contain the functional group, since in this case replacement of $COOCH_3$ by CH_2OH would have caused a displacement of the peak by 28 mass units. Removal of parts of the stable indole system is impossible for energetic reasons. A fragment which is formed by loss of both the functional group (59 mass units) and the indole part (115 mass units) from pleiocarpamine (molecular weight 322) will have a maximum molecular weight of $322 - (59 + 115) = 148$. Since the key fragment had a molecular weight of 180, it must still contain the indole system, and so the only possible empirical formula for the fragment with molecular weight 180 is $C_{13}H_{10}N$. If in addition it is considered that the indole nitrogen is substituted, then this ion must be a quinolinium ion (rearrangements of 3-substituted indoles to quinolinium ions are frequently observed in mass-spectrometric decomposition reactions).

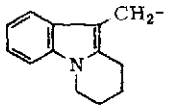
[30] *K. Biemann*, Tetrahedron Letters *1960*, No. 15, 9.

[31] *M. Hesse, W. v. Philipsborn, D. Schumann, G. Spiteller, M. Spiteller-Friedmann, W. I. Taylor, H. Schmid*, and *P. Karrer*, Helv. chim. Acta *47*, 878 (1964).

[32] *W. G. Kump* and *H. Schmid*, Helv. chim. Acta *44*, 1503 (1961).



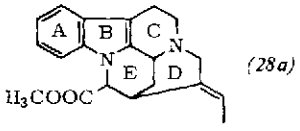
(29), mass number 180



(30)

These findings suggested a six-membered ring [structure *(30)*] which links the indole nitrogen with the neighboring carbon-atom.

These results together with evidence obtained from spectra and chemical decomposition reactions, led *Schmid* et al. to postulate a provisional structural formula *(28a)* for pleiocarpamine [31].



(28a)

This formula has been confirmed by a detailed analysis of the 100 Mc ^1H-NMR spectrum and by a combined chemical and mass-spectrometric degradation in which many of the reaction products were not characterized by elementary analysis but by their mass spectra.

The mass spectrum of pleiocarpamine (Fig. 9) contains no fragments indicating the presence of a piperidine ring. Evidently such fragments are absent because stabilization of a positive charge is far better in the indole system than in the piperidine part of the molecule. Reduction of the indole to the indoline system greatly reduces stabilization of the positive charge in the aromatic part of the molecule, so that the mass spectrum of dihydropleiocarpamine *(31)* (Fig. 10) is entirely different.

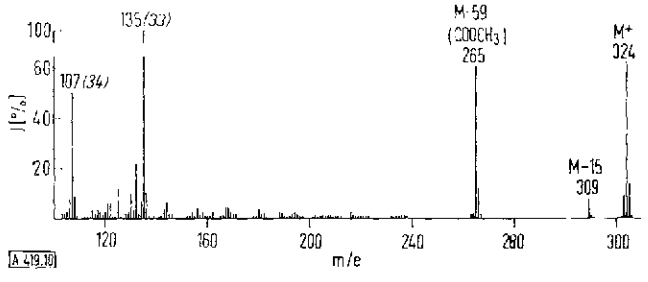
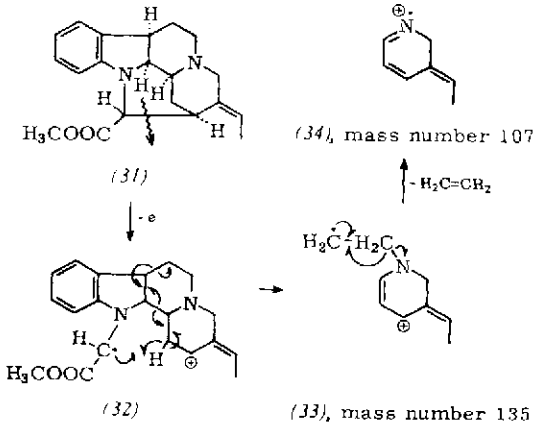


Fig. 10. Mass spectrum of 2,7-dihydropleiocarpamine *(31)* [31].
Ordinate: Intensity I [%].
Abscissa: m/e.

During decomposition of the dihydro derivative *(31)*, an allyl cation *(32)* seems to be formed initially, which then undergoes rearrangement with displacement of a hydrogen radical to form the key fragment *(33)*. The elimination of one molecule of ethylene from *(33)* finally leads to formation of the fragment *(34)*.

In this way, the existence of a tryptamine bridge linking the piperidine part with the indole ring was made probable in addition to the presence of a piperidine ring. Besides, the decomposition reaction indicated that the methoxycarbonyl group must be located in ring E.



V. Elucidation of the Structures of Compounds in Mixtures without Isolation of the Components

Isolation in pure form is not always necessary for the mass-spectrometric elucidation of the structure of an unknown compound. By fractional evaporation of the sample into the reservoir of the mass spectrometer [7a] or better by continuous gradual volatilization of the substance in the ion source, a mixture of substances can be partly or even completely separated. From the alterations in the intensities of ion peaks it is then possible to recognize which fragments are formed from the components of the mixture.

In mixtures of very similar compounds, it is possible under certain conditions to derive the structures of the individual components (without isolation of pure substances) by chemical reactions on a microscale followed by a mass-spectrometric study of the mixture of reaction products. One example is the structural elucidation of eight alkaloids from only 30 mg of material [33].

VI. Summary

The principal rules governing the fragmentation of organic compounds in the mass spectrometer have been discussed; whether a mass spectrum can be successfully interpreted depends to a large extent on the magnitude of the energy difference between the possible decomposition paths of the compound studied. In general, spectra characterized by the presence of few key fragments can be expected only from compounds which decompose preferentially in a few directions. This is the case when stable fragments can be formed, as in the decomposition of aromatic or heterocyclic derivatives or of compounds with substituents releasing negatively charged portions, since in all these substances a positive charge may become stabilized.

Simple chemical reactions alter the ability of various substituents to stabilize charges. Thus the course of mass-spectrometric degradations can be varied to some extent, with consequent formation of key fragments from either one or the other part of a molecule.

A particular advantage is that all reactions can be carried out on a microscale, since impurities usually do not interfere with the subsequent mass-spectrometric investigation of the reaction products.

We should like to thank Prof. F. Wessely and our collaborators R. Kaschnitz, N. Neuner-Jehle, and Dr. S. Eggers for numerous stimulating discussions and the Österreichischer Forschungsrat for the provision of a mass spectrometer.

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Translated by Express Translation Service, London

[33] *G. Spiteller* and *M. Spiteller-Friedmann*, Mh. Chem. *94*, 779 (1963); Ind. chim. belge *29*, 357 (1964).

Sequence Distribution in Copolymers

Chemical Studies [*]

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Various chemical procedures are available for studying the sequence distribution in copolymers, but none can be applied routinely. The run-number approach permits the results of such studies to be treated with ease; all results obtained to date are consistent with classical copolymerization theory.

A. Introduction

Copolymerization of two monomers can lead to a variety of copolymers differing in composition and in the arrangement of the monomer units. The monomer units may be randomly distributed, may tend to alternate, or may tend to cluster in blocks of like units.

	~~ABAABBAABB~~~	Random type
A + B →	~~~ABABABABAB~~~	Alternating type
	~~AAAAABBBBB~~~	Block type

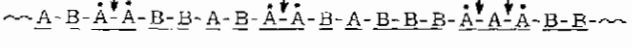
Knowledge of the composition and sequence distribution [1–3] of copolymers is necessary for investigating copolymerization mechanisms and the properties of copolymers. Unfortunately, only information on copolymer composition is easy to obtain.

Chemical studies on sequence distribution in copolymers will be reviewed here, physical approaches will be discussed in a later article. Studies on the characterization of tacticity in homopolymers will be mentioned only when they involve techniques which can be applied to determine the sequence distribution in copolymers as well.

B. Theory and Principles Governing the Determination of Sequence Distribution

In principle, the experimental determination of the sequence distribution in copolymers is very simple. It is only necessary to determine the extent of any single recurring structural feature. In most chemical approaches the percentage of A–A, A–B, or B–B linkages is determined, whereas most physical or spectroscopic approaches yield the percentage of A or B units present in the middle of various triads, pentads, or heptads. For example, in copolymer *(1)*, the percentage of A–A linkages (indicated by arrows) or the fraction of A units in the middle of triads of the type A–A–B (indicated by asterisks) might be determined.

The results obtained by various approaches can be compared using the concept of run numbers [4]. The run number R of a copolymer is defined as the average number of uninterrupted monomer sequences (or runs) which occur in a copolymer chain per 100 monomer units. There are twelve runs (underlined) in the twenty-unit copolymer *(1)*; this chain therefore has a run number of 60 (*i.e.* 12 runs/20 monomer units = 60/100).



(1)

Equations (a)–(f) are examples relating the run number R to the molar composition of the copolymer (% A and % B) and to measurable aspects of the copolymer structure. The symbol f in Equations (d)–(f) denotes the fraction of A monomers to be found in the middle of the triads AAA, BAA (and AAB), and BAB.

% A–B linkages (including B–A linkages)	R	(a)
% A–A linkages	$-\%\ A\ (R/2)$	(b)
% B–B linkages	$-\%\ B\ (R/2)$	(c)
AAA triads (f_{AAA})	$\frac{[\%\ A-(R/2)]^2}{(\%\ A)^2}$	(d)
BAA (and AAB) triads (f_{BAA})	$\frac{R[\%\ A-(R/2)]}{(\%\ A)^2}$	(e)
BAB triads (f_{BAB})	$\frac{R^2}{4(\%\ A)^2}$	(f)

These expressions, in conjunction with analogous expressions for B-centered triads, will usually be adequate for most sequence-distribution studies; however, sometimes A or B units in pentads or larger sequences must be considered. Equation (g) expresses the fraction f of A monomers in the middle of the pentad ABABA.

$$f^{*}_{ABABA} \quad \frac{R^2}{4(\%\ A)^2} \quad \frac{R^2}{4(\%\ B)^2} \quad \frac{R^4}{16(\%\ A)^2(\%\ B)^2} \qquad (g)$$

In general, the extent of any measurable feature of the copolymer structure that is related to sequence distribution can be expressed as a function of the run number R and the composition of the copolymer.

[*] An article on physical investigations of the sequence distribution in copolymers will appear shortly in this journal.

[1] *E. Merz, T. Alfrey*, and *G. Goldfinger*, J. Polymer Sci. *1*, 75 (1946).

[2] *T. Alfrey* and *G. Goldfinger*, J. chem. Physics *12*, 205 (1944).

[3] *F. T. Wall*, J. Amer. chem. Soc. *66*, 2050 (1944).

[4] *H. J. Harwood* and *W. M. Ritchey*, Polymer Letters *2*, 601 (1964).

Run numbers R can also be predicted for copolymers when the mechanism of polymerization is known. For example, Equation (h) expresses the run number of a copolymer with a random structure.

$$R_{random} \quad \frac{2\,(\%\ A)\,(\%\ B)}{100} \qquad (h)$$

Run numbers for vinyl copolymers may be predicted from monomer reactivity ratios (r_A and r_B) and the molar percentages of monomers (A_x and B_x) in the polymerization mixtures using Equation (i).

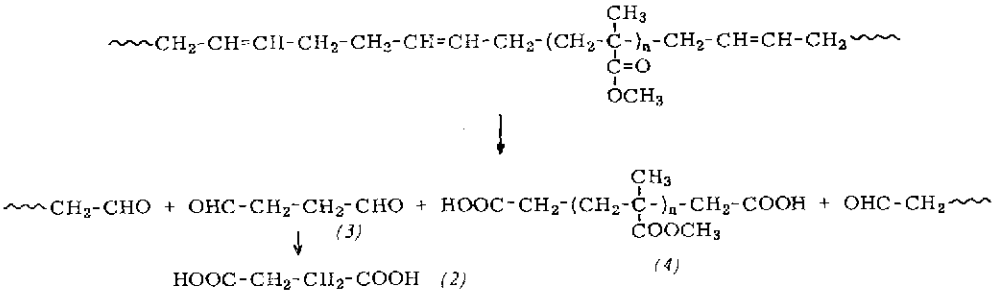
$$R \quad \frac{200}{2 + r_A A_x/B_x + r_B B_x/A_x} \qquad (i)$$

Many theoretical treatments of tacticity and sequence distribution have been published [1–3, 5–12], and methods [13] or parameters [5–8] for characterizing such distributions have been proposed. However, the run-number approach is used exclusively in this review.

C. Chemical Methods for Determining Sequence Distributions

1. Oxidative Degradation

In one of the earliest studies on copolymer structure, *Hill, Lewis,* and *Simonsen* [14] investigated the ozonolysis of a 50:50 butadiene (B)/methyl methacrylate (M) copolymer. The principal products were succinic acid *(2)*, succindialdehyde *(3)*, and dicarboxylic acids containing several methyl methacrylate residues *(4)*, [isolated as their methyl esters].

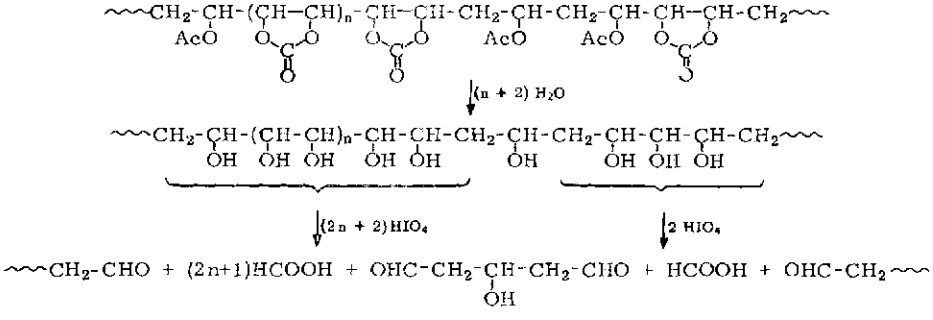


The percentage of butadiene (9.2%) recovered as succinic acid and succindialdehyde provided a measure of the 1,4-butadiene-1,4-butadiene linkages in the copolymers, and the percentage of methyl methacrylate units (> 51%) recovered as trimethyl 2-methylbutane-1,2,4-tricarboxylate *(4)*, n = 1, provided a measure of the methyl methacrylate units in the middle of BMB triads. Applying these results, the run number of the copolymer is found to be between 71 [value obtained from the content of methylbutane tricarboxylate using Equation (f)] and 91 [value obtained from the content of succinic acid and succindialdehyde using Equation (b)].

These values are considerably larger than the value of 50 expected for a random 50:50 copolymer. This work provided the earliest chemical evidence for the strong alternation tendency exhibited by many vinyl copolymerization systems.

Marder and *Schuerch* [15] utilized another procedure of selective oxidation for studying the sequence distribution of hydrolysed vinyl acetate/vinylene carbonate copolymers. The hydrolysed copolymers were degraded with periodic acid, and the amount of formic acid produced was measured. Here, the amount of periodic acid consumed (M_{HIO_4}) should provide a measure of copolymer composition, and comparison of this with the amount of formic acid liberated (M_{HCOOH}) should indicate the number of vinylene glycol sequences present. The run number of a copolymer is related to these quantities and the molar percentage of vinylene glycol

$$R \quad 4 \cdot \%\ VG \cdot (1 - M_{HOOCH}/M_{HIO_4}) \qquad (k)$$



[5] *B. D. Coleman*, J. Polymer Sci. *31*, 155 (1958).

[6] *R. L. Miller* and *L. E. Nielsen*, J. Polymer Sci. *46*, 303 (1960).

[7] *G. Natta, G. Mazzanti, A. Valvassori, G. Sartori,* and *D. Morero*, Chem. e Ind. *42 (2)*, 125 (1960).

[8] *A. Miyake* and *R. Chujo*, J. Polymer Sci. *46*, 163 (1960).

[9] *L. Peller*, J. chem. Physics *36*, 2976 (1962).

[10] *F. P. Price*, J. chem. Physics *36*, 209 (1962).

[11] *B. D. Coleman* and *T. G. Fox*, J. Polymer Sci. *A 1*, 3183 (1963).

[12] *W. Ring*, Polymer Letters *1*, 323 (1963).

[13] *S. Igarashi*, Polymer Letters *1*, 359 (1963).

[14] *R. Hill, J. R. Lewis,* and *J. L. Simonsen*, Trans. Farad. Soc. *35*, 1073 (1939).

[15] *H. L. Marder* and *C. Schuerch*, J. Polymer Sci. *44*, 129 (1960).

(%VG) present according to Equation (k). Unfortunately, products formed by oxidation of the polymer also consumed periodic acid and liberated formic acid. *Marder* and *Schuerch* managed to predict the approximate amount of overoxidation. In Table 1, the experimentally determined M_{HCOOH}/M_{HIO_4} ratios are compared with those predicted from calculated sequence distributions, taking the effects of overoxidation into account.

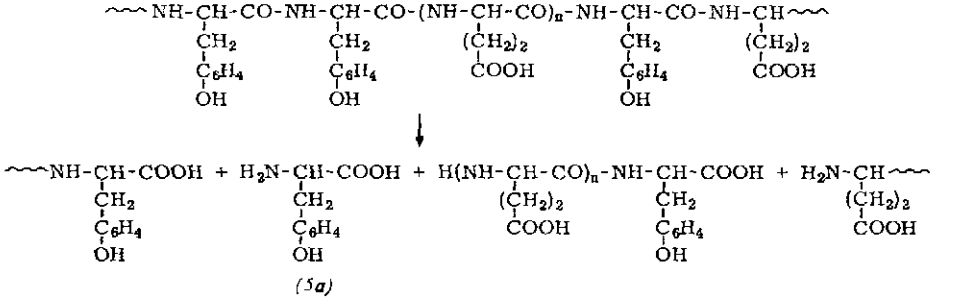
Table 1. Degradation of hydrolyzed vinylene carbonate-vinyl acetate copolymers with periodic acid [15] [a].

VG in copolymer [mole %]	M_{HIO_4} [moles/g] × 10^3		M_{HCOOH} [moles/g] × 10^3		M_{HCOOH}/M_{HIO_4}	
	calc.	obs.	calc.	obs.	calc.	obs.
30.0	22	18	11.8	8.7	0.54	0.49
25.7	17.5	15	9.3	7.8	0.53	0.51
20.9	13.3	13	7.0	5.6	0.52	0.43

[a] VG = vinylene glycol; M = amount.

2. Enzymatic Degradation

Kanakkanatt [16] investigated the degradation of L-glutamic acid/L-tyrosine copolymers with chymotrypsin. Chymotrypsin effects selective hydrolysis of *C*-tyrosyl peptide linkages in the copolymers, so that free tyrosine and a series of glutamic acid peptides containing *C*-tyrosine end groups are formed during hydrolysis. The amount of free tyrosine *(5a)* obtained provides a measure of the number of tyrosine-tyrosine linkages present in the copolymers. The fraction F of tyrosine which was



(5a)

recovered as free tyrosine was related in a simple manner to the run number R and the molar percentage of tyrosine %T in the copolymer (cf. Equation b).

$$\%\ \text{T–T linkages} = F\ \%\ T + \%\ T - (R/2) \qquad (l)$$

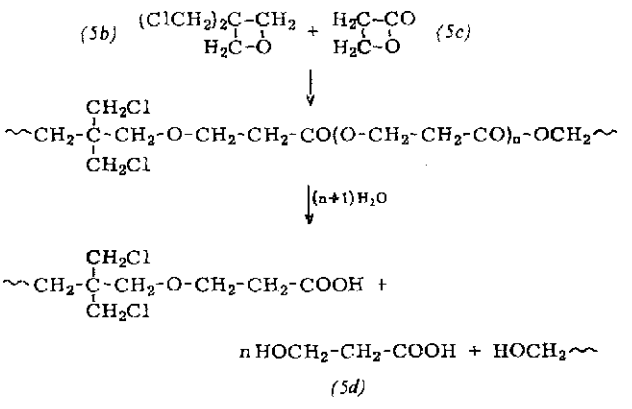
$$F = 1 - [R/(2 \cdot \%\ T)]$$

Kanakkanatt studied the degradation of a supposedly random 5:95 L-tyrosine/L-glutamic acid copolymer. Since R_{random} for such a copolymer would be 9.5, only a very small fraction (F = 0.05) of the tyrosine in the copolymer was expected to be liberated by digestion with chymotrypsin. However, tyrosine was recovered from the hydrolysis mixture in over 90% yield, and dialysis of the hydrolysate afforded high molecular-weight poly-L-glutamic acid in 53% yield. These results indicate that the copolymer was block-polyblend in structure, and did not have the random structure expected. Consequently, current ideas about the copolymerization behavior of *N*-carboxy anhydrides should be modified. Although these materials were formerly assumed to copolymerize randomly, it now appears that some of them do not copolymerize readily.

[16] *A. T. Kanakkanatt*, Ph. D. Thesis, University of Akron, 1963; to be published.

3. Selective Hydrolysis

An approach similar to that taken by *Kanakkanatt* was used to study the sequence distribution in copolymers derived from 3,3-bischloromethyloxacyclobutane *(5b)* plus β-propiolactone *(5c)* [17]. The amount of β-hydroxypropionic acid *(5d)* liberated on hydrolysis of such copolymers provided a measure of the number of ester-ester linkages present and indicated the copolymers to have block-polyblend structures.



(5d)

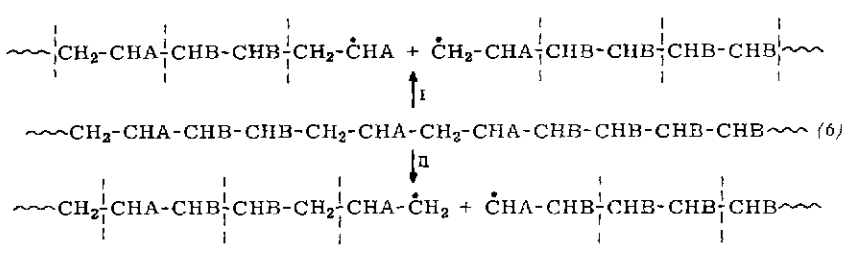
4. Thermal Degradation

Thermal degradation of copolymers often regenerates large amounts of monomer. Such degradations generally occur by depropagation or unzipping mechanisms. Depending on how the depropagation chains are initiated, the regenerated monomers may contain either only original atoms or atoms initially associated with neighboring monomer units as well.

The copolymer chain *(6)* may be considered to have resulted from polymerization of monomers CH_2=CHA and CHB=CHB. Depropagations initiated by homolysis of CHA–CHB bonds (intermonomer or external bonds; Reaction I) regenerate the original monomers, whereas depropagations initiated by homolysis of CH_2–CHA or CHB–CHB bonds (intramonomer or internal

[17] *K. Tada, T. Saegusa*, and *J. Furukawa*, Makromolekulare Chem. *71*, 71 (1964).

bonds; Reaction II) produce the hybrid monomers, CH_2=CHB and CHA=CHB. Similar effects may be observed in the pyrolysis of copolymers derived from CH_2=CHA and CH_2=CHB monomers provided that one of the monomers contains labelled methylene groups.



(6)

Wall [18] has suggested that the quantity $\Theta/2$ be used to represent the fraction of internal monomer bonds broken during a copolymer pyrolysis. Random degradation of a copolymer would then be characterized by $\Theta = 1$, and the yields Y of regenerated and hybrid monomers can be expressed in terms of the copolymer composition, R, and Θ [Equations (m)–(o)].

$$Y_{CH_2\cdot CHB} \quad Y_{CHA\cdot CHB} = R\cdot\Theta/4 \qquad (m)$$

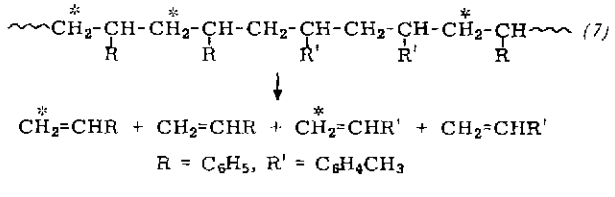
$$Y_{CH_2\cdot CHA} \quad \%\,(CH_2\cdot CHA) = R\cdot\Theta/4 \qquad (n)$$

$$Y_{CHB\cdot CHB} \quad \%\,(CHB\cdot CHB) = R\cdot\Theta/4 \qquad (o)$$

Since few polymers are degraded to give exclusively monomer units, *Wall* attempted to correct for oligomer formation by comparing the yield of regenerated monomer obtained during copolymer degradation with that obtained on pyrolysis of the corresponding homopolymer. This approach is sometimes helpful, but occasionally leads to bizarre results, especially with copolymers derived from dienes.

On pyrolysis of β-deuteriostyrene/methyl methacrylate and styrene/dimethyl fumarate copolymers, *Wall* succeeded in correlating the amounts of products formed with the expected sequence distribution, utilizing values of about 1.0 and 1.25, respectively, for Θ for the two systems. Deuteriostyrene/methyl methacrylate copolymers thus appeared to undergo random degradation, whereas styrene/dimethyl fumarate copolymers exhibited a slight preference for cleavage of internal monomer bonds.

Morthland and *Brown* [19] prepared copolymers *(7)* of [β-^{14}C]-styrene with *m*- and *p*-methylstyrene and pyrolysed films of the copolymers at 300–400 °C. The radioactivity of the styrene recovered was less than that of the original monomer owing to dilution with "hybrid" styrene units formed during the degradation; the regenerated methylstyrene was also radioactive.



(7)

$$\overset{*}{CH_2}{=}CHR + CH_2{=}CHR + \overset{*}{CH_2}{=}CHR' + CH_2{=}CHR'$$

$$R = C_6H_5,\ R' = C_6H_4CH_3$$

Assuming complete regeneration of monomers, the activity a_S of the recovered styrene (S) would be proportional to the fraction of styrene units regenerated in original form, and the activity a_{MeS} of the recovered methylstyrene units (MeS) to the fraction of such units obtained as hybrids.

$$a_S \quad \frac{(\%\ S) - R\ \Theta/4}{(\%\ S)}\ a_S^0 \qquad (p)$$

$$a_{MeS} \quad \frac{R\ \Theta}{4\ (\%\ MeS)}\ a_S^0 \qquad (q)$$

$$\frac{a_S}{a_{MeS}} \quad \frac{(\%\ MeS)}{(\%\ S)}\ \frac{(\%\ S) - R\Theta/4}{R\Theta/4} \qquad (r)$$

a_S^0 = activity of the original styrene monomer.

Brown and *Morthland* predicted a_S/a_{MeS} values for several [β-^{14}C]-styrene/methylstyrene copolymers, assuming the degradations to occur randomly (Θ=1), and assuming the copolymers to have random distributions of monomer units [R = (%S)·(%MeS)/50]. The results given in Table 2 support these assumptions.

Table 2. Pyrolysis of [β-^{14}C-styrene (S)/methylstyreoe (MeS) copolymers [19].

Comonomer	Styrene in copolymer [%]	Pyrolysis time [min]	Pyrolysis temp. [°C]	Monomer yield [%]	a_S/a_{MeS} [a] found	a_S/a_{MeS} [a] calc.
p-Methylstyrene	46.9	60	310	5.5	3.059	3.141
	46.9	75	355	28.5	3.102	3.141
	46.9	135	375	8.7	3.937	3.141
m-Methylstyrene	48.2	30	400	60.0	3.279	3.075
	48.4	1560	300	68.6	2.612	3.066

[a] a = activity [counts/min/mole].

Vapor-phase chromatography and mass speetrometry are powerful tools for the study of copolymer pyrolysis products. *Shibasaki* and *Kambe* [20,21] used vapor-phase chromatography to determine the monomer yields obtained on pyrolysis of styrene/acrylonitrile and styrene/methyl methacrylate copolymers. Their results were interpreted in terms of "boundary-effect" parameters β_A and β_B for the monomers A and B. These parameters are mathematically equivalent to *Wall*'s $\Theta_A/2$ and $\Theta_B/2$ values but have a different physical significance. The parameter β_A, for example, is a function of the probability P_{AB} of obtaining monomer A from ~~BA-radicals relative to that P_{AA} of obtaining A from ~~AA-radicals.

$$\beta_A = \frac{P_{AA} - P_{AB}}{P_{AA}} \qquad (s)$$

Boundary-effect parameters obtained from experimental results by using relationships similar to Equations (m) to (o), for example, were reasonably constant for a given copolymer over a wide range of composition, provided that the experimental conditions were kept constant. The constancy obtained indicates that this approach has pro-

[18] *L. A. Wall* and *J. H. Flynn*, Rubber Chem. Technol. *35*, 1195 (1962); *L. A. Wall* in *M. Kline*: Analytical Chemistry of Polymers. Interscience, New York, 1962, Part II, Chapter V.

[19] *F. W. Morthland* and *W. G. Brown*, J. Amer. chem. Soc. *78*, 469 (1956).

[20] *Y. Shibasaki* and *H. Kambe*, Chem. high Polymers (Tokyo) *21*, 71 (1964).

[21] *Y. Shibasaki*, Chem. high Polymers (Tokyo) *21*, 125 (1964).

mise as a method for determining sequence distributions. *Shibasaki* used experimentally determined β-values for styrene (S) and acrylonitrile (AN) to determine the percentages S–AN and AN–S linkages present in several commercial styrene/acrylonitrile copolymers.

Pyrolysis plus vapor-phase chromatography in which copolymer decomposition and product analysis are combined in essentially a single operation are likely to be valuable in future studies, especially when only approximate or relative information on sequence-distribution is required. In the first such study, *Bombaugh, Cook*, and *Clampitt* [22] reported that the amount of methanol formed on pyrolysis of ethylene/methyl acrylate copolymers increases with the block character of the copolymers. The relative amounts of methanol and methyl acrylate formed on pyrolysis proved useful for distinguishing copolymers from homopolymer blends. Copolymers indicated by this technique as having block structures were shown to be partly crystalline by differential thermal analysis; random copolymers of the same composition were non-crystalline.

Furthermore, the amount of methyl methacrylate regenerated when ethylene/methyl methacrylate copolymers were pyrolysed decreased as the number of ethylene/methyl methacrylate junctions in the copolymers increased. The results obtained in this study are presented in Figure 1

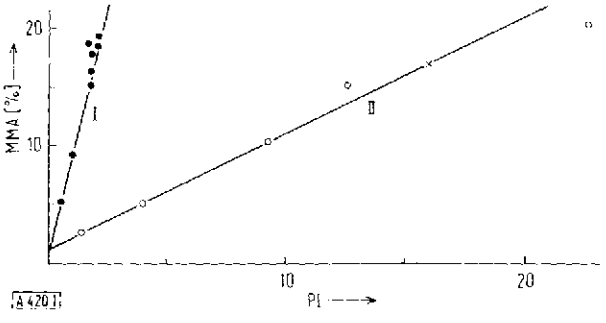


Fig. 1. Pyrolysis and vapor-phase chromatography of ethylene/methyl methacrylate copolymers [22].

Abscissa: PI = pyrolysis index = area under the methyl methacrylate peak multiplied by the mole-fraction of ethylene in the copolymers and divided by the area under the C_8-peak.

Ordinate: MMA = methyl methacrylate [% by weight].

–•–•–: Random copolymers

–○–○–: Homopolymer mixtures

×: Graft copolymer

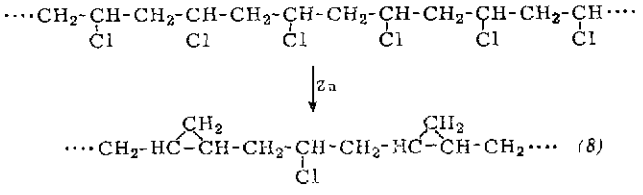
D. Copolymer Alteration Studies

1. Intrasequence Cyclization Reactions

The monomer units in many homopolymers can be made to cyclize. Examples of such reactions are the dechlorination of poly(vinyl chloride) with zinc [23], the self-condensation of methyl vinyl ketone [24], and the cyclizations observed in poly(α-halogenoacrylic acids) or their esters [25–27].

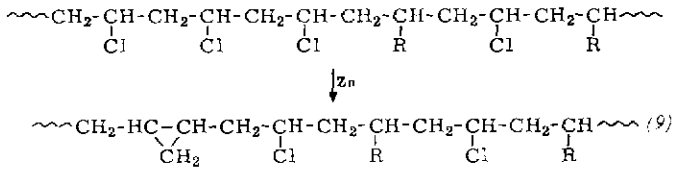
Such cyclizations are usually incomplete because reactive groupings become isolated between cyclized structures as the cyclization proceeds, *e.g.* as in *(8)* from poly(vinyl chloride).

The maximum extent of cyclization has been calculated for several reactions [28,29] assuming the cyclizations to occur randomly; experimental results [23,30] have been in excellent agreement with these calculations.



(8)

In copolymers, cyclizable monomer units may become isolated between comonomer units or between comonomer units and cyclized portions, as in *(9)* from a vinyl chloride copolymer.



(9)

Thus, the maximum extent of cyclization occurring in a copolymer should be less than that possible in the corresponding homopolymer and should be strongly influenced by sequence distribution. This problem has been treated by statistics for vinyl chloride copolymers [31,32] and random methyl vinyl ketone copolymers [29], but only vinyl chloride/vinyl acetate copolymers have been studied experimentally. The results of early studies [33] on such copolymers seemed in reasonable agreement with statistical expectations, but later results indicated that about 87% of the chlorine atoms in such copolymers can be removed with zinc, regardless of copolymer composition [34]. The early results were therefore a reflection only of the relative rates of degradation, rather than a measure of the amounts of isolated vinyl chloride units in the copolymer structure.

2. Intersequence Cyclization Reactions

Cyclization reactions which can occur only at intersequence (run) junctions can provide information about sequence distribution. Lactonization of hydrolysed vinyl acetate/maleic anhydride copolymers *(10)* is a good

[22] *K. J. Bombaugh, C. E. Cook*, and *B. H. Clampitt*, Analytic. Chem. *35*, 1834 (1963).

[23] *C. S. Marvel, J. H. Sample*, and *M. F. Fox*, J. Amer. chem. Soc. *61*, 3241 (1939).

[24] *C. S. Marvel* and *C. L. Levesque*, J. Amer. chem. Soc. *60*, 280 (1938).

[25] *G. Smets* and *P. Flore*, J. Polymer Sci. *35*, 519 (1959).

[26] *C. S. Marvel, E. D. Weil, L. B. Wakefield*, and *C. W. Fairbanks*, J. Amer. chem. Soc. *75*, 2327 (1953).

[27] *L. M. Minsk* and *W. O. Kenyon*, J. Amer. chem. Soc. *72*, 2651 (1950).

[28] *P. J. Flory*, J. Amer. chem. Soc. *61*, 1518 (1939).

[29] *F. T. Wall*, J. Amer. chem. Soc. *64*, 269 (1942).

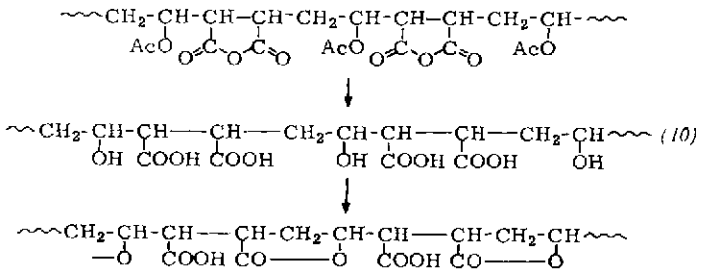
[30] *C. S. Marvel* and *C. L. Levesque*, J. Amer. chem. Soc. *60*, 280 (1938).

[31] *F. T. Wall*, J. Amer. chem. Soc. *62*, 803 (1940).

[32] *F. T. Wall*, J. Amer. chem. Soc. *63*, 1862 (1941).

[33] *C. S. Marvel, G. D. Jones, T. W. Mastin*, and *G. L. Schertz*, J. Amer. chem. Soc. *64*, 2356 (1942).

[34] *T. Alfrey, jr., H. C. Haas*, and *C. W. Lewis*, J. Amer. chem. Soc. *73*, 2851 (1951).

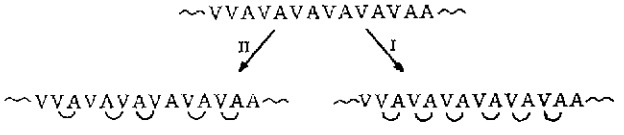


(10)

example. For example, *Minsk*, *Waugh*, and *Kenyon* [35] noted that a hydrolysed 1:1 vinyl acetate/maleic anhydride copolymer could be converted into material having 46.8% of its carboxyl groups lactonized. This indicates that the copolymer had an almost completely alternating structure, in agreement with the copolymerization characteristics of the vinyl acetate/maleic anhydride system.

The possibility, first suggested by *Price*, that the extent of lactone formation in hydrolysed vinyl acetate/acrylate ester copolymers could provide a measure of their sequence distribution, was discussed in one of the early theoretical papers on copolymerization [1].

Two independent research groups [36,37] derived expressions predicting, in terms of monomer reactivity ratios and copolymerization mixture compositions, the extent of lactone formation to be expected for low-conversion copolymers prepared from given monomer mixtures. Both treatments assume that lactone formation occurs randomly in alternating portions of the copolymer chains but only at vinyl alcohol (V) –acrylic acid (A) junctions. Assumptions of this kind should not be made indiscriminately, however. When very stable rings can be formed reversibly, maximum cyclization (Path I) rather than random cyclization (Path II) may occur.



In calculating the amount of lactone formation expected for a given copolymer, *Sakurada* and *Kawashima* [37] considered the behavior of carboxylic acid units in the middle of the ten possible pentads towards alcohol units. Obviously, acid units $\overset{*}{A}$ centered in AA$\overset{*}{A}$AA, AA$\overset{*}{A}$AV, or VA$\overset{*}{A}$AV pentads cannot form lactones. Acid units $\overset{*}{A}$ in VV$\overset{*}{A}$VV, VV$\overset{*}{A}$VA, VV$\overset{*}{A}$AA, or VV$\overset{*}{A}$AV are almost certain to lactonize since they have sole access to at least one neighboring alcohol (V) group. Acid units centered in AA$\overset{*}{A}$VA and in VA$\overset{*}{A}$VA pentads have approximately a 50:50 chance of being converted in to lactone. Finally, all acid units centered in AV$\overset{*}{A}$VA type pentads were assumed to be converted into lactone; although this assumption was recognized to be incorrect (only about 80% can be cyclized), it simplified the treatment, and the error it introduced was fairly small. In order to calculate the expected number of lactone linkages, *Sakurada* and *Kawashima* added up the number of acid groups in a 100-unit copolymer which could be converted into lactone. In our terminology, this number would be given by Equation (t) [cf. Equations (d) to (g)]:

$$\text{Lactone units/100 monomer units} = \%\,A\,(f_{VVAVV} + f_{VVAVA} + f_{VVAAA} + f_{VVAAV} + f_{AVAVA} + {}^1/_2\,f_{AAAVA} + {}^1/_2\,f_{VAAVA}) \qquad (t)$$

% A = the percentage of monomers with acid groups;
f_{VVAVV} = the fraction of A units centered in VVAVV pentads.

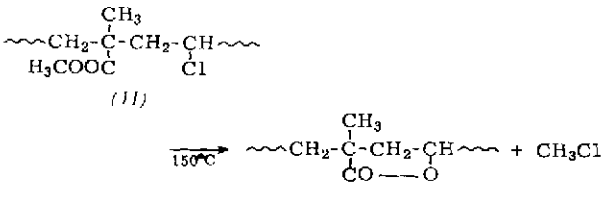
Using a conductometric technique developed by *Matsumoto* [38], *Sakurada* and *Kawashima* [37] determined the compositions and lactone contents of a series of hydrolysed vinyl acetate/methyl acrylate copolymers. The copolymers were prepared in various yields from several monomer mixtures. The hydrolysed copolymers lactonized spontaneously in acidic solution.

Graphical methods were used to calculate the average composition and amount of lactone formation expected for each sample; in Table 3, the experimental results are compared with those calculated by *Sakurada* and *Kawashima*.

Table 3. Lactone content of hydrolyzed vinyl acetate/methyl acrylate copolymers [37].

Methyl acrylate in polymerization mixture [mole%]	Yield of copolymer [%]	Acrylic acid in hydrolysed copolymer [mole%]		Lactone content in hydrolysed copolymer [mole%]	
		found	calc.	found	calc.
20	32.8	47.5	44.4	29.1	29.9
20	37.2	46.4	42.4	22.2	29.3
20	87.0	22.3	23.0	13.4	17.1
50	87.0	53.9	57.0	22.9	21.7

Zutty and *Welch* [39] recently reported another promising example of intersequence cyclization. They observed that vinyl halide/methyl methacrylate copolymers can lactonize on heating, liberating methyl halide and forming rigid foams of good compressive strengths. It was shown that this reaction occurred only intramolecularly



(11)

and presumably only at intersequence junctions [as in *(11)*]. *Smets* [40] called attention to other cyclizations observed in polymers, *e.g.* imide, lactam, α-tetralone,

[35] *L. M. Minsk, G. P. Waugh*, and *W. O. Kenyon*, J. Amer. chem. Soc. *72*, 2646 (1950).

[36] *T. Alfrey, jr., C. Lewis*, and *B. Nagel*, J. Amer. chem. Soc. *71*, 3793 (1949).

[37] *I. Sakurada* and *K. Kawashima*, Chem. high Polymers (Tokyo) *8*, 142 (1951); Chem. Abstr. *47*, 344 (1953).

[38] *T. Matsumoto*, Chem. high Polymers (Tokyo) *7*, 142 (1950); Chem. Abstr. *45*, 7816 (1951).

[39] *N. L. Zutty* and *F. J. Welch*, J. Polymer Sci. *1*, 2289 (1963).

[40] *G. Smets*, Makromolekulare Chem. *34*, 190 (1959).

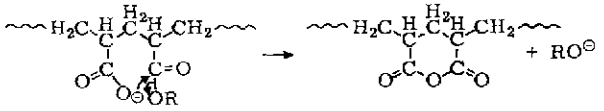
and indane ring formation. It is therefore possible that cyclization techniques may be used in other sequence distribution studies.

Little use has so far been made of cyclizations to characterize tacticity in homopolymers, but acetals based on isotactic and syndiotactic poly(vinyl alcohol) differ in stability [41]. Equilibrium constants for acetal formation differ for various stereoregular poly(vinyl alcohols), and the corresponding acetals are hydrolyzed at different rates [42].

3. Reactivity of Copolymers

Neighboring group effects [43] may play an important role in the reactions of copolymers, and it is possible that the reactivity of monomer units in copolymers will be affected by their immediate or sequential environment. The autocatalysis or autoinhibition noted in the hydrolysis [44,45] or pyrolysis [46] of polymeric esters has been traced to such effects [47-49].

Most studies have involved copolymers in which reactive groups were isolated, so that their environments were easily specified. *Morawetz* and *Zimmering* [50] studied the alkaline hydrolysis and methanolysis of acrylic acid/*p*-nitrophenyl methacrylate copolymers. Ester groups in the copolymers *(12)* were hydrolyzed up to 10^6 times as fast as comparable monomeric models (*p*-nitrophenyltrimethylacetate). Since the rates of hydrolysis of the copolymers increase with the extent of carboxyl ionization, the rapid hydrolysis rates observed were attributed to the participation of neighboring carboxylate groups.



(12)

Results reported somewhat later by *Cooper* [51] supported this suggestion; autocatalysis was observed in the alkaline hydrolysis of poly(ethyl acrylate), but not in the alkaline hydrolysis of a 70:30 butadiene/ethyl acrylate copolymer, where the ester groups are probably almost entirely isolated.

Subsequent work [52] has shown that such neighboring group effects are very sensitive to chain configuration or tacticity. Measurements of hydrolysis rates are often used to characterize tacticity in ester or amide homopolymers [53,54]. Isotactic polymers have been found to be more reactive than syndiotactic or atactic polymers.

In studies involving hydrolysis of ester or amide groups in copolymers, it is very difficult to differentiate between effects due to sequence distribution and those due to tacticity. *Smets* and *Van Humbeeck* [55] recently reported that the rate of alkaline hydrolysis of acrylic acid/ethyl ethacrylate copolymers is directly proportional to the fraction of ester units in the middle of acid-ester-acid triads, but is independent of the fraction of ester units centered in acid-ester-ester triads (Figure 2). However, only about 60% of such ester groups were hydrolyzable;

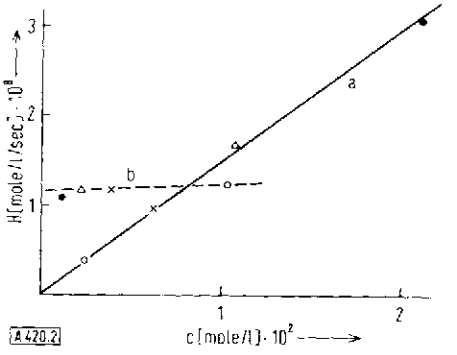


Fig. 2. Rates of hydrolysis of acrylic acid/ethyl ethacrylate copolymers containing a constant concentration of acid-ester-ester triads (0.32×10^{-2} mole/l, Curve a), or of acid-ester-acid triads (0.77×10^{-2} mole/l, Curve b), and varying concentrations of acid-ester-acid and acid-ester-ester triads, respectively.

o: Copolymer with 50 mole% acid groups [55]
x: Copolymer with 67 mole% acid groups
Δ: Copolymer with 77 mole% acid groups
•: Copolymer with 85 mole% acid groups

Abscissa: Concentration c of the acid-ester-acid triads (Curve a) and acid-ester-ester triads (Curve b) [mole/l]$\times10^2$ [55].

Ordinate: Rate of hydrolysis H [mole/l/sec]$\times10^8$.

the resistance of the unreacted ester groups to hydrolysis was explained on stereochemical (tacticity) grounds. In this connection, *Smets* and *von Humbeeck* noted that isotactic acrylic acid/metbyl acrylate copolymers could be hydrolyzed 3–5 times faster and to greater extents than conventional copolymers with the same compositions. Similar results had been obtained earlier with methacrylic acid/methyl methacrylate copolymers.

Arcus [56] observed that alkaline hydrolysis of polymethacrylamide ceased after 70% conversion. He suggested that the hydrolysis-resistant amide groups were stabilized by hydrogen bonding with two neighboring acid groups. *Pinner* [57] tested this suggestion by examining the behavior of methacrylic acid/methacrylami-

[41] *K. Fujii, J. Ukida*, and *M. Matsumoto*, Polymer Letters *1*, 696 (1963).

[42] *F. Fujii, J. Ukida*, and *M. Matsumoto*, Makromolekulare Chem. *65*, 86 (1963).

[43] *M. L. Bender*, Chem. Reviews *60*, 53 (1960).

[44] *I. Sakurada* and *Y. Sakaguchi*, Chem. high Polymers (Tokyo) *13*, 441 (1956); Chem. Abstr. *51*, 13765.

[45] *I. Sakurada, Y. Sakaguchi*, and *S. Fuki*, Chem. high Polymers (Tokyo) *13*, 355 (1956); Chem. Abstr. *51*, 18687h.

[46] *J. R. Schaefgen* and *I. M. Sarasohn*, J. Polymer Sci. *58*, 1049 (1962).

[47] *J. B. Keller*, J. chem. Physics *37*, 2584 (1962); *38*, 325 (1963).

[48] *T. Alfrey, jr.*, and *W. G. Lloyd*, J. chem. Physics *38*, 318 (1963).

[49] *C. B. Arends*, J. chem. Physics *38*, 322 (1963).

[50] *H. Morawetz* and *P. E. Zimmering*, J. physic. Chem. *58*, 753 (1954).

[51] *W. Cooper*, Chem. and Ind. (London) *1958*, 263.

[52] Reviewed by *G. Smets*, Angew. Chem. *74*, 337 (1962); Angew. Chem. internat. Edit. *1*, 306 (1962).

[53] *W. R. Krigbaum*, in *B. Ke*: Newer Methods of Polymer Characterization. Interscience, New York 1964, Chap. I.

[54] *C. E. H. Bawn* and *A. Ledwith*, Quart. Rev. *16*, 361 (1962).

[55] *G. Smets* and *W. Van Humbeeck*, J. Polymer Sci. *A 1*, 1227 (1963).

[56] *C. L. Arcus*, J. chem. Soc. (London) *1949*, 2732.

[57] *S. H. Pinner*, J. Polymer Sci. *10*, 379 (1953).

de copolymers on hydrolysis. He assumed that the copolymers have random structures, that amide hydrolysis occurs randomly, and that isolated amide groups are unreactive, and thus predicted the extent of hydrolysis. The predictions agreed well with experimental results, as shown in Table 4.

Table 4. Extent of hydrolysis of methacrylic acid/methacrylamide copolymers [57].

Methacrylamide [mole %]		Polymerization [%]	Amide units hydrolysed [% of total]		
polymerization mixture	copolymer		found	calc. [a]	calc. [b]
80	54.5	7	46.3	44	52
60	37.7	12	34.5	34	36
50	30.0	10	31.5	27.7	31
20	8.97	18	13.5	8.9	8.2
10	4.18	35	4.3	4.2	–

[a] Values taken from *Pinner* [57].

[b] Values calculated by *Harwood* (see text).

Although random hydrolysis of amide groups was assumed by *Pinner*, this is not compatible with the autoacceleration observed. It is interesting that the experimental results also agree with those calculated on the assumption that one amide group in each amide sequence becomes resistant to hydrolysis. Such a result would be

~~~acid-amide-amide-amide-acid~~~
↓
~~~acid-acid-amide-amide-acid~~~
↓
~~~acid-acid-amide-acid-acid~~~
↓
no further reaction

obtained if only amide groups having a single acid neighbor hydrolyse rapidly; the proportion of unaccessible amide groups then equals the ratio of amide runs to amide units in the copolymer, or R/[2(% Amide)].

Results predicted from this relationship using reactivity ratios determined by *Pinner* (random structure not assumed), are also included in Table 4.

In a novel chemical study of sequence distribution, *Rodriguez* [58] investigated the photochemical bromination of styrene (S)/fumaronitrile (F) copolymers. The bromination was shown to occur exclusively by substitution at aliphatic (presumably benzylic) sites. Since free-radical bromination is relatively selective and occurs at sites of high electron density [59], styrene units in the middle of SSS type triads should be more easily brominated than those in the middle of triads of the types FSF or FSS. *Rodriguez* noted that the copolymers could be brominated only partially. By studying the kinetics of the bromination, he determined the bromine content of copolymers at infinite reaction time.

For copolymers containing less than 60 mole% styrene, such bromine contents correlate very well with those expected if only styrene units in the middle of SSS type triads can be brominated. However, as shown in Table 5, this correlation does not apply when the copolymers contain more than 60% styrene; not all styrene units in the middle of triads of SSS type can be brominated in such polymers.

Table 5. Bromination of styrene/fumaronitrile copolymers [58].

Styrene [mole %]		Polymerization [%]	Bromine in copolymer		
polymerization mixture	copolymer		found	calc. [a]	calc. [b]
12.5	51.3	2.5	0.125	0.123	0.122
25.0	54.5	3.1	1.30	1.56	1.14
58.2	55.8	13.4	2.05	2.05	1.64
58.2	57.5	12.8	2.59	3.24	2.42
75.0	64.4	10.5	6.35	12.1	5.65
76.9	66.7	1.7	8.35	12.9	6.52
–	72.0	–	11.2	18.3	9.63

[a] Calculated assuming that only styrene units in the middle of triads of the SSS type can be brominated (R = 2% F).

[b] Calculated, assuming that only one bromine atom is incorporated into each styrene run in the copolymers (R = 2% F), where each run has 3 or more styrene units.

Rodriguez obtained a better correlation with the experimental results by assuming that only one bromine atom was introduced into each styrene run of three or more units [60]. Such a correlation might be expected for copolymers of relatively low styrene content if styrene units adjacent to brominated styrene units do not react with bromine. Thus, only one of the two styrene units of SSS type marked with asterisks in the sequence *(13)* should be brominated.

~~~F-S-F-S-S*-S*-S-F-S-F-S-S-F~~~ *(13)*
↓ Br_2
~~~F-S-F-S-S(Br)-S-S-F-S-F-S-S-F~~~

This correlation applies to copolymers containing less than *65 mole% styrene* (see Table 5). As might be expected, the correlation does not hold for copolymers where the average styrene runs are relatively long.

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[58] *L. Rodriquez*, Makromolekulare Chem. *12*, 110 (1954).

[59] *C. Walling*: Free Radicals in Solution. Wiley, New York, 1957. Chap. 8.

[60] The number of such runs (N) in a 100-unit copolymer can be calculated in terms of run numbers by the following expression:
$N = R/2 - \%\ S\ (f_{FSF} + {}^1/_2 f_{FSSF})$
where $f_{FSSF} = f_{SFSSF} + f_{FFSSF}$.
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New Findings in the Chemistry of the Lower Oxides of Sulfur [1]

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Dedicated to Professor Erika Cremer on the occasion of her 65th birthday

Important advances have recently been made in the chemistry of the lower oxides of sulfur, both in the preparative sphere and by the application of modern physical methods of investigation. In this paper the knowledge gained to date on the compounds SO, S_2O_2, S_2O, S_2O_3, and the polysulfur oxides is reviewed and critically appraised.

Definition

In the present paper, the term "lower oxides of sulfur" refers to oxides in which the oxidation number z of sulfur is $\leqslant 2$. Thus, although S_2O_3 is discussed briefly, it does not belong to this group, particularly since the sulfur in this compound is evidently present in two very different oxidation states. However, the term does encompass the oxides SO, S_2O_2, S_2O, and the polysulfur oxides of general formula $(S_nO)_x$ in which $n > 2$. According to their properties, compounds containing hydrogen in addition to sulfur and oxygen should be grouped together with the polysulfur oxides. These compounds will be referred to as polysulfane oxides.

A. Sulfur Monoxide SO

I. Stability

The ultraviolet and microwave spectra of SO show that the electronic ground state of this molecule, like that of O_2 and S_2, is a $^3\Sigma$ state [2–5]. Unlike O_2, however, SO is thermodynamically unstable, with regard to both its theoretical dissociation into the elements and its actual dissociation into sulfur and SO_2. The enthalpy of formation at 0 °K of SO from its elements in the standard state is not yet known with certainty, but is approximately zero ($\Delta H_0^0 = +1.6$ kcal/mole [6]).

The enthalpy of its decomposition [Equation (a)] is $\Delta H_0^0 = -36.8$ kcal/mole. This agrees with the fact that

$$SO \rightarrow {}^1/_2\, S_{rhomb.} + {}^1/_2\, SO_2 \qquad (a)$$

SO (like S_2) is present in an appreciable concentration only at high temperatures. The enthalpy of formation of sulfur monoxide is found by investigation of equilibria such as those shown in Equations (b) and (c) [9, 10].

$$2\, SO_2 \rightleftarrows SO + SO_3 \text{ at } 1500\,^\circ C \qquad (b)$$
$$\Delta H_0^0 = +48.6 \text{ kcal/mole of SO}$$

$$SO_2 + {}^1/_2\, S_2 \rightleftarrows 2\, SO \text{ at } 1250\,^\circ C \qquad (c)$$
$$\Delta H_0^0 = +58.3 \text{ kcal/mole of } SO_2$$

A thermodynamic treatment of the Equilibria (c)–(e) is given in the literature [1], but this calculation is based

$${}^1/_2\, S_2 + {}^1/_2\, O_2 \rightleftarrows SO \qquad (d)$$
$$\Delta H_0^0 = -13.8 \text{ kcal/mole of SO}$$

$$SO_2 \rightleftarrows SO + {}^1/_2\, O_2 \qquad (e)$$
$$\Delta H_0^0 = +72.0 \text{ kcal/mole of SO}$$

on earlier values for the enthalpies of the reactions. The results indicate that appreciable dissociation of SO_2 into $S_2 + O_2$ and into $SO + O_2$ occurs only at very high temperatures. Only Equilibrium (d) is entirely displaced to the right at room temperature [1]. More recent calculations [8] have indicated that there is 16% SO present in Equilibrium (c) at 1500 °C and 7.6 mm pressure.

Sulfur monoxide is found to be a true biradical which is extremely reactive and decomposes immediately into sulfur or S_2O and SO_2. In order to detect its occurrence as an intermediate, it is therefore necessary to use mild reaction conditions (vapor phase, low pressure) and sensitive physical methods of measurement (see Table 1).

It is often possible to recognize the formation of SO indirectly by the detection of S_2O as a subsequent product.

[1] For an earlier review, see *P. W. Schenk*, Chemiker-Ztg. *67*, 251, 273 (1943).

[2] *E. V. Martin*, Physic. Rev. *41*, 167 (1932).

[3] *A. L. Myerson, F. R. Taylor*, and *P. L. Hanst*, J. chem. Physics *26*, 1309 (1957).

[4] *M. Winnewisser, K. V. L. N. Sastry*, and *W. Gordy*, Bull. Amer. physic. Soc. *9*, 488 (1964); *M. Winnewisser, K. V. L. N. Sastry, R. L. Cook*, and *W. Gordy*, J. chem. Physics *41*, 1687 (1964).

[5] *A. B. Scott*, J. Amer. chem. Soc. *71*, 3145 (1949).

[6] All enthalpy values given in the present paper are taken from [7], or calculated from the data given there; see also [8].

[7] *R. Steudel* and *P. W. Schenk*, Z. physik. Chem. NF *43*, 33 (1964).

[8] *R. Hagemann*, C. R. hebd. Séances Acad. Sci. *255*, 899, 1102 (1962); Commissariat l'Energie Atomique (France) Rapp. No. 2398 (1964).

[9] *G. St. Pierre* and *J. Chipman*, J. Amer. chem. Soc. *76*, 4787 (1954).

[10] *E. W. Dewing* and *F. D. Richardson*, Trans. Faraday Soc. *54*, 679 (1958).

Table 1. Formation and detection of sulfur monoxide.

Starting Material	Reaction	Detection of SO	Ref.
SO_2 [a]	UV photolysis γ-photolysis	UV spectrum deposition of S	[12–14]
SO_2 [b]	glow discharge HF discharge MW discharge	S_2O ESR spectrum microwave spectrum	[4, 15–17]
SO_2	shock waves	UV spectrum	[11]
SO_2 [c]	thermal dissocn.	UV spectrum S_2O	[18–21]
SO_3	UV photolysis	UV spectrum	[12]
SOX_2	thermal dissocn. [d] dehalogenation	S_2O S_2O	[19, 22] [19, 23, 24]
Sulfites	thermolysis	S_2O [e]	[25]
Sulfides	roasting [f]	S_2O [g]	[23, 26]
H_2S	photolysis with O_2	UV spectrum, mass spectrum, S_2O	[27–29]
	with atomic oxygen	ESR spectrum, mass spectrum	[30, 31]
CS_2, COS	photolysis or combustion with O_2	UV spectrum, mass spectrum, S_2O	[3, 27, 32, 33]
COS	with atomic oxygen	mass spectrum	[31, 34]
Sulfur	combustion with O_2 [h]	S_2O	[24, 33]
Sulfur	combustion with CuO	S_2O	[35]
Sulfur	heating with SO_2 electr. discharge [i]	S_2O	[15, 36, 37]
Sulfur (solid)	with atomic oxygen, HF or glow discharge with O_2	mass spectrum, S_2O, microwave spectrum	[4, 8, 31, 38, 39]
Polysulfur oxides and polysulfane oxides	thermolysis	S_2O	[40–42]

[a] Ultraviolet photolysis at 10–100 mm. γ-Photolysis of liquid SO_2 yields sulfur and SO_3 as endproducts [14].

[b] Electric discharges in SO_2 at 0.01–1.0 mm. Particularly high SO concentrations (up to 100 %) are obtained if sulfur is also present in the discharge tube, in accordance with Equilibrium (c) [17].

[c] Thermal dissociation of SO_2 either at a Nernst rod or in a luminous arc in the presence of sulfur vapor.

[d] The decomposition temperatures of the thionyl halides and pseudohalides decrase in the order $SOCl_2 > SOBr_2 > SO(CN)_2 > SO(SCN)_2$ [22].

[e] Detection of S_2O by formation of sulfide with $Ag^{\oplus}$ solution [25].

[f] At temperatures of up to 435 °C and oxygen pressures of 0.1–4.0 mm, pyrites and zinc sulfide yield only SO_2 and metal oxide on roasting. S_2O is obtained in small quantities only from Ag_2S [23].

[g] Detectinn of S_2O by its oltraviolet spectrum.

[h] With pure oxygen at 10–40 mm.

[i] The formation of SO may be quantitative. The gas obtained consists of a stoichiometric (1:1) mixture of S_2O and SO_2 [15, 19, 27, 36, 37, 40].

II. Formation of SO

Ways in which sulfur monoxide is formed as an intermediate are listed in Table 1, together with methods for its detection.

SO is formed from SO_2 in accordance with Equation (f).

$$SO_2 \rightarrow SO + O \qquad (f)$$

This reaction requires about 131 kcal/mole [7], *i.e.* it is effected only by high-energy radiation, an electric discharge, or high temperatures. After the activation process $SO_2 \rightarrow SO_2^*$, Reactions (g) and (h) are possible [11].

$$SO_2^* \rightarrow SO + O \qquad (g)$$

$$SO_2^* + SO_2 \rightarrow SO + SO_3 \qquad (h)$$

SO is formed from $SOCl_2$, $SOBr_2$, $SO(CN)_2$, and $SO(SCN)_2$ by thermal decomposition in accordance with Equation (i), or by dehalogenation of thionyl chloride or bromide with silver or antimony [*e.g.* Equation (k)] at 100–400 °C and about 1 mm pressure.

$$SOX_2 \rightarrow SO + X_2 \qquad (i)$$

$$SOCl_2 + 2\,Ag \rightarrow SO + 2\,AgCl \qquad (k)$$

[11] *A. G. Gaydon, G. H. Kimbell*, and *H. B. Palmer*, Proc. Roy. Soc. (London), Ser. A *276*, 461 (1963).

[12] *R. G. W. Norrish* and *G. A. Oldershaw*, Proc. Roy. Soc. (London), Ser. A *249*, 498 (1958).

[13] *P. Warneck, F. F. Marmo*, and *J. O. Sullivan*, J. chem. Physics *40*, 1132 (1964).

[14] *W. G. Rothschild*, J. Amer. chem. Soc. *86*, 1307 (1964).

[15] *P. W. Schenk*, Z. anorg. allg. Chem. *211*, 150 (1933).

[16] *J. M. Daniels* and *P. B. Dorain*, J. chem. Physics *40*, 1160 (1964).

[17] *P. W. Schenk* and *W. Holst*, Z. anorg. allg. Chem. *319*, 337 (1963).

[18] *P. W. Schenk* and *H. Platz*, Z. anorg. allg. Chem. *222*, 177 (1935).

[19] *P. W. Schenk* and *H. Triebel*, Z. anorg. allg. Chem. *229*, 305 (1936).

[20] *G. Pannetier*, C. R. hebd. Séances Acad. Sci. *228*, 478 (1949).

[21] *T. M. Sugden, E. M. Bulewicz*, and *A. Demerdache*: Proceedings Internat. Symposium on Chemical Reactions in the Lower and Upper Atmosphere, San Francisco, Calif., 1961, p. 89; Chem. Abstr. *56*, 13583 (1962).

[22] *P. W. Schenk* and *H. Bloching*, Chem. Ber. *92*, 2333 (1959).

[23] *P. W. Schenk* and *R. Steudel*, unpublished experiments.

[24] *P. W. Schenk* and *H. Platz*, Z. anorg. allg. Chem. *215*, 113 (1933).

[25] *C. C. Bisi* and *A. Clevici*, Gazz. chim. ital. *93*, 1444 (1963); Chem. Abstr. *60*, 11602 (1964).

[26] *N. P. Diyev* et al., Trudy Inst. Met. Akad. Nauk SSSR, Ural, Filial Sbornik Rubot *1*, 17 (1957); Chem. Abstr. *53*, 21085 (1959).

[27] *J. J. McGarvey* and *W. D. McGrath*, Proc. Roy. Soc. (London), Ser. A *278*, 490 (1963).

[28] *D. G. H. Marsden*, Canad. J. Chem. *41*, 2607 (1963).

[29] *N. M. Emanuel*, Dokl. Akad. Nauk SSSR *59*, 1137 (1948); Chem. Abstr. *42*, 7142 (1948); *G. Markovich* and *N. M. Emanuel*, Zhur. fiz. Khim. *21*, 1251, 1259 (1947); Chem. Abstr. *42*, 5313 (1948); *N. N. Semenov*: Some Problems of Chemical Kinetics and Reactions. Pergamon Press, London 1959.

[30] *C. C. McDonald*, J. chem. Physics *39*, 2587 (1963).

[31] *G. Liuti, S. Dondes*, and *P. Harteck*: Abstract 40T, Division of Physical Chemistry, American Chemical Society, New York, Sept. 1963.

[32] *J. Akriche*, J. Chim. physique Physico-Chim. biol. *60*, 732 (1963).

[33] *P. W. Schenk*, Z. anorg. allg. Chem. *220*, 268 (1934).

[34] *J. O. Sullivan* and *P. Warneck*, Ber. Bunsenges. physik. Chem. *69*, 7 (1965).

[35] *A. R. V. Murthy*, Nature (London) *193*, 773 (1962); *S. R. Satyanarayana* and *A. R. V. Murthy*, Z. anorg. allg. Chem. *330*, 245 (1964); Proc. Indian Acad. Sci., Sect. A 59, 263 (1964).

[36] *H. Cordes* and *P. W. Schenk*, Z. anorg. allg. Chem. *214*, 33 (1933).

[37] *H. Cordes* and *P. W. Schenk*, Z. Elektrochem. angew. physik. Chem. *39*, 594 (1933).

[38] *P. W. Schenk*, Z. physik. Chem. B *51*, 113 (1942).

[39] *F. X. Powell* and *D. R. Lide*, J. chem. Physics *41*, 1413 (1964).

[40] *P. W. Schenk*, Z. anorg. allg. Chem. *233*, 385 (1937).

[41] *P. W. Schenk* and *W. Kretschmer*, Angew. Chem. *74*, 695 (1962); Angew. Chem. internat. Edit. *1*, 550 (1962).

[42] *P. W. Schenk*, Z. anorg. allg. Chem. *248*, 297 (1941).

SO and SO_2 are formed on decomposition of the sulfites (MSO_3) of Sc, Y, La, *etc.* in a current of nitrogen at 300–800 °C:

$$SO_2 + MSO_3 \rightarrow SO + MSO_4 \quad (l)$$

$$2\,SO_2 + 3\,MSO_3 \rightarrow S_2O + 3\,MSO_4 \quad (m)$$

Roasting of sulfides at 700–1000 °C in a current of nitrogen containing oxygen also yields S_2O [26], which is undoubtedly derived from SO formed as an intermediate.

When a mixture of metal oxides is heated with sulfur *in vacuo*, disulfur monoxide is formed *via* sulfur monoxide:

$$2\,CuO + S \rightarrow CuS + SO \quad (n)$$

The disulfur monoxide can be detected as such [35].

High concentration of SO are obtained in mixtures of sulfur vapor and SO_2 at a Nernst rod, in a glow disharge, or in a high-voltage luminous arc at pressures of 0.1 to 100 mm. The SO can be detected as its subsequent reaction product S_2O.

SO is evolved from solid polysulfur oxides and polysulfane oxides on dry distillation *in vacuo*, possibly in accordance with Equation (o).

$$-S-\underset{\underset{O}{\|}}{S}-S- \longrightarrow SO + 2\,S_{rhomb.} \quad (o)$$

III. Properties of SO

In order to investigate the decomposition of SO, the compound was prepared by the following methods: photolysis of SO_2 [12], photolysis of an H_2S/O_2 mixture [27,28], combustion of CS_2 and COS with O_2 or atomic oxygen [3,27,32,34]. The reaction conditions entailed temperatures between 20 and 3000 °C and total pressures of 0.1 to 100 mm. The SO could no longer be detected after about 1–10 msec.

Sulfur monoxide decomposes spontaneously in accordance with Equation (a) to form sulfur and sulfur dioxide. At temperatures below 100 °C and pressures below 100 mm, however, it is possible to detect several intermediate products. Thus, an equimolar mixture of S_2O and SO_2, which was long thought to be SO itself, is formed directly by disproportionation of SO [Equation (p)].

$$3\,SO \rightarrow S_2O + SO_2 \quad (p)$$

Disulfur monoxide S_2O was first prepared as a mixture with SO_2 in 1933 [15,24,36]. On the basis of the methods of synthesis (action of glow discharge on SO_2; dehalogenation of SOX_2) and the composition of the gas mixture (S:O = 1:1), the new oxide was assigned the formula SO. However, molecular-weight determinations in the vapor phase gave a value of about 70 [42] instead of 48, as expected for SO, and the ratio of the original to the final volume on decomposition of the gas into sulfur and SO_2 [Equation (a)] was not 2:1, but 4:3 [18,42,43]. These results could not be reconciled with the simple formula SO and led to the assumption that part of the gas was either irreversibly dimerized ($2\,SO \rightarrow S_2O_2$) or disproportionated in accordance with Equation (p) [42,44].

There was no preparative method available around 1940 to solve this question. Although several publications suggested that the product was probably S_2O_2 [29,45,47a] (cf. the criticism by *Schenk* [46,47b]), *Meschi* and *Myers* later showed by mass spectroscopy that it was in fact an equimolar mixture of S_2O and SO_2 [48].

Thus, data given in the earlier literature on the preparation, isolation, and properties of a stable gas SO or S_2O_2 are erroneous, and actually apply to the S_2O/SO_2 mixture [49].

Owing to the rapidity of the decomposition of sulfur monoxide, practically nothing is known of its chemical properties, apart from a few facts regarding the decomposition itself. The reaction is known to proceed in accordance with the overall Equation (p) because of the constant composition of the gas (S:O = 1:1) [17], the mean molecular weight of about 70 (calculated value = 72) [42], and the fact that the intensities of the S_2O and SO_2 peaks in the mass spectrum are equal [31].

The disproportionation of SO proceeds extremely rapidly, even at pressures under 1 mm; the half-life of the compound is about 2 msec [34]. Attempts to freeze out SO immediately after its formation have so far led only to the S_2O/SO_2 mixture [49a].

IV. Mechanism of the Decomposition of SO

The high rate of decomposition of SO rules out a three-body collision [Equation (p)]. The first step is probably a dimerization:

$$2\,SO \rightarrow (SO)_2 \quad (q)$$

This assumption is supported by the detection of $(SO)_2$. Because of the low heat of reaction involved, this first step can proceed by a two-body collision (see Section B).

In considering possible mechanisms for the rapid decomposition of $(SO)_2$, the Reactions (r) and (s) occasionally proposed can be rejected, since both are endothermic. The only other possibility would be Reaction (t).

$$(SO)_2 \rightarrow S_2O + O \quad (r)$$
$$\Delta H_0^0 = +33.0\ \text{kcal/mole}$$

$$(SO)_2 \rightarrow S_2 + O_2 \quad (s)$$
$$\Delta H_0^0 = +27.5\ \text{kcal/mol}$$

$$(SO)_2 \rightarrow SO_2 + S \quad (t)$$

The enthalpy of Reaction (t) is practically zero. However, even if this reaction were feasible on energetic grounds, it does not lead to an S_2O/SO_2 mixture unless

[43] *E. A. Evans, A. B. Scott,* and *J. L. Huston*, J. Amer. chem. Soc. *74*, 5525 (1952).

[44] *B. S. Rao*, Proc. Indian Acad. Sci., Sect. A *10*, 491 (1939); Chem. Abstr. *34*, 3198 (1940).

[45] *A. Yakovleva* and *V. Kondratyev*, Acta physicochim. SSSR *2*, 241 (1940); *Y. Kondratyeva* and *W. Kondratyev*, Zhur. fiz. Khim. *14*, 1528 (1940).

[46] *P. W. Schenk*, Z. physik. Chem. B *52*, 295 (1942).

[47a] *A. V. Jones*, J. chem. Physics *18*, 1263 (1950).

[47b] *P. W. Schenk*, Z. anorg. allg. Chem. *270*, 301 (1952).

[48] *D. J. Meschi* and *R. J. Myers*, J. Amer. chem. Soc. *78*, 6220 (1956).

[49] The publications in question include: [1], [3], [15], [18], [19], [24], [26], [29], [33], [36], [37], [38], [40], [42], [43], [45], [46], [47a], [47h], [56], [59], [61], [62], [64], [65], [91].

[49a] Recently a yellow substance has been isolated at low temperatures which is probably condensed SO (*R. Steudel*, Ph. D. Thesis, Technische Universität Berlin, 1965).

the sulfur reacts quantitatively in accordance with Equation (u). This is however improbable. Reaction (u) is

$$S + SO \rightarrow S_2O \qquad (u)$$
$$\Delta H_0^0 \quad 90.5 \text{ kcal/mole}$$

only conceivable as a wall reaction or as a three-body collision reaction. Thus, Reaction (t) can also be ruled out.

There is therefore no alternative but to assume that $(SO)_2$ in equilibrium with monomeric SO has a sufficiently long life time to enable it to react in accordance with Equation (v).

$$(SO)_2 + SO \rightarrow S_2O + SO_2 \qquad (v)$$
$$\Delta H_0^0 \quad 97.8 \text{ kcal/mole}$$

This reaction is supported by the observation that, if an excess of sulfur vapor is present during the decomposition of sulfur monoxide, the disproportionation is partially suppressed in favor of Reaction (w):

$$(SO)_2 + S_2 \rightarrow 2\,S_2O \qquad (w)$$
$$\Delta H_0^0 = -79.4 \text{ kcal/mole}$$

Here the S_2O is obtained in 85% purity [17].

Comparison of the dissociation energies D_0 [7] (Table 2) shows that the bond strength in sulfur monoxide is greater than that in O_2 and in S_2. Table 2 also includes the interatomic distances r, the force constants k, and the bond orders n calculated from these data.

Table 2. Dissociation energies D_0, bond lengths r, force constants k, and bond orders n in O_2, SO, and S_2.

	D_0 [kcal/mole]	r [Å]	k [mdyne/Å]	n	Ref.
O–O	118.0	1.208	11.39	1.45	[50]
S–O	123.5	1.481	7.94	1.98	[39, 51]
S–S	101.5	1.893	4.99	2.00	[52]

B. Dimeric Sulfur Monoxide $(SO)_2$

It is only recently that a molecule S_2O_2 has been discovered in mass-spectroscopic studies on the reaction of atomic oxygen with sulfur, H_2S, and COS. In addition to the SO band, the mass spectrum of the reaction product also contains peaks due to S_2O, SO_2, and S_2O_2 in intensity ratios of 1:1:0.04. The peak at mass 96 is assigned to S_2O_2 because another peak is observed at mass 98, and these peaks correspond in their intensity ratio to half the natural $^{32}S/^{34}S$ ratio [31].

Although no details are available regarding the nature of the new compound, it can be assumed to be a molecule similar to dimeric O_2, *i.e.* O_4. It is therefore preferable to use the formula $(SO)_2$. Owing to the low enthalpy of formation (from the monomers) of such dimers ($\Delta H_0^0 = -0.13$ kcal/mole for O_4), they can result from two-body collisions [Equation (x)], if the excess energy is stored in internal degrees of freedom.

$$2\,SO \rightleftharpoons (SO)_2 \qquad (x)$$

[50] *H. Siebert*, Z. anorg. allg. Chem. *273*, 170 (1953).

[51] *W. Moffitt*, Proc. Roy. Soc. (London), Sect. A *200*, 409 (1950).

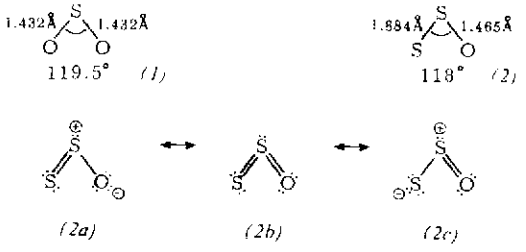
[52] *A. F. Wells*: Structural Inorganic Chemistry. Clarendon Press, Oxford 1962, p. 414.

According to Equilibrium (x), $(SO)_2$ can be expected to appear only in the mass spectrum of nascent SO, since one second is long enough for complete decomposition of the SO [8, 48].

C. Disulfur Monoxide S_2O

I. Stability of S_2O

The microwave spectrum of S_2O *(2)* indicates that this molecule has a structure similar to that of SO_2 *(1)* [53].



(2a) (2b) (2c)

The dipole moments of the bonds were calculated to be $\mu_{SS} = 0.30$ D and $\mu_{SO} = 1.58$ D; the resultant molecular moment is $\mu_{S_2O} = 1.47$ D, the individual moments being opposite in sign [53]. The resonance structure *(2c)* can therefore contribute little to the ground state, and the bond order n of the S–S bond should be close to 2. Using *Moffitt*'s formulae [51], *Giguère* [54] obtained a value of n = 1.80 for the S–O bond.

The standard enthalpy of formation of S_2O is calculated from the sharp predissociation limit to be $\Delta H_0^0 = -22.7$ kcal/mole. The dissociation energy of the S–S bond is $D_0(OS-S) = 90.5$ kcal/mole; that of the S–O bond is $D_0(SS-O) = 112.5$ kcal/mole [7]. Recently, the enthalpy of formation of S_2O was calculated from the appearance potential of $SO^{\oplus}$ from S_2O and from equilibrium measurements on sulfur vapor/SO_2 mixtures to be $\Delta H_0^0 = -9.6$ kcal/mole [8]. Thus, S_2O is thermodynamically stable, although it tends to polymerize.

On heating, disulfur monoxide decomposes into sulfur and SO_2 [Equation (y)]. Gravimetric determination of the sulfur formed is used for quantitative analysis of

$$2\,S_2O \rightarrow 3\,S_{\text{rhomb.}} + SO_2 \qquad (y)$$
$$\Delta H_0^0 = -12.5 \text{ kcal/mole of } S_2O$$

S_2O (polysulfur oxide is formed first, but is completely decomposed by heating above 100 °C) [40].

In the vapor phase disulfur monoxide is stable for a few hours to a few days, but only at pressures of about 1 mm [40]. Its molecular weight corresponds to the simple formula S_2O [42]. Its decomposition is accelerated by heating and proceeds quantitatively in one minute at 180 °C [36]. Free S_2O is not stable in the condensed phase; polysulfur oxides are always formed.

Very sensitive methods are available for qualitative detection of S_2O. When gas containing S_2O is cooled to

[53] *D. J. Meschi* and *R. J. Myers*, J. molecular Spectroscopy *3*, 405 (1959).

[54] *P. A. Giguère*, J. physic. Chem. *64*, 190 (1960).

−195.8 °C (liquid nitrogen), an orange to deep red condensate is obtained. In this way it is possible to detect as little as 5–10% S_2O in a gas mixture; the color deepens with increasing S_2O content. The red condensate undergoes a characteristic color change to yellow on warming to between −150 °C and −100 °C [23,55]; at room temperature a solid, deep yellow residue of polysulfur oxide, together with SO_2, is all that remains. When the quantity of S_2O present is small, the polysulfur oxide is found in the cold trap as a yellow to whitish-yellow ring; this provides a very sensitive indication of the presence of S_2O if a large quantity of gas has been condensed [19].

An unambiguous and extremely sensitive method of detection involves ultraviolet spectroscopy, which permits the detection of S_2O at partial pressures as low as 10^{-3} mm in a cell 100 cm long. The most intense bands lie between 2800 and 3200 Å [15,40,47a,56].

Jones [47a] discovered two absorption regions at 679 and 1165 cm^{-1} in the infrared spectrum of S_2O (which he thought to be S_2O_2). These absorptions can be assigned to the S–S and S–O valence vibrations, respectively. The deformation vibration absorbs at 387 cm^{-1} [53].

II. Formation of S_2O

Disulfur monoxide can be obtained by two routes:

1. From sulfur monoxide, by disproportionation or by treatment with sulfur [Equations (z) and (α), respectively].

$$(SO)_2 + SO \rightarrow S_2O + SO_2 \quad (z)$$

$$(SO)_2 + S_2 \rightarrow 2\,S_2O \quad (\alpha)$$

2. By direct synthesis [Equations (β)–(ε)].

$$SOCl_2 + H_2S \rightarrow S_2O + 2\,HCl \quad (\beta)\ [57]$$

$$SOCl_2 + MS \rightarrow S_2O + MCl_2 \quad (\gamma)\ [58]$$

$$S_2Cl_2 + H_2O \rightarrow S_2O + 2\,HCl \quad (\delta)\ [57]$$

$$S_2Cl_2 + MO \rightarrow S_2O + MCl_2 \quad (\varepsilon)\ [57]$$

In Syntheses (γ) and (ε), the gaseous component (thionyl chloride or disulfur dichloride) is passed at about 1 mm over the heated metal sulfides (*e.g.* Ag_2S or Sb_2S_3) or oxides (*e.g.* Ag_2O, Sb_2O_3, or CdO). Some of the S_2O decomposes on the metal sulfide to form SO_2 [59]. If both of the reactants are gaseous, the gas mixture is allowed to pass rapidly at about 1 mm through a furnace and is subsequently condensed in a cold trap.

Reactions (β), (δ), and (ε) do not proceed to completion. Disulfur monoxide has so far been obtained only together with SO_2, but according to Reaction (γ) at a purity of up to 97% [58].

[55] *R. Steudel*, Diploma Thesis, Freie Universität Berlin, 1963.
[56] *H. Cordes*, Z. Physik *105*, 251 (1937).
[57] *P. W. Schenk*, *R. Steudel*, and *M. Töpert*, Z. Naturforsch. *19b*, 535 (1964).
[58] *P. W. Schenk* and *R. Steudel*, Angew. Chem. *76*, 97 (1964); Angew. Chem. internat. Edit. *3*, 61 (1964).
[59] *B. S. Rao* and *M. R. A. Rao*, Current Sci. *12*, 323 (1943).

III. Properties of S_2O

The most striking property of disulfur monoxide is its ease of polymerization, which prevents the establishment of phase equilibria, and hence also the characterization of the compound by its melting or boiling point. The deep red condensate described above (Section C. I) probably owes its color to congealed monomeric S_2O. Like SO_2, which has a similar structure, disulfur monoxide reacts with trimethylamine to form a crystalline donor-acceptor complex *(3)*, which is in equilibrium with its components [60]. The yellow solid *(3)* condenses out

$$(CH_3)_3N: + S_2O \rightleftharpoons (CH_3)_3\overset{\oplus}{N}\text{-}\underset{\ddot{O}:}{\overset{:\ddot{S}:}{\ddot{S}}}\text{=}\ddot{O} \longleftrightarrow (CH_3)_3\overset{\oplus}{N}\text{-}\underset{:\ddot{S}:}{\overset{\ddot{S}}{\ddot{S}}}\text{-}\ddot{O}:^{\ominus}$$

(3)

from a mixture of the components at 1 mm and −30 °C and is stable at this temperature for a few days. It can be sublimed *in vacuo* above −27 °C. Spectroscopic evidence shows the presence of free S_2O in the vapor; the complex therefore represents S_2O which is "stabilized" in the solid state. The complex *(3)* gives an intensely yellow solution in anhydrous inert organic solvents ($CHCl_3$ or CS_2) but decomposes at room temperature to yield sulfur, SO_2, and trimethylamine, owing to the cleavage of the S–S bonds by amine nitrogen [23]. Disulfur monoxide also appears to form a stable solid complex with triphenylphosphine [61]. BF_3 and S_2O (like BF_3 and SO_2) yield only very unstable adducts [60].

Disulfur monoxide does not react with nitrogen [18], and reacts with oxygen only after ignition or at elevated temperatures [37,62]; however, it reacts immediately with chlorine to form $SOCl_2$ and S_2Cl_2 [1].

Water vapor decomposes S_2O with deposition of sulfur and formation of H_2S; however, the decomposition is not so fast as to prevent the detection of S_2O in any reaction in which it is formed together with H_2O [23,24, 28,63].

Introduction of an S_2O/SO_2 mixture into ice-water leads to the formation of sulfur, hydrogen sulfide, and sulfur dioxide, while sulfide, sulfite, and thiosulfate are formed in alkaline solutions. Surprisingly, no polythionic acids can be detected [64].

Potassium iodide solutions are oxidized by S_2O to iodine with simultaneous formation of sulfur and hydrogen sulfide [64].

D. Polysulfur Oxides and Polysulfane Oxides

These names are used to denote products which always contain sulfur and oxygen, but which may also contain hydrogen, depending on their mode of preparation. They are generally mixtures of more or less polymeric compounds, which have not yet been extensively studied.

[60] *P. W. Schenk* and *R. Steudel*, Angew. Chem. *75*, 793 (1963); Angew. Chem. internat. Edit. *2*, 685 (1963).
[61] *K.-D. Wiebusch*, Ph. D. Thesis, Universität Heidelberg, 1948.
[62] *Y. Kondratyeva* and *W. Kondratyev*, Dokl. Acad. Sci. SSSR *31*, 128 (1941); Chem. Zbl. *1943*, I 246.
[63] *M. Töpert*, Diploma Thesis, Freie Universität Berlin, 1964.
[64] *P. W. Schenk*, Z. anorg. allg. Chem. *265*, 169 (1951).

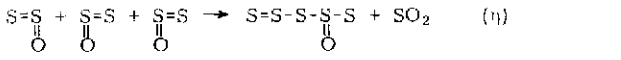
I. Polysulfur Oxides

"Pure" polysulfur oxides are formed during the polymerization of disulfur monoxide, which is always associated with partial disproportionation ("degradative polymerization") [40].

$$S_2O \rightarrow (S_nO)_x + SO_2 \quad n \geq 2 \qquad (\xi)$$

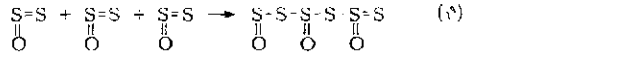
This decomposition reaction always occurs when the S_2O concentration is raised above a critical value by condensation of the gas at −196 °C and subsequent thawing, by introduction of the gas into organic solvents, or by raising the pressure in the vapor phase.

It may be assumed that polymerization proceeds by opening of the S–S double bonds, and that SO_2 is eliminated when the OS groups of two S_2O molecules come together, *e.g.* as shown in Equation (η).



$$(\eta)$$

However, owing to the polarity of the S_2O molecule, polymerization is also possible with similarly oriented molecules [Equation (ϑ)]. Thus Reaction (ϑ) can yield



$$(\vartheta)$$

polysulfur oxides with the composition S:O = 2:1 (cf. the composition S:O = 3:1 calculated on the basis of Equation (η) [40,42,55]). The remaining S–S double bond in the polysulfur oxides is probably delocalized, as in π-sulfur [67].

A characteristic feature with all polysulfur oxides is the course of their thermal decomposition *in vacuo*, which results in regeneration of disulfur monoxide (maximum 50 mole% S_2O) [40], probably in accordance with Equations ($\varkappa$) and (p).

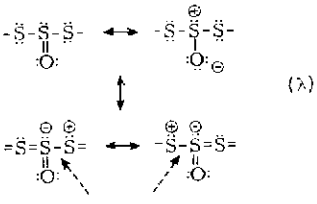
$$(S_nO)_x \rightarrow xSO + (n-1)xS \qquad (\varkappa)$$

In compounds containing sulfur chains, the S atoms are not simply linked by single bonds; instead, the "lone" electron pairs also participate, with occupation of the bonding d-orbitals [52,68–71]. This can be expressed by the formulae *(4a)* and *(4b)*.

(4a) *(4b)*

Sulfur chains, such as those in π-sulfur [67], and S_2 and S_2O, with almost pure S–S double bonds and electron deficiencies [68] at the terminal sulfur atoms, exhibit a strong tendency to polymerize.

In the polysulfur oxides, the uniformity of the bond order along the sulfur chain is upset. The triply bonded sulfur atoms attain a stable configuration with 12 valence electrons which prevents the formation of two double bonds to the two adjacent sulfur atoms. This explains the ease of thermolysis of polysulfur oxides; the reaction probably involves elimination of SO [cf. Scheme (λ)].



$$(\lambda)$$

1. Preparation of Polysulfur Oxides by Freezing out S_2O

On thawing, the red condensate of disulfur monoxide (cf. Section C. I) becomes deep yellow between −150 and −100 °C. This color change is regarded as a sign of polymerization. At room temperature, a solid, yellow polysulfur oxide is obtained, the gas phase then consisting of SO_2 together with some S_2O [23,40]. Thus, condensed S_2O cannot be vaporized without decomposition. After the gas has been pumped off, the stoichiometric composition of the polysulfur oxide is found to be approximately S_3O [42,65]. The substance is amorphous to X-rays [1], and its molecular weight is unknown. Only a small portion dissolves in carbon disulfide, giving a deep yellow solution [1,72].

Murthy [65] claims that warming condensed S_2O to −30 °C leads to pure, orange-red S_2O, if the sulfur dioxide which is still present from the preparation of the S_2O is removed by purging with nitrogen. However, this color could not be reproduced at −30 °C [23,55]. It is doubtful whether the SO_2 could be completely removed from the yellow polymer in this way. The composition S:O = 2:1 is probably merely fortuitous [66] and furnishes no proof of the presence of pure disulfur monoxide.

2. Preparation of Polysulfur Oxides by Dissolution of S_2O

When a mixture of S_2O and SO_2 is led into cooled (−20 °C) chloroform or methyl phenyl ether, the S_2O immediately polymerizes. The yellow solution can be freed from SO_2 by purging with nitrogen. The dissolved material has a molecular weight of 210–380 or higher and a composition S:O = 2.2:1–5.6:1; it is therefore a polysulfur oxide [42,44,73].

Nevertheless *Murthy* described the reactions of these solutions with water and piperidine as "reactions of S_2O" [74,75].

Solutions of polysulfur oxides oxidize hydrogen iodide stoichiometrically to iodine, in accordance with Equation (μ). This provides a convenient titrimetric method

$$(S_nO)_x + 2xHI \rightarrow nxS + xI_2 + xH_2O \qquad (\mu)$$

[65] *A. R. V. Murthy*, IUPAC Colloquium, Division of Inorganic Chemistry, Münster (Germany) 1954, Verlag Chemie, Weinheim/Bergstr. 1955, p. 141; *A. R. V. Murthy*, Proc. Indian Acad. Sci., Sect. A *36*, 388 (1952).

[66] *P. W. Schenk*, Z. anorg. allg. Chem. *285*, 297 (1956).

[67] *P. W. Schenk* and *U. Thümmler*, Z. anorg. allg. Chem. *315*, 271 (1962).

[68] *J. Goubeau*, Angew. Chem. *69*, 77 (1957).

[69] *L. Pauling*: The Nature of the Chemical Bond. 3rd edit., Cornell Univ. Press, Ithaca 1960.

[70] *M. Schmidt*, Österr. Chemiker-Ztg. *64*, 236 (1963).

[71] *F. Fehér* and *H. Münzer*, Chem. Ber. *96*, 1131 (1963).

[72] *W. Holst*, Ph. D. Thesis, Freie Universität Berlin, 1960.

[73] *M. Goehring* and *K.-D. Wiebusch*, Z. anorg. allg. Chem. *257*, 227 (1948).

[74] *K. Sharada* and *A. R. V. Murthy*, J. Indian Inst. Sci. *44*, 49 (1962).

[75] *C. G. R. Nair* and *A. R. V. Murthy*, Canad. J. Chem. *41*, 898 (1963).

for the volumetric determination of the oxidation state [73 76].

3. *Preparation of Polysulfur Oxides by Compression of Gaseous S_2O*

Gaseous disulfur monoxide is stable for a few hours to a few days, but only at about 1 mm [40]; on compression of the gas to about 40 mm, polysulfur oxide separates out as an aerosol and as a film on the wall of the vessel [36]. However, gaseous S_2O can be handled at higher pressures when diluted with nitrogen or sulfur dioxide, provided its partial pressure remains low [1].

II. Polysulfane Oxides (Polysulfur Oxides Containing Hydrogen)

1. *Preparation of Polysulfane Oxides from SO_2 and H_2S*

H_2S and SO_2 react at room temperature and below in the presence of traces of water to form polysulfane oxides. When the moist gases are mixed, the polysulfane oxide is deposited on the walls of the vessel [64]; if the gases are led into cooled organic solvents, they form solutions of polysulfane oxides, from which the latter can be precipitated [73].

The most important of these polymers is "Wackenroder's sulfur"; it is precipitated when a vigorous current of H_2S is led into ice-water saturated with SO_2. After filtration, washing, and drying at 10^{-2} mm and 0 °C, the approximate composition of the yellow, plastic product is $S:O:H \approx 5:1:1.1$ [41,63]. The substance can be stored at −20 °C for several days without decomposing. On thermolysis *in vacuo*, SO_2, S_2O, and H_2O are liberated, possibly with some H_2S, leaving a residue of sulfur. It is not improbable that some of the hydrogen here is bound in the form of occluded water [63,77].

The yellow solutions obtained by dissolving H_2S and SO_2 in organic solvents tend to become turbid and to fluorescence, and must be stabilized by drying over phosphorus pentoxide, since they otherwise decompose to form SO_2 and sulfur. After removal of residual synthesis gases with a filter pump, the composition was $S:O = 4:1-8:1$. The molecular weight of one product was found to be 360 [73]. As expected, the dissolved polysulfane oxide disproportionates on heating to form sulfur and SO_2 [73]. The yellow solutions oxidize hydrazoic acid to nitrogen and liberate an equivalent amount of iodine from a solution of hydrogen iodide in formic acid [73].

The reaction of H_2S and SO_2 in CCl_4 at −10 to −15 °C yields a polysulfane oxide with a particularly high oxygen content. This product is obtained as an intensely yellow precipitate with a composition corresponding closely to the formula $H(S_2O)_nSH$; this formula can be derived from Equations (ν) and (π) [78].

[76] *H. Stamm* and *K.-D. Wiebusch*, Naturwissenschaften *32*, 42 (1944).

[77] *W. Kretschmer*, Diploma Thesis, Freie Universität Berlin, 1962.

[78] *R. Ludwig*, Diploma Thesis, Technische Universität Berlin, 1965.

In our opinion, the initial product of the Wackenroder reaction is (as has long been thought [79]) thiosulfurous acid, which exists in equilibrium with H_2S and H_2SO_3 [24,41,64,80]. The unsymmetrical form of thiosulfurous

$$H_2S + H_2SO_3 \rightleftarrows H_2S_2O_2 + H_2O \qquad (\nu)$$

acid, HO–SO–SH, is initially formed and slowly rearranges to the symmetrical form HO–SS–OH. This then condenses with sulfurous acid to form tetrathionic acid *(5)*, which is the first and principal product of the Wackenroder reaction [81].

$$HO{-}SS{-}OH + 2\ H_2SO_3 \rightarrow \underset{(5)}{H_2S_4O_6} + 2\ H_2O \qquad (\xi)$$

When H_2S is led rapidly into the SO_2 solution, some of the unsymmetrical thiosulfurous acid condenses to form the deep yellow polysulfane oxide, which precipitates out (Wackenroder's sulfur) [see Scheme π].

$$HSH + HO{-}\overset{\overset{O}{\|}}{S}{-}OH + HSH + HO{-}\overset{\overset{O}{\|}}{S}{-}OH \qquad (\pi)$$

$$\rightarrow HS{-}\overset{\overset{O}{\|}}{S}{-}OH + HS{-}\overset{\overset{O}{\|}}{S}{-}OH + 2\ H_2O$$

$$\xrightarrow{H_2S} HS{-}\overset{\overset{O}{\|}}{S}{-}S{-}\overset{\overset{O}{\|}}{S}{-}SH + 2\ H_2O$$

The ideal composition of polysulfane oxide, $H(S_2O)_nSH$, is never quite attained because of the sensitivity of the substance towards water. The oxygen content of polysulfane oxide increases as the quantity of water present decreases. The fluffy powder is stable for several days at −20 °C. No monomeric S_2O can be detected during the Wackenroder reaction [24].

2. *Preparation of Polysulfane Oxides from $SOCl_2$ and H_2S*

Liquid thionyl chloride reacts with H_2S at room temperature in accordance with Scheme *(ρ)*.

$$HSH + Cl{-}\overset{\overset{O}{\|}}{S}{-}Cl + HSH + Cl{-}\overset{\overset{O}{\|}}{S}{-}Cl + HSH \qquad (\rho)$$

$$\xrightarrow[-4\ HCl]{} H{-}S{-}\overset{\overset{O}{\|}}{S}{-}S{-}\overset{\overset{O}{\|}}{S}{-}S{-}H$$

The yellow, plastic reaction product was formerly thought to be sulfur, but has been identified as a polysulfane oxide by thermolysis *in vacuo* and spectroscopic detection of the S_2O formed [57]. If H_2S is passed into a solution of $SOCl_2$ in absolute ether at −10 °C, polysulfane oxide again precipitates out as a light powder. After drying *in vacuo*, the composition of a product obtained in this manner was found to correspond approximately to the formula $H_2S_{14}O_5$. Thus the terminal atoms of the chains are hydrogen, and not chlorine [78].

[79] *R. Foerster* and *A. Hornig*, Z. anorg. allg. Chem. *125*, 86 (1922).

[80] *H. Stamm* and *M. Goehring*, Naturwissenschaften *27*, 317 (1939).

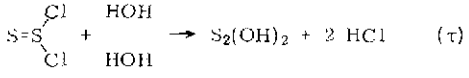
[81] *R. Krämer*, Ph. D. Thesis, Technische Universität Berlin, 1964.

3. Preparation of Polysulfane Oxides from S_2Cl_2 and H_2O

When S_2Cl_2, preferably dissolved in CCl_4, is hydrolysed with ice-water, polysulfane oxide is formed, probably *via* thiosulfurous acid [Equation (σ)], as in the Wackenroder reaction [57,63].

$$S_2Cl_2 + 2\ H_2O \rightarrow H_2S_2O_2 + 2\ HCl \qquad (\sigma)$$

The analogy with the Wackenroder reaction would be particularly striking if the disulfur dichloride could react as thiothionyl chloride *(6)*, as shown in Equation (τ).



$$(\tau)$$

(6)

The syntheses of S_2O from S_2Cl_2 vapor suggest that the isomer *(6)* does perhaps exist in equilibrium with the dichlorodisulfane Cl–S–S–Cl detected. This is also supported by other reactions of S_2Cl_2 [82]. In the case of S_2F_2, both isomers are actually obtained and have been characterized by their infrared and microwave spectra [83,84].

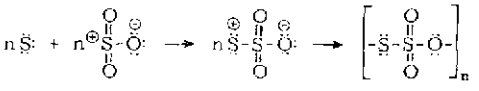
E. Disulfur Trioxide S_2O_3

I. Formation of S_2O_3

Disulfur trioxide is a blue-green solid formed in a vigorous reaction when sulfur is introduced into liquid sulfur trioxide. After a few hours, the product can be separated from the excess SO_3 by decantation; residual traces of SO_3 are removed in a current of CO_2 [85] or with a filter pump, care being taken to exclude moisture [77].

II. Constitution of S_2O_3

Disulfur trioxide is thought to exist as a polymeric substance *(7)* [85] formed by insertion of sulfur into the electron deficiencies of the Lewis acid SO_3.



(7)

The sulfur acts here as an electron donor and can consequently be displaced by stronger donors. For example, S_2O_3 is decomposed by pyridine, with formation of the adduct pyridine·SO_3 and sulfur; the sulfur is extremely reactive [85]. This reaction and the discovery that S_2O_3 synthesized from radioactive elemental sulfur and SO_3 yields only inactive SO_3 on degradation support the structural formula *(7)* [86].

III. Properties of S_2O_3

Disulfur trioxide gradually assumes a light brown color and is stable only at −80 °C under CO_2, and even then for only a few hours [85]. It is insoluble in liquid sulfur trioxide, but dissolves in fuming sulfuric acid to give a deep blue solution. Similar blue solutions are also obtained on direct addition of sulfur to fuming sulfuric acid.

Depending on the SO_3 content of these solutions, the ESR spectrum shows the presence of one of two different free sulfur radicals, namely a blue compound at high SO_3 contents and a brown substance at low SO_3 contents [87]. It has been concluded from comparison of the visible, ultraviolet, and ESR spectra of the solutions of sulfur in oleum that the blue paramagnetic substance is monomeric S_2O_3, which slowly polymerizes to colorless $(S_2O_3)_x$. The solutions do become colorless on standing, but the blue color can be regenerated by gentle warming [88].

The brown radical present in solutions with low SO_3 contents is thought to be similar to the radicals present in molten sulfur [89], being a stage intermediate between S_2O_3 and the sulfur precipitated on dilution of sulfur-oleum solutions.

The only products of hydrolysis of S_2O_3, apart from sulfur, are H_2SO_4 and H_2SO_3 in a ratio of about 5:1. The sulfurous acid results from reduction of SO_3 by elemental sulfur [85].

Decomposition of solid disulfur trioxide at temperatures of up to 150 °C yields sulfur, SO_2, and SO_3 [85]. It was thought earlier that SO was formed as an intermediate, and decomposed in accordance with Equation (a) [90]. However, attempts to detect SO by ultraviolet spectroscopy as its derivative S_2O yielded no experimental evidence for the intermediate formation of lower oxides of sulfur [24]. The earlier results were confirmed recently after evidence had meanwhile been given to the contrary [91]; the S_2O spectrum was not observed, and no polymeric sulfur oxide residue was found on evaporation of the condensed gases [77].

It may therefore be assumed that the decomposition proceeds according to Equation (φ), and that the extremely reactive sulfur produced reduces some of the S_2O_3 to SO_2 [Reaction (χ)].

$$S_2O_3 \rightarrow S + SO_3 \qquad (\varphi)$$

$$2\ S_2O_3 \rightarrow S + 3\ SO_2 \qquad (\chi)$$

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Translated by Express Translation Service, London

[82] Cf. Gmelins Handbuch der anorganischen Chemie, Sulfur B, Section 3. Verlag Chemie, Weinheim/Bergstr. 1963, p. 1765.

[83] *F. Seel* and *R. Budenz*, Chimia *17*, 355 (1963); *F. Seel* and *H. D. Gölitz*, Z. anorg. allg. Chem. *327*, 32 (1964).

[84] *R. L. Kuczkowski*, J. Amer. chem. Soc. *85*, 3617 (1963).

[85] *R. Appel* and *M. Goehring*, Z. anorg. allg. Chem. *265*, 312 (1951).

[86] *R. Appel*, Naturwissenschaften *40*, 509 (1953).

[87] *D. J. E. Ingram* and *M. C. R. Symons*, J. chem. Soc. (London) *1957*, 2437.

[88] *M. C. R. Symons*, J. chem. Soc. (London) *1957*, 2440.

[89] *D. M. Gardner* and *G. K. Fraenkel*, J. Amer. chem. Soc. *78*, 3279 (1956).

[90] *L. Wöhler* and *O. Wegwitz*, Z. anorg. allg. Chem. *213*, 129 (1933).

[91] *A. R. V. Murthy*, Nature (London) *168*, 475 (1951).

The Prostaglandins

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Prostaglandins occur in many animal species and tissues. They are C_{20}-carboxylic acids containing one five-membered ring, one keto group, two or three hydroxy groups, and one to three C=C double bonds. Their structures were elucidated by chemical, radiochemical, and physical methods in combination with gas chromatography and mass spectrometry. The prostaglandins are biosynthesized from essential fatty acids. By their action smooth muscles are stimulated and lipid metabolism is affected.

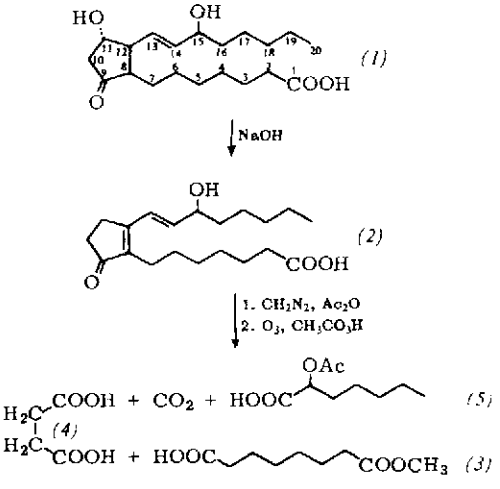
Introduction

In 1933–1934 *Goldblatt* [1,2] and *von Euler* [3] independently demonstrated the presence of vasodepressor and smooth muscle stimulating material in extracts of human seminal plasma and of vesicular glands of sheep. *Von Euler* also showed that the biological activity was due to lipid soluble material with acidic properties, and named the factor prostaglandin [4–7].

In 1957, *Bergström* and *Sjövall* reported the isolation of two biologically active crystalline compounds, PGE_1 and $PGF_{1\alpha}$, from vesicular gland of sheep [8–10]. PGE_1 was a very potent vasodepressor and smooth muscle stimulant, whereas $PGF_{1\alpha}$ only possessed smooth muscle stimulating activity. Later, additional compounds having similar biological activity, *i.e.* PGE_2 and PGE_3, were isolated from the same tissue [11]. However, investigations which will be described in more detail below have demonstrated that the prostaglandins are more widely distributed in animal tissues. These findings and the recent experiments demonstrating that the prostaglandins are biosynthesized from essential fatty acids have provided a new impetus for studies of the physiological role of the prostaglandins.

I. Chemistry

It was demonstrated with different physical methods that PGE_1 is a C_{20}-carhoxylic acid ($C_{20}H_{34}O_5$) containing two hydroxy groups, one keto group in a five-membered ring and one *trans*-double bond. Treatment of PGE_1 *(1)* with alkali gave a compound (PGE_1–278) *(2)* with λ_{max} at 278 mμ [12,13]. On oxidative ozonolysis, the acetylated methyl ester of this derivative gave monomethyl suberate *(3)*, succinic acid *(4)*, and α-acetoxyheptanoic acid *(5)*, *i.e.* all but one of the carbon atoms of PGE_1 – 278 were accounted for. The degradation products were



separated by gas-liquid chromatography and identified by mass spectrometry. The isolation of succinic acid, which must originate in the ring, showed that two vicinal methylene groups were present in the five-membered ring and that, accordingly, the three carbon atoms carrying the side chains and the keto group must be adjacent. Furthermore, the isolation of monomethyl suberate, produced by oxidation of the vicinal diketone originally formed, indicated that the carboxyl side chain must be attached to the carbon atom that is in α-position relative to the keto group. The proposed structure of PGE_1–278 was also supported by the infrared data.

Another derivative was prepared by treatment of hydrogenated PGE_1 *(6)* with 0.5 N NaOH at 100 °C. This compound, PGE_1–237 *(7)* [λ_{max} = 237 mμ in ethanol], was degraded by oxidative ozonolysis after conversion to the methyl ester and acetate. Only two products were formed, *i.e.* monomethyl suberate *(3)* and 7-acetoxy-4-oxododecanoic acid *(8)*. The structure of the latter compound was deduced from mass-spectrometric and gas-

[1] *M. W. Goldblatt*, Chem. and Ind. *52*, 1056 (1933).

[2] *M. W. Goldblatt*, J. Physiology *84*, 208 (1935).

[3] *U. S. v. Euler*, Naunyn-Schmiedebergs Arch. exp. Pathol. Pharmakol. *175*, 78 (1934).

[4] *U. S. v. Euler*, Klin. Wschr. *33*, 1182 (1935).

[5] *U. S. v. Euler*, J. Physiology *88*, 213 (1936).

[6] *U. S. v. Euler* and *S. Hammarström*, Skand. Arch. Physiol. *77*, 96 (1937).

[7] *U. S. v. Euler*, Skand. Arch. Physiol. *81*, 65 (1939).

[8] *S. Bergström* and *J. Sjövall*, Acta chem. scand. *11*, 1086 (1957).

[9] *S. Bergström* and *J. Sjövall*, Actachem. scand. *14*, 1693 (1960).

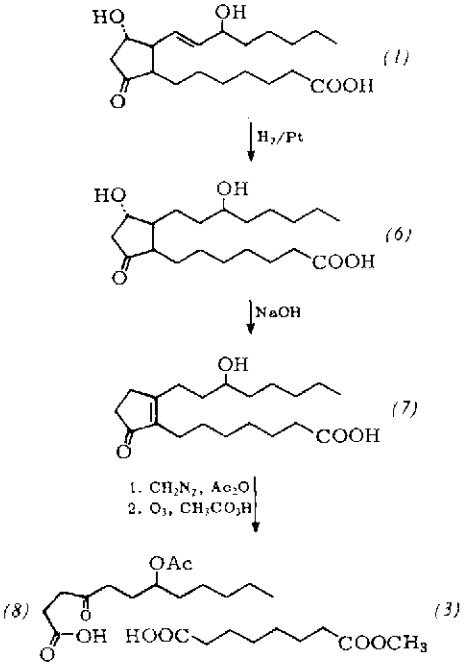
[10] *S. Bergström* and *J. Sjövall*, Acta chem. scand. *14*, 1701 (1960).

[11] *S. Bergström, F. Dressler, R. Ryhage, B. Samuelsson*, and *J. Sjövall*, Ark. Kemi *19*, 563 (1962).

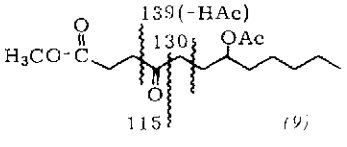
[12] *S. Bergström, R. Ryhage, B. Samuelsson*, and *J. Sjövall*, Acta chem. scand. *16*, 501 (1962).

[13] *S. Bergström, R. Ryhage, B. Samuelsson*, and *J. Sjövall*, J. biol. Chemistry *238*, 3555 (1963).

chromatographic data. In the mass spectrum of methyl 7-acetoxy-4-oxododecanoate *(9)* no molecular ion could be observed but peaks at m/e=226 (elimination of acetic acid) and at m/e=195, (subsequent loss of a methoxy



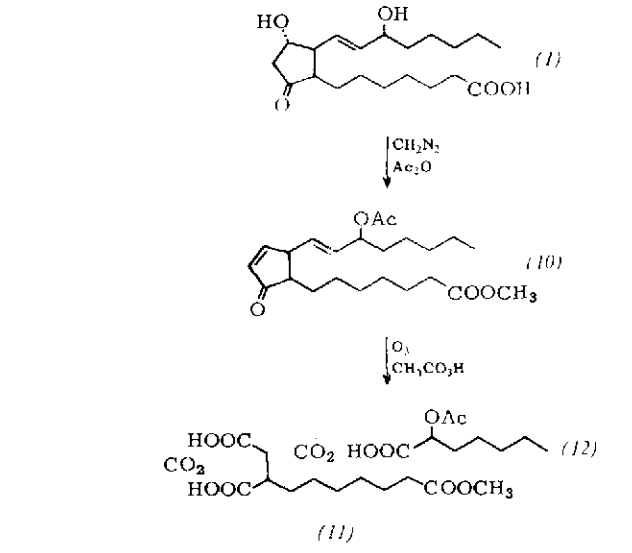
group) are seen. The position of the keto group in *(9)* was determined from the peaks at m/e=115, 139 and 130. The ion at m/e=130 is formed by cleavage of the

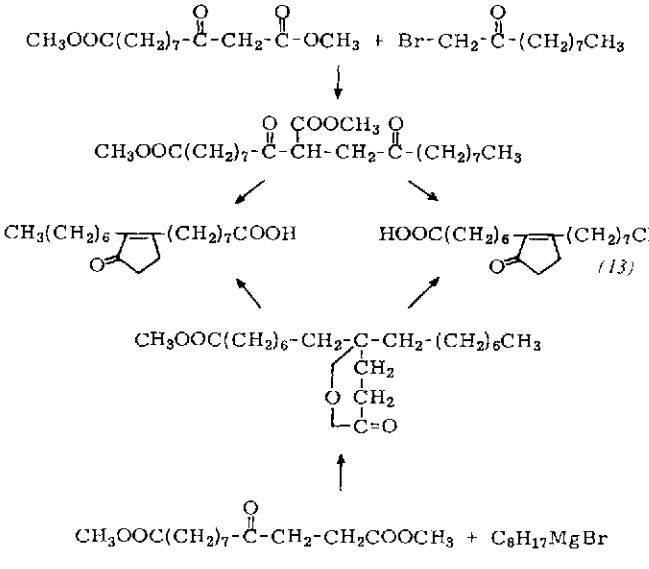


C(5)–C(6) bond and transfer of a hydrogen atom from C–7 to the oxygen of the keto group. The presence of the acetoxy group at C–7 was indicated by a peak at m/e=155, probably formed by cleavage of *(9)* between C–7 and C–8 and elimination of acetic acid. All of the 20 carbon atoms of the prostaglandin molecule were thus identified.

The formation of the two degradation products *(3)* and *(8)* has been visualized as follows: Initial attack on the tetrasubstituted double bond in *(7)* results in formation of two keto groups, one of which is vicinal to the original one. Oxidative cleavage of the C–C bond between the vicinal keto groups by peracetic acid affords the two carboxyl groups of monomethyl suberate *(3)* and of 7-acetoxy-4-oxododecanoic acid *(8)*. The ultraviolet absorption of PGE_1–237 *(7)* was in accordance with the values reported for a number of trisubstituted α,β-unsaturated cyclopentenones and the tetrasubstitution of the double bond was confirmed by the absence of signals for olefinic protons in the NMR spectrum of *(7)*. Treatment of PGE_1 *(1)* with acetic anhydride yielded a derivative *(10)* with λ_{max} = 218 mμ in ethanol. Oxidative ozonolysis of the methyl ester acetate of this compound gave 1,2,8-octanetricarboxylic acid *(11)*, α-acetoxyheptanoic acid *(12)*, and CO_2. The formation of these degradation products provided firm support for the proposed structure of PGE_1–218 *(10)*.

The physical data of the derivatives of PGE_1 [PGE_1–278 *(2)*, PGE_1–237 *(7)*, and PGE_1–218 *(10)*] and the identification of their degradation products rigorously established their structures. From this work followed the structures of the side chains of PGE_1 *(1)* as well as their positions on the ring and the position of the keto group. The position of the hydroxy group was derived from indirect evidence. Acylation experiments as well as NMR data ruled out that the hydroxy group was attached to a tertiary carbon atom and the remaining two positions could easily be differentiated. A hydroxy group at the secondary carbon atom α to the keto group was excluded by the finding that neither PGE_1 *(1)* nor $PGF_{1\alpha}$ or $PGF_{1\beta}$ (see Section II) were oxidized by periodate or lead tetraacetate. However, the presence of the hydroxy group at the secondary carbon atom β to the keto group was in agreement with the facile elimination of water with formation of a monosubstituted α,β-unsaturated ketone on treatment of PGE_1 *(1)* with acetic anhydride. Finally, the carbon skeleton of PGE_1 was established by comparing the derivative *(13)* with a synthetic specimen prepared by two different procedures [14]. The structure of PGE_1 was confirmed by a three-dimensional single crystal X-ray analysis of the tris-*p*-bromobenzoate of the





[14] *B. Samuelsson* and *G. Ställberg*, Acta chem. scand. *17*, 810 (1963).

methyl ester of $PGF_{1\beta}$ [15–17]. In addition, this investigation provided the stereochemical features of the molecule which are shown in Figure 1.

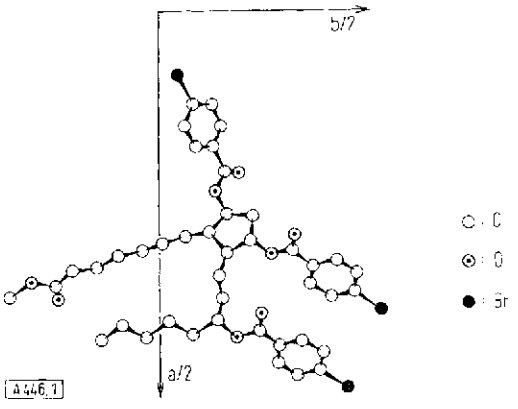
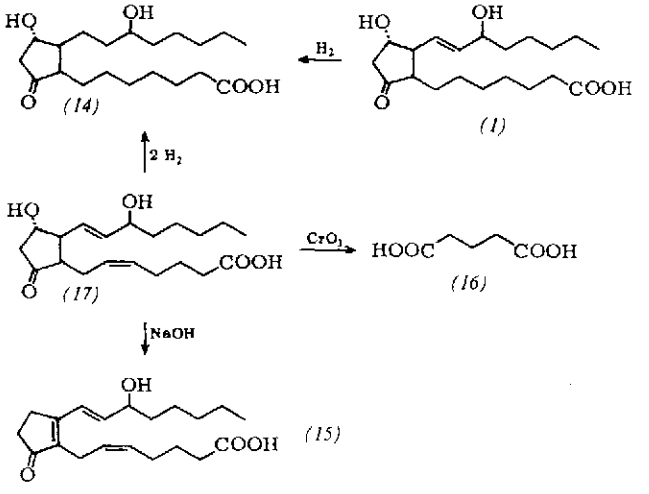


Fig. 1. Molecular model of the methyl ester of prostaglandin $PGF_{1\beta}$ (in the form of its tris-*p*-bromobenzoate) as derived from X-ray analysis.

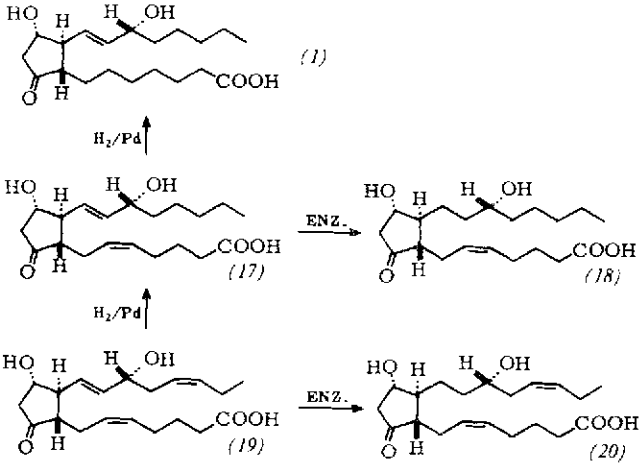
The structures of PGE_2 *(17)* and PGE_3 *(19)* were partly elucidated by mass spectrometry, which showed that the molecular weight of PGE_3 was two units less than that of PGE_2 and four units less than that of PGE_1 [11]. That the parent structure was the same for all three compounds followed from their conversion by catalytic reduction into the same derivative *(14)* as judged by mass-spectrometric analysis. Since all three compounds were



transformed into chromophores *(15)* with the same λ_{max} on treatment with alkali, it was evident that they all had the Δ^{13}-double bond demonstrated for PGE_1 *(1)*. The location of the additional double bond of PGE_2 *(17)* in the carboxyl side chain was indicated by mass spectrometry and its position was established by the identification of glutaric acid *(16)* as a product of chromic acid oxidation. Using the same methods it could also be established that PGE_3 *(19)* only differed from PGE_2 *(17)* by having an additional double bond.

The final elucidation of the structure of PGE_3 was achieved by NMR spectroscopy [18]. The NMR spectrum of PGE_3 showed six olefinic protons between 4.25 and 4.8 τ. Two of these protons appeared at low frequencies (4.25 to 4.5 τ) and in the same region as the two olefinic protons in PGE_1 due to the deshielding by the allylic hydroxy group at C–15. The other four olefinic protons in PGE_3 *(19)* had the same chemical shift as the olefinic protons in the carboxyl side chain of PGE_2 *(17)*. Of particular interest for the structure determination was the absorption due to the protons of the methyl group in PGE_3, appearing as a clear triplet at 9.04 τ. The spin-spin splitting and chemical shift of the methyl protons in PGE_3 demonstrated that the double bond in the terminal pentyl group was located between C–17 and C–18.

That the stereochemical features of PGE_1 *(1)*, PGE_2 *(17)* and PGE_3 *(19)* are identical was recently demonstrated through conversions of PGE_2 into PGE_1 and of PGE_3 into PGE_2 by selective catalytic hydrogenation of the Δ^{17}-and Δ^{5}-double bonds, respectively [19, 20].



With regard to the stereochemistry of the double bonds, it was observed that PGE_1 *(1)* exhibits infrared absorption at 10.3 μ, demonstrating that the Δ^{13}-double bond has the *trans* configuration. PGE_2 *(17)* and PGE_3 *(19)* also show absorptions at this wavelength but it could not be decided wether the absorption was due to the Δ^{5}-and Δ^{17}-double bonds in addition to the Δ^{13}-double bond. This question has recently been solved by selective reduction of the Δ^{13}-double bond of PGE_2 and PGE_3 by enzymes from lung tissue [21]. The reduction products *(18)* and *(20)* do not show any absorption at 10.3 μ, demonstrating that the Δ^{5}-and the Δ^{17}-double bonds of PGE_2 and PGE_3 have the *cis* configuration.

Chemical reduction of PGE_1 *(1)* results in formation of two trihydroxy acids epimeric at C–9. These have been designated $PGF_{1\alpha}$ and $PGF_{1\beta}$ [15]. Similarly, PGE_2 gives $PGF_{2\alpha}$ and $PGF_{2\beta}$, and PGE_3 gives $PGF_{3\alpha}$ and $PGF_{3\beta}$ [11]. Only the PGF compounds with the hydroxy group at C–9 in α-position occur naturally. Recently, a systematic nomenclature based on the trivial name prostanoic acid for the parent C_{20}-acid has been introduced (see Table 1).

[15] *S. Bergström, L. Krabisch, B. Samuelsson*, and *J. Sjövall*, Acta chem. scand. *16*, 969 (1962).

[16] *S. Abrahamsson, S. Bergström*, and *B. Samuelsson*, Proc. chem. Soc. (London) *332*, (1962).

[17] *S. Abrahamsson*, Acta crystallogr. *16*, 409 (1963).

[18] *B. Samuelsson*, J. Amer. chem. Soc. *85*, 1878 (1963).

[19] *B. Samuelsson*, J. biol. Chemistry *239*, 4091 (1964).

[20] *K. Green* and *B. Samuelsson*, unpublished work.

[21] *E. Änggård* and *B. Samuelsson*, unpublished work.

Table 1. Systematic names of prostaglandins.

(1)	PGE_1	11α,15-Dihydroxy-9-oxo-13-prostenoic acid
(17)	PGE_2	11α,15-Dihydroxy-9-oxo-5,13-prostadienoic acid
(19)	PGE_3	11α,15-Dihydroxy-9-oxo-5,13,17-prostatrienoic acid
	$PGF_{1\alpha}$	9α,11α,15-Trihydroxy-13-prostenoic acid
	$PGF_{2\alpha}$	9α,11α,15-Trihydroxy-5,13-prostadienoic acid
	$PGF_{3\alpha}$	9α,11α,15-Trihydroxy-5,13,17-prostatrienoic acid

II. Occurrence

PGE_1 and $PGF_{1\alpha}$ were isolated in pure form for the first time from the vesicular gland of sheep in 1957 [8–10]. A few years later two additional compounds, *i.e.* PGE_2 and PGE_3 were isolated from the same source [11]. Seminal plasma of the sheep has been shown to contain PGE_1 and one other smooth muscle stimulating component [22]. No reinvestigation has been performed after PGE_2 and PGE_3 were recognized.

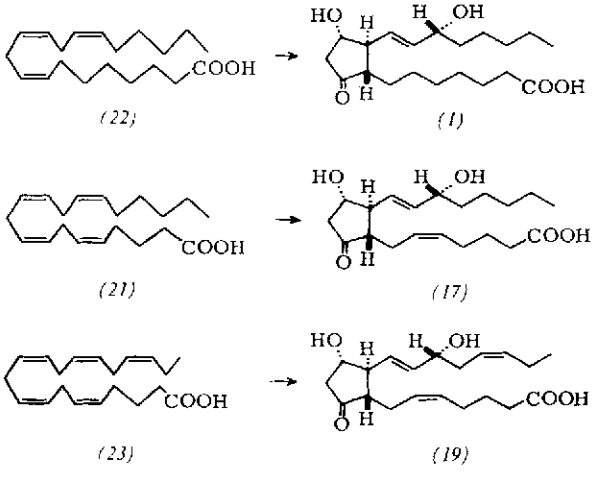
Human seminal plasma, which has been investigated in more detail recently, was shown to contain five different prostaglandins, *viz.* PGE_1, PGE_2, PGE_3, $PGF_{1\alpha}$, and $PGF_{2\alpha}$ [23]. The concentrations of these compounds have been determined in single samples of seminal plasma by a method which was recently developed [24]: After group separation of the prostaglandins into PGE and PGF compounds by chromatography on silicic acid, the PGE group was further separated by thin-layer chromatography using silica gel impregnated with silver nitrate. The PGE compounds were eluted from the plates and determined quantitatively by measuring the absorption at 278 mμ, which develops on treatment of the eluates with alkali. The chromophore with λ_{max} at 278 mμ is due to a dienone formed by dehydration of the β-ketol system and isomerization of the introduced double bond. The PGF compounds, $PGF_{1\alpha}$ and $PGF_{2\alpha}$, were converted into their methyl esters and treated with hexamethyldisilazane in tetrahydrofuran with trimethylchlorosilane as catalyst. The resulting trimethylsilyl ether derivatives were separated and determined quantitatively by gas-liquid chromatography. The concentrations of prostaglandins in seminal plasma of normal males were: PGE_1: 25 μg/ml, PGE_2: 23 μg/ml, PGE_3: 6 μg/ml, $PGF_{1\alpha}$: 3 μg/ml and $PGF_{2\alpha}$: 4 μg/ml.

Recent experiments demonstrated that the prostaglandins are present in a variety of tissues and species. $PGF_{2\alpha}$ was thus first isolated from lung tissue of sheep and pig [25] and has more recently also been demonstrated in lungs of guineapig, monkey, and man [26]. The concentration of $PGF_{2\alpha}$ in lung tissue of sheep was determined to be about 0.5 μg/g tissue (fresh weight) by use of isotope dilution [27]. PGE_2 has recently also been identified in sheep lung [27] and $PGF_{3\alpha}$ in bovine lung [28]. In calf thymus only PGE_1 could be detected [29].

The presence of smooth muscle stimulating material in extracts of iris and brain tissue from various species has been reported [30,31]. Since the properties of these substances to some extent agreed with those of the prostaglandins, the material was further investigated. Sheep iris contained several lipid soluble and smooth muscle stimulating compounds which could be separated by chromatography on silicic acid. One of these components was identified as $PGF_{2\alpha}$ [32]. The same compound could be identified in extracts of bovine brain and was present in a concentration of about 0.3 μg/g tissue (fresh weight) [33]. PGE_2 and $PGF_{2\alpha}$ have also been detected in menstrual fluid [34].

III. Biosynthesis

It was recently demonstrated [35,36] that [^{3}H]-arachidonic acid *(21)* [all-*cis*-eicosa-5,8,11,14-tetraeonic acid] is converted into labelled PGE_2 *(17)* by homogenates of the vesicular gland of sheep and it was also predicted that homo-γ-linolenic acid *(22)* [all-*cis*-8,11,14-trienoic acid] and all-*cis*-eicosa-5,8,11,14,17-pentaenoic acid *(23)* would be precursors of PGE_1 and PGE_3, respectively. The conversion of homo-γ-linolenic acid *(22)* into PGE_1



(1) has been demonstrated experimentally with the ^{14}C-labelled precursor [37,38]. It could also be shown that the net formation of PGE_3 *(19)* increased after addition of all-*cis*-eicosa-5,8,11,14,17-pentaenoic acid *(23)* [37]. This conversion has been confirmed with [14c]-

[22] *S. Bergström, L. Krabisch,* and *J. Sjövall,* Acta chem. scand. *14,* 1706 (1960).

[23] *B. Samuelsson,* J. biol. Chemistry *238,* 3229 (1963).

[24] *M. Bygdeman* and *B. Samuelsson,* Clin. chim. Acta (Amsterdam), in the press.

[25] *S. Bergström, F. Dressler, L. Krabisch, R. Ryhage,* and *J. Sjövall,* Ark. Kemi *20,* 63 (1962).

[26] *E. Änggård,* Abstracts, Sixth International Congress of Biochemistry, New York 1964, VII, 562

[27] *E. Änggård* and *B. Samuelsson,* Acta physiol. scand. *59,* Suppl. No. 213, p. 170 (1963).

[28] *B. Samuelsson,* Biochim. biophysica Acta *84,* 707 (1964).

[29] *S. Bergström* and *B. Samuelsson,* Acta chem scand. *17,* 282 (1963).

[30] *N. Ambache,* Biochem. Pharmacol. *12,* 412 (1963).

[31] *N. Ambache, M. Reynolds,* and *J. Whiting,* J. Physiology *166,* 251 (1963).

[32] *E. Änggård* and *B. Samuelsson,* Biochem. Pharmacol. *13,* 281 (1964).

[33] *B. Samuelsson,* Biochim. biophysica Acta *84,* 218 (1964).

[34] *T. Eglington, R. A. Raphael, N. Smith, W. J. Hall,* and *V. R. Pickles,* Nature (London) *200,* 993 (1963).

[35] *D. A. van Dorp, R. K. Beerthuis, D. H. Nugteren,* and *H. Vonkeman,* Biochim. biophysica Acta *90,* 204 (1964).

[36] *S. Bergström, H. Danielsson,* and *B. Samuelsson,* Biochim. biophysica Acta *90,* 207 (1964).

[37] *S. Bergström, H. Danielsson, D. Klenberg,* and *B. Samuelsson,* J. biol. Chemistry *239,* PC 4006 (1964).

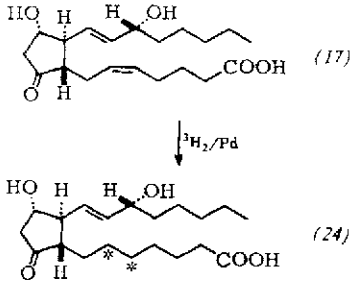
[38] *D. A. van Dorp, R. K. Beerthuis, D. H. Nugteren,* and *H. Vonkeman,* Nature (London) *203,* 839 (1964).

pentaenoic acid *(23)*, prepared biosynthetically in *Euglena gracilis* [39].

The specificity of the enzyme system for the substrate in the formation of prostaglandin-type compounds has been studied with precursors of different chain lengths. It was thus demonstrated that [4-^{14}C]-all-*cis*-docosa-10,13,16,-trienoic acid is converted into a product with properties expected for "bishomo"-PGE_1 [37] and that nor-PGE_1 and nor-PGE_2 were formed from all-*cis*-nonadeca-7,10,13-trienoic acid and all-*cis*-nonadeca-4,7,10,13-tetraenoic acid, respectively [38]. However, a C_{18}-trienoic acid, *i.e.*, all-*cis*-octadeca-6,9,12-trienoic acid, did not appear to be a substrate for this enzyme system.

IV. Metabolism

[5,6-$^3H_2$]-prostaglandin E_1 *(24)* with high specific activity has recently been prepared by selective reduction of the Δ^5-double bond of PGE_2 *(17)* with carrier-free tritium gas using palladium as catalyst [19]. When *(24)* was administered to rats, about 50% of the tritium was recovered in the urine and about 10% in feces within 20 hours. Administration of labelled PGE_1 to a rat with cannulated bile duct gave similar recoveries in the urine and the bile, respectively [19].

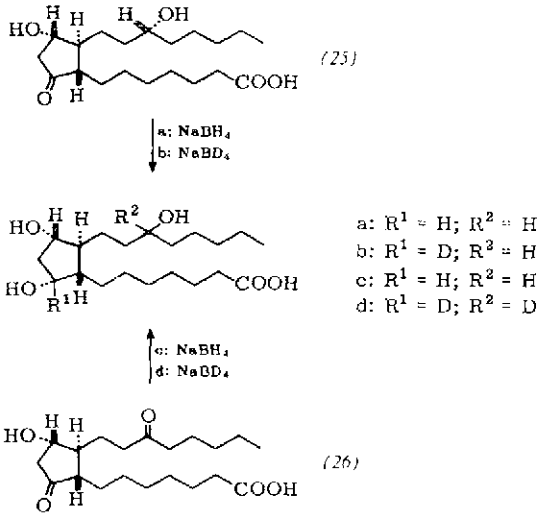


Fractionation of the labelled products excreted in the urine of rats after administration of labelled PGE_1 demonstrated that PGE_1 is completely metabolized to more polar derivatives. This is also the case in man. As yet none of these metabolites have been identified.

Studies of the distribution of radioactivity in various organs of the rat following administration of small amounts (0.2 μg) of labelled PGE_1 showed high concentrations of tritium in the kidneys and the liver [19]. In the lungs, pituitary gland, adrenals, ovaries, and uterus the tritium concentrations were slightly above the blood level, whereas brain, adipose tissue, muscle and thymus had very low concentrations of tritium.

The distribution of tritium after administration of labelled PGE_1 to sheep has also been investigated. This species has been shown to have prostaglandin in the seminal plasma and the uptake in the reproductive organs was therefore of particular interest. Significant concentrations of tritium were found in the fallopian tubes, uterus and ovaries of the female and in the vesicular gland of the male [40]. The distribution of tritium in the other organs of the sheep was similar to that found in the rat.

The metabolism of prostaglandins has also been studied *in vitro* in lung tissue [41]. These experiments demonstrated that PGE_1 was transformed into two less polar metabolites in homogenates of guinea-pig lung. The enzymes responsible for these transformations resided in the particle-free fraction of a lung homogenate. One of the metabolites was identified as 11α,15-dihydroxy-9-oxoprostanoic acid *(25)* and is formed by reduction of the double bond of PGE_1. The other metabolite *(26)* was less polar than the first one, and its infrared data demonstrated that here, too, the double bond was reduced. In



order to determine the number of keto groups in the limited amounts (0.5 mg) of material available, a combination of isotope labelling and mass spectrometry was used. The isolated metabolites were reduced with sodium borohydride and sodium borodeuteride. The products were converted to the methyl esters and acetylated prior to the mass spectrometric analyses. 11α,15-Dihydroxy-9-oxoprostanoic acid *(25)* was used as reference and subjected to the same sequence of reactions. After reduction of the reference compound with sodium borodeuteride, the m/e-values for the major fragments [M-59, M-(2×60), M-(3×60)] were *1 unit* higher than those obtained after reduction with sodium borohydride. However, the increment observed on reduction of the metabolite *(26)* with sodium borodeuteride as compared with sodium borohydride was *2 units*. After reduction with sodium borohydride the metabolite *(26)* gave essentially the same mass spectrum as the reduced reference compound *(25)*. These experiments therefore demonstrated that the metabolite *(26)* contained two keto groups. Their location followed from the infrared data, which excluded a 1,3-diketone in the five-membered ring (no absorption at 6.4 μ), and the metabolite *(26)* was therefore most likely 11α-hydroxy-9,15-dioxoprostanoic acid. Unequivocal proof for this structure was obtained by comparison with a sample prepared through partial synthesis from PGE_1 *(1)* via *(27)*.

The formation of the two metabolites *(25)* and *(26)* has been demonstrated in lung tissue of man, sheep, rabbit and rat [42]. A survey of different organs and tissues of the guinea-pig has shown that the same transformations take place in the kidney and the small intestine [42]. The formation of these metabolites *in vivo* has also been de-

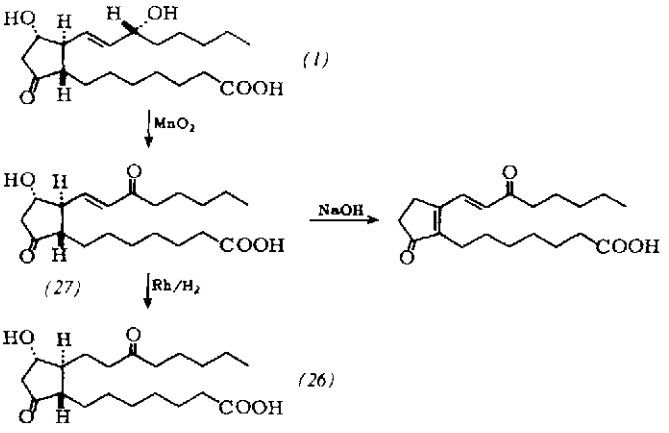
[39] *E. Änggård* and *B. Samuelsson*, unpublished work.

[40] *B. Samuelsson*, Proceedings of the Second International Congress of Endocrinology, London 1964, p. 966. Excerpta Medica Foundation, Amsterdam, in the press.

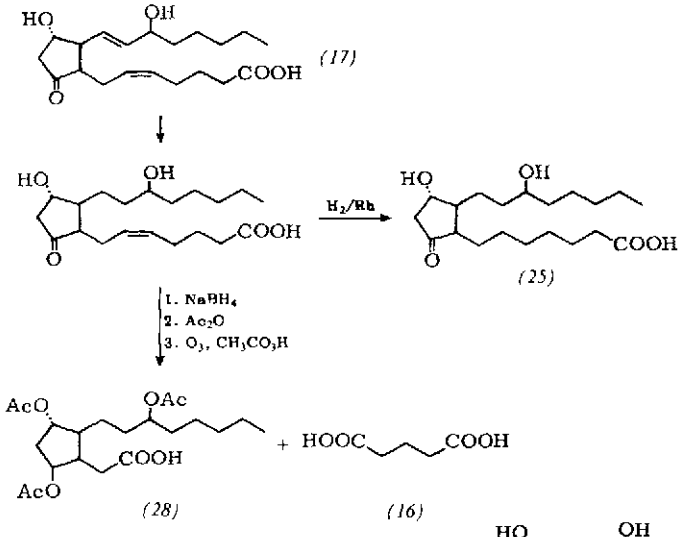
[41] *E. Änggård* and *B. Samuelsson*, J. biol. Chemistry *239*, 4097 (1964).

[42] *E. Änggård* and *B. Samuelsson*, unpublished work.

monstrated in the rat: they could be identified in the blood 15 minutes after administration of labelled PGE_1 [19]. However, their absence in the urine indicates that they are further metabolized before being excreted.

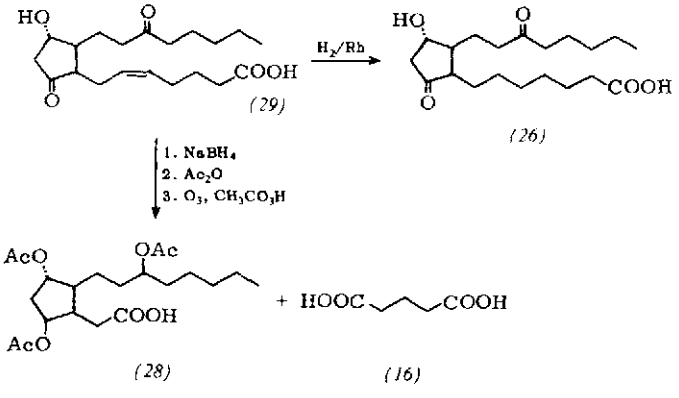


The metabolism of PGE_2 *(17)* in lung tissue of the guinea-pig was also recently studied. Two weakly polar metabolites were isolated and characterized. Catalytic reduction converted one of these into 11α,15-dihydroxy-9-oxoprostanoic acid *(25)*, and oxidative ozonolysis after reduction with borohydride and acetylation gave a C_{15}-fragment *(28)* consisting of two epimeric C_{15}-carboxylic acids. These acids were identified by gas-liquid chromatography [42].



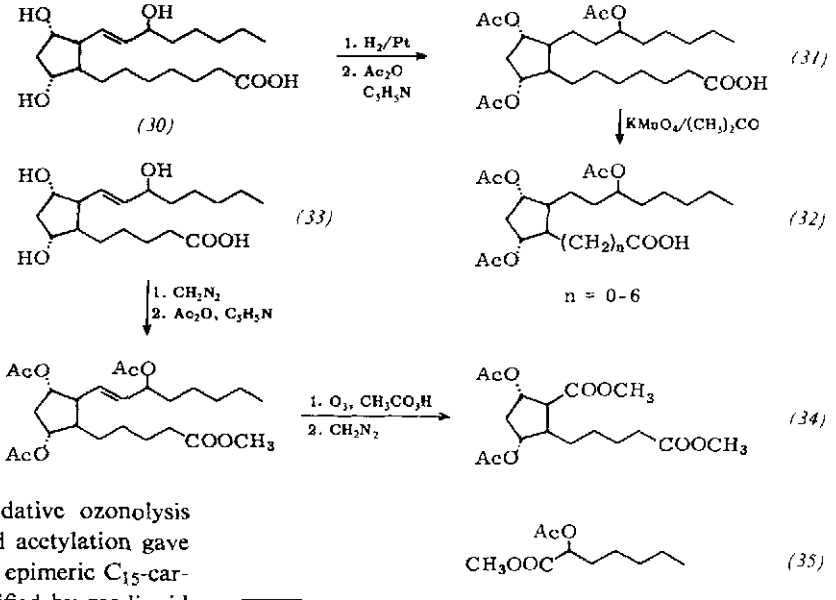
The least polar metabolite *(29)* was converted into 11α-hydroxy-9,15-dioxoprostanoic acid *(26)* by catalytic hydrogenation. Reduction by sodium borohydride followed by acetylation and oxidative ozonolysis gave the C_5-*(16)* and C_{15}-fragments *(28)*, demonstrating that the metabolite was 11α-hydroxy-9,15-dioxoprost-5-enoic acid. PGE_1 and PGE_2 are thus metabolized in the same way in lung tissue, *i.e.* by reduction of the Δ^{13}-double bond and oxidation of the secondary alcohol at C-15 to a ketone.

The metabolism of $PGF_{1\alpha}$ *(30)* was recently studied *in vivo* in the rat [43]. Labelled $PGF_{1\alpha}$ was prepared by borohydride reduction of [^{3}H]-PGE_1 *(24)*. The major part of the radioactivity excreted after administration of the labelled $PGF_{1\alpha}$ appeared in the urine (30% of the administered radioactivity) and about 8% appeared in feces. The structure of the major urinary metabolite *(33)*



was determined as follows: The infrared spectrum showed that the *trans* double bond was retained, and the mass spectrum indicated that the carboxyl side chain of the metabolite contained two methylene groups less than the administered $PGF_{1\alpha}$.

In order to prepare reference compounds for direct comparison, $PGF_{1\alpha}$ was hydrogenated and acetylated. The derivative *(31)* was then degraded from the caboxyl end



[43] *E. Granström, U. Inger,* and *B. Samuelsson,* J. biol. Chemistry *240*, 457 (1965).

by oxidation with permanganate in acetone. A series of seven acids *(32)*, n = 0–6, was obtained and analysed by gas-liquid chromatography. The relationship between the logarithms of the retention times of the methyl esters and the number of carbon atoms of the parent acids is shown in Figure 2. It was also confirmed by direct mass spectrometric analyses of the effluent from the gas chromatograph that the various components corresponded to the acids indicated. When the radioactive metabolite *(33)* was hydrogenated, acetylated, and subjected to gas chromatography, the main mass and radioactivity peaks had retention times corresponding to a parent acid with 18 carbon atoms.

The position of the double bond in the main metabolite *(33)* was determined by ozonolysis which yields the esters *(34)* and *(35)*.

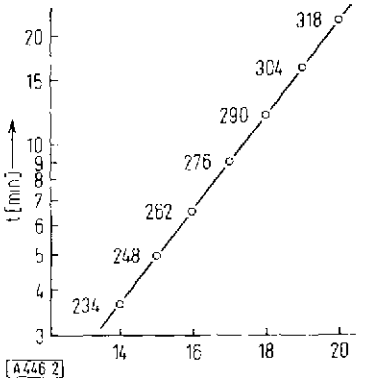


Fig. 2. Gas-chromatographic retention times of the methyl esters of carboxylic acids *(32)*, n = 0–6.

Ordinate: Retention time t [min].

Abscissa: Number of carbon atoms in the acids *(32)*.

The numbers on the curve are *m/e*-values for M– (3×60)
[M = mass of the molecular ion of the ester].

It is not the aim of this review to describe the large number of physiological studies which have been performed on the effects of prostaglandin on various smooth muscle organs. In recent studies, however, it has been possible to demonstrate effects of the prostaglandins on lipid metabolism and these experiments will be briefly discussed. The release of glycerol in rat adipose tissue, which is stimulated by catecholamine, was inhibited *in vitro* by PGE_1 [44]. The same effects were observed *in vivo* in dogs where PGE_1, PGE_2, and PGE_3 reduced the increased concentration of free fatty acids in blood plasma, induced by administration of norepinephrine [45]. Studies of the turnover rate of free fatty acids demonstrated that PGE_1 blocks the mobilization of lipids, which is induced by norepinephrine. The response of plasma glucose to epinephrine was only slightly diminished.

More recently, the effects of PGE_1 on the free fatty acids in plasma of man was investigated [46]. Intravenous infusion of PGE_1 caused an increase of the concentrations of free fatty acids and glycerol. However, when both norepinephrine and PGE_1 were infused together the increase of the concentrations of free fatty acids and glycerol due to norepinephrine was reduced by PGE_1.

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German version: Angew. Chem. *77*, 445 (1965)

[44] *D. Steinberg, M. Vaughan, P. Nestel*, and *S. Bergström*, Biochem. Pharmacol. *12*, 764 (1963).

[45] *S. Bergström, L. A. Carlsson*, and *L. Orö*, Acta physiol. scand. *60*, 170 (1964).

[46] *S. Bergström, L. A. Carlsson, L. G. Ekelund*, and *L. Orö*, Biochem. J. *92*, 42 P (1964).

The Use of Silylation in Organic Syntheses

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The term silylation is used to denote the introduction of a triorganosilyl moiety, especially the trimethylsilyl species, into organic compounds. – Silylated amino acids and sugars are particularly suitable for the syntheses of peptides and saccharides, respectively, since the silyl group can be cleaved off readily under mild conditions. Many diamines undergo ring closure, e.g. with phosgene, only after silylation. – O-Silylated lactim ethers (i.e. cyclic imino ethers) are converted into N-alkyl derivatives by alkyl halides. Compounds with a strongly polarized Si–C bond may be used for chain extension. Silyl esters of halogeno fatty acids yield lactones with silver cyanate. – Trimethylsilyl azide is thermally very stable and behaves like organic azides. It reacts with acetylenic compounds, trialkylphosphines, and triarylphosphines to yield silylated triazole derivatives, trialkylphosphine N-silylimines, and triarylphosphine N-silylimines, respectively, from which the silyl groups can be removed under mild conditions.

I. Introduction
  1. Methods of trimethylsilylation
  2. Physical properties of organosilicon compounds
II. Reactions involving substitution of trialkylsilyl groups
  1. Cleavage of Si-N bonds in heterocyclic compounds
  2. The course of *N*-acylation
  3. The structure of trialkylsilylated carboxamides
  4. *N*-Alkyiation of *O*-silylated carboxamides
  5. The course of *N*-alkylation of *O*-trialkylsilyl lactims
  6. Cleavage of Si-O bonds
  7. The course of cyclization
  8. Substitution at Si-C bonds
  9. The mechanism of substitution
  10. Substitution in silylated acetylenes
III. The trimethylsilyl group as an electron acceptor
  1. Thermolysis of silylated tetrazoles
  2. The course of thermolysis
IV. The trimethylsilyl moiety as a protective group
  1. Reactions of trimethylsilyl azide
  2. Carbamidation of silylated diamines; cyclic ureas and a new uric acid synthesis
  3. Preparation of trimethylsilylalkoxy compounds and glucose derivatives; disaccharide synthesis
  4. Peptide syntheses using silylated amino acids and peptides
V. Removal of the carbobenzoxy group with triethylsilane
VI. Practical procedures

I. Introduction

1. Methods of Trimethylsilylation

The use of the trimethylsilyl moiety in organic syntheses is favored by the ready availability of trimethylchlorosilane *via* the Müller-Rochow synthesis [1] and by the relative compactness of the $Si(CH_3)_3$ group, which facilitates silicon elimination reactions. Although OH, NH, and SH groups can be silylated with trimethylchlorosilane even in the absence of an HCl acceptor, it is normally convenient to add a substance such as triethylamine or pyridine for this purpose, and thus to lower the reaction temperature, shorten the reaction time, and increase the yields. An auxiliary amine should be added during the silylation of primary or secondary amines which are difficult to obtain, in order to avoid loss of starting material by formation of its hydrochloride as the reaction proceeds.

Silylation with hexamethyldisilazane, which must usually be carried out by heating under reflux, yields no by-products other than NH_3. Hexamethyldisilazane is also the most suitable reagent [3] for direct trimethylsilylation of amino acids, for which trimethylchlorosilane cannot be used [2].

N-Trimethylsilylacetamide *(92)* is particularly useful, since it quantitatively trimethylsilylates hydroxy groups, sometimes even at room temperature [4]. Acetamide is formed as a by-product but can be removed easily by filtration.

[*] The articles of the previous three series have been collected and published in three volumes in German by Verlag Chemie, Weinheim, Bergstr. (Germany); and in English by Academic Press, New York-London.

[**] At present Dow Corning Research Fellow, The Pennsylvania State University, University Park, Pa. (U.S.A.).

[1] German Patent Application C 57411 (1952), inventor: *R. Müller*; U.S. Pat. 2380995 (1945), General Electric, inventor: *E. G. Rochow*; Chem. Abstr. *39*, 4889 (1945).

[2] *F. A. Henglein* and *W. Knoch*, Makromolekulare Chem. *28*, 10 (1958).

[3] *L. Birkofer* and *A. Ritter*, Chem. Ber. *93*, 424 (1960).

[4] *L. Birkofer*, *A. Ritter*, and *F. Bentz*, Chem. Ber. *97*, 2196 (1964).

Since nearly all organosilicon compounds containing O–Si, N–Si, or S–Si bonds are sensitive towards hydrolysis, moisture must be rigorously excluded.

Basically, only two methods of general applicability are known at present for *C*-silylation: reaction of a Grignard reagent or other organometallic compound with trimethylchlorosilane [5], or addition of silanes onto unsaturated systems [6].

2. Physical Properties of Organosilicon Compounds

The most striking feature of the organosilicon compounds under discussion is their excellent solubility in ordinary solvents which contain no active hydrogen. Substances which are insoluble in hydrocarbons owing to the presence of –OH, –NH–, $-CONH_2$ groups, *etc.* dissolve readily in these solvents on replacement of their protons by the trimethylsilyl group; reactions can then be carried out conveniently in a homogeneous organic phase.

Moreover, trialkylsilylation changes the volatility of organic compounds, many of which can then be distilled without decomposition [2,4,7,8]. However, crystallizability is sometimes considerably impaired.

II. Reactions Involving Substitution of Trialkylsilyl Groups

1. Cleavage of Si-N Bonds in Heterocyclic Compounds

N-Trialkylsilylated heterocyclic compounds are obtained by silylation of free N-heterocycles with trimethylchlorosilane, hexamethyldisilazane, or triethylaminosilane [9]. *N*-Trimethylsilylimidazole *(1)* (cf. Section VI.1) reacts almost quantitatively with acid halides, with elimination of trimethylchlorosilane *(3)* (see Table 1).

$$n\ R^1\text{-}Si(CH_3)_3 + R^2Cl_n \rightarrow R^1_n\text{-}R^2 + n\ (CH_3)_3SiCl$$

(1) *(3)*

R^1 =

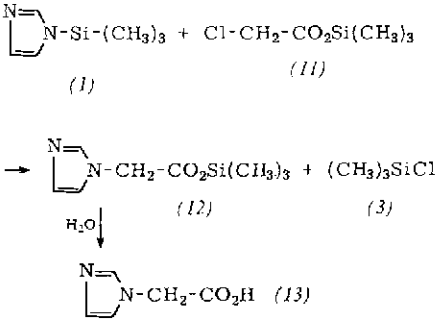
N,N' Thionyldiimidazole *(10)* [11], was first prepared in analytical purity from *(1)* [10].

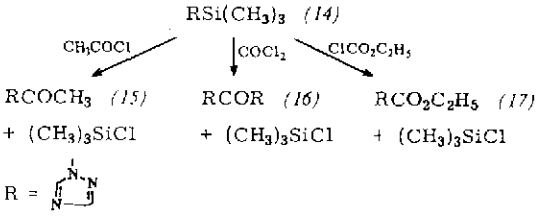
The Si-N bond in *N*-trimethylsilylimidazole *(1)* is so reactive that it even reacts with α-halogenocarboxylic esters *(11)* [9] which are inert towards free imidazole. Thus, trimethylsilyl α-(*N*-imidazolyl)acetate *(12)* is formed by the reaction of *(1)* with trimethylsilyl α-chloroacetate, and is quantitatively converted by water into α-(*N*-imidazolyl)acetic acid *(13)* [12], together with trimethylsilanol or its condensation product, hexamethyldisiloxane. Like *(1)*, *N*-trimethylsilyl-1,2,4-triazole *(14)* reacts with acid chlorides to give the acylated triazoles *(15)–(17)* [9].

Table 1. Reaction of *N*-trimethylsilylimidazole *(1)* with acid halides.

n	R^2Cl_n	$R^1_n\text{–}R^2$	Ref.
1	CH_3COCl	R^1COCH_3 *(2)* [*]	[9]
1	H_5C_6COCl	$R^1\text{–}COC_6H_5$ *(4)*	[9]
1	$Cl\text{–}CO_2C_2H_5$	$R^1\text{–}CO_2C_2H_5$ *(5)*	[9]
2	$COCl_2$	R^1CO *(6)* [**]	[9]
2	SCl_2	R^1S *(7)*	[9]
3	PCl_3	R^1P *(8)*	[10]
3	$POCl_3$	R^1PO *(9)*	[10]
2	$SOCl_2$	R^1SO *(10)*	[10]

[*] Cf. Section VI.2.
[**] Cf. Section VI.3.





2. The Course of *N*-Acylation

On acylation, *N*-trialkylsilyl-substituted heterocyclic compounds (see Table 2) show widely varying reactivities. It can therefore be concluded that the polarity of the Si–N bond differs from one compound to another and that the higher the polarity of the bond, the more reactive the compound. Comparative nuclear magnetic resonance measurements (see Table 3) on the methyl protons of the trimethylsilyl group [13, 14] show that the shielding effect of the silicon atom depends on the amine component, being particularly weak in *N*-trimethylsilyl-1,2,4-triazole *(14)* and *N*-trimethylsilylimidazole *(1)*.

The chemical shifts of the methyl protons may be regarded as a measure of the extent to which the silicon atom shares the lone pair of electrons on the nitrogen atom of the Si–N bond, increasing δ-values corresponding to reduced shielding.

[5] *K. C. Frisch* and *R. B. Young*, J. Amer. chem. Soc. *74*, 4853 (1952); *A. D. Petrov* and *L. L. Shchukovskaya*, Dokl. Akad. Nauk U.S.S.R. *86*, 551 (1952); Chem. Zbl. *1953*, 2103; Chem. Abstr. *47*, 12225 (1953).

[6] See *C. Eaborn*: Organosilicon Compounds. Butterworth, London 1960, p. 45f.

[7] *L. Birkofer* and *A. Ritter*, Angew. Chem. *71*, 372 (1959).

[8] *L. Birkofer, H. P. Kühlthau*, and *A. Ritter*, Chem. Ber. *93*, 2810 (1960).

[9] *L. Birkofer, P. Richter*, and *A. Ritter*, Chem. Ber. *93*, 8204 (1609).

[10] *L. Birkofer, W. Gilgenberg*, and *A. Ritter*, Angew. Chem. *73*, 143 (1961).

[11] *H. A. Staab* and *K. Wendel*, Angew. Chem. *73*, 26 (1961).

[12] Prepared by a very complicated route by *A. P. T. Easson* and *F. L. Pyman*, J. chem. Soc. (London) *1932*, 1806.

[13] *H. Beumling*, Ph.D. Thesis, Universität Köln, 1965.

[14] The authors are indebted to Dr. *H. Walz*, Leverkusen, for recording and interpreting all the NMR spectra mentioned in the present article.

Table 2. Reaction of heterocyclic compounds with hexamethyldisilazane to form *N*-trimethylsilyl compounds.

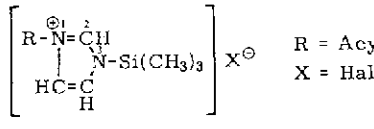
N-trimethylsilyl derivative of	Yield [%]	B.p. [°C/mm]
Imidazole *(1)*	85	91/12
Pyrazole	72	153/760
3,5-Dimethylpyrazole	59	73/12
1,2,4-Triazole *(14)*	81	74/12
Benzimidazole	89	112/0.3
Indazole	79	132/18
Pyrrolidine	72	142/760
Piperidine	42	161/760

Table 3. Chemical shifts δ of the methyl protons in the $(CH_3)Si$ group of trimethylsilylated heterocyclics and amines.
Internal standard: tetramethylsilane.

Parent compound	$\delta_{R-Si(CH_3)_3}$	$\delta_{R-C(CH_3)_3}$	Difference
Imidazole	−0.38	−1.46	1.08
Pyrrole	−0.23	−1.40	1.17
Pyrrolidine	0	−1.08	ca. 1.08
Diethylamine	0	−1.08	ca. 1.08
1,2,4-Triazole	0.40 *(14)*	1.47	1.07

The difference between the δ-values of *N*-trimethylsilyl compounds and those of the analogous t-butyl compounds is approximately constant. Since carbon is incapable of d_π p_π bonding, the different δ-values of the t-butyl compounds are simply due to the inductive effects of the amine or heterocyclic component. The chemical shifts of the methyl protons on the trimethylsilyl moiety are evidently reduced [16] by the back-donation [15] which can occur there. However, *N*-trimethylsilylpyrrole, whose δ-value of −0.23 is nearest to that of compounds *(1)* and *(14)*, is much more difficult to acylate than might be expected from the differences in the δ-values [17].

The differences in reactivity of the *N*-trimethylsilyl heterocyclics must therefore depend not so much on the ground state, but rather on the possible transition state formed during the course of acylation or alkylation. Compounds *(1)* and *(14)* may form an "onium" complex *(18)* which can eliminate the trimethylsilyl group by 1,3-induction.

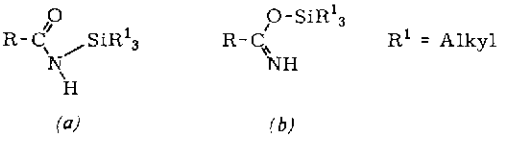
(18)  R = Acyl, Alkyl; X = Halogen

This mechanism is not possible with *N*-trimethylsilylpyrrole. Investigations are being carried out with a view to explaining this phenomenon.

3. The Structure of Trialkylsilylated Carboxamides

Trialkylsilylated carboxamides were first described by *Hurwitz* and *de Benneville* [18], who did not, however, discuss their structures.

In theory, silylation of a carboxamide can yield either compound *(a)* or compound *(b)*. However, since carboxamides are highly stabilized by resonance [19] and are susceptible to nucleophilic attack on both the nitrogen and oxygen atoms [20], it is possible that mono-trialkylsilylated carboxamides tend towards the *O*-silyl imino-ether structure *(b)*.



(a) *(b)*

O-Substitution would even be favored by the greater thermodynamic stability of the Si-O bond relative to the Si-N bond [21]. However, this is opposed by the fact that resonance stabilization is no longer possible in the *O*-silyl imino-ether, although the *N*-trialkylsilyl carboxamides benefit from this phenomenon. The irreversible isomerization of alkylated imino-ethers to *N*-alkyl carboxamides, which is known as the Chapman rearrangement [22], indicates the importance of resonance in the amide as a factor affecting its structure.

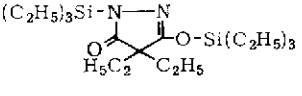
Infrared and NMR spectra [25] lead to the following conclusions regarding the substitution of silylated carboxamides:

1. The following open-chain mono-trialkylsilylated amides exist in the amide form *(a)* [23,24]: *N*-trimethylsilyl-acetamide *(92)* [26], -propionamide [26], -butyramide [26], -trichloroacetamide [26], -benzamide [26], -*N*-methylacetamide [25], -*N*-ethylacetamide [25], -acetanilide [26], -*N*-ethylpropionamide [25], and *N*-triethylsilylacetamide [25].

2. In the following alicyclic amides, the trimethylsilyl group becomes attached to the nitrogen atom: γ-butyrolactam [26], δ-valerolactam [26], and ε-caprolactam [25].

3. Only the *O*-silylated (lactim) form of the following six-membered cyclic lactams which can undergo heteroaromatization has been detected: 2-trimethylsiloxypyridine *(24)* [27], 2,4,6-tristriethylsiloxypyrimidine [28], 2,4-bistrimethylsiloxy-5,6-bistrimethylsilylaminopyrimidine [27], 2,3-bistrimethylsiloxyquinoxaline *(26)* [27], 2,4-bistrimethylsiloxyquinazoline [25], 3,6-bistrimethylsiloxypyridazine [25], and 1,4-bistrimethylsiloxyphthalazine [25]. For tristriethylsilylxanthine *(32)* [27], see Table 4.

4. Both *N*- and *O*-silylation occur simultaneously in 1-triethylsilyl-3-triethylsiloxy-4,4-diethylpyrazol-5-one *(19)* [29] and in the tetrakistrialkysilyluric acids *(20)*

 *(19)*

[15] Discussion of this effect with trissilylamine: *K. Hedberg*, J. Amer. chem. Soc. *77*, 6491 (1955).

[16] The authors wish to thank Prof. *R. Taft* and Prof. *R. Bernheim*, Pennsylvania State University, for a discussion.

[17] Unpublished results.

[18] U.S. Pat. 2876234 (Mar. 3rd, 1959), Rohm and Haas, inventors: *M. J. Hurwitz* and *P. L. De Benneville;* Chem. Abstr. *53*, 12238 (1959); *L. Birkofer, A. Ritter*, and *H. Dickopp*, Chem. Ber. *96*, 1473 (1963).

[19] *L. Pauling:* The Nature of the Chemical Bond. 3rd edit., Cornell University Press, Ithaca 1960.

[20] *R. Gompper* and *O. Christmann*, Chem. Ber. *92*, 1935 (1959).

[21] Cf. [6], p. 90, Table 3.2.

[22] *A. W. Chapman*, J. chem. Soc. (London) *127*, 1992 (1925); *1926*, 2296; *1927*, 1743; *1930*, 2462.

[23] *J. Pump*, Ph.D. Thesis, Technische Hochschule Aachen, 1962.

[24] *J. Pump* and *U. Wannagat*, Mh. Chem. *93*, 352 (1962).

[25] *W. Gießler*, Ph.D. Thesis, Universität Köln, 1963.

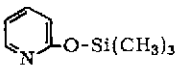
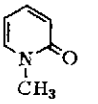
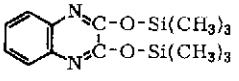
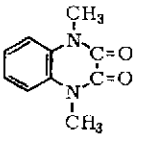
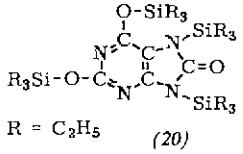
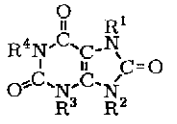
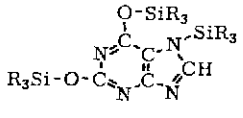
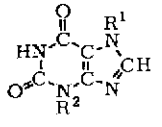
[26] *H. Dickopp*, Diploma Thesis, Universität Köln, 1962.

[27] *L. Birkofer, A. Ritter*, and *H. P. Kühlthau*, Chem. Ber. *97*, 934 (1964).

[28] *U. Krause*, Diploma Thesis, Universität Köln, 1961.

[29] *L. Georgias*, Diploma Thesis, Universität Köln, 1963.

Table 4. Alkylation of trialkylsilyl compounds [27].

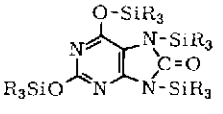
Silyl compound	Alkylating agent	Temp. [°C]	Time [h]	Final product	Yield [%]
 *(24)*	CH_3I	ca. 60	2	 *(25)*	80
 *(26)*	CH_3I	125	10 (autoclave)	 *(27)*	71
 $R = C_2H_5$ *(20)*	CH_3I	ca. 60	12	 *(28)*: $R^1=R^2=R^3=H$; $R^4=CH_3$ [a]	85
	$(CH_3)_2SO_4$	150	1 [b]	*(29)*: $R^1=R^2=R^4=CH_3$; $R^3=H$	90
	$(CH_3)_2SO_4$	150	1 [c]	*(30)*: $R^1=R^2=R^3=R^4=CH_3$	90
	$(C_2H_5)_2SO_4$	130	1	*(31)*: $R^1=R^2=R^3=R^4=C_2H_5$	84
 *(32)* $R = C_2H_5$	CH_3I	20	50	 *(33)*: $R^1=CH_3$; $R^2=H$	66
	CH_3I	ca. 60	12	*(34)*: $R^1=R^2=CH_3$	55

[a] Cf. Section VI.5.

[b] Obtained on pouring the reaction mixture into methanol.

[c] Obtained on pouring the reaction mixture into 2 N NaOH.

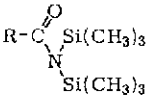
[7] and *(21)* [8] (cf. Sections VI.4 and VI.14, respectively). Despite numerous attempts [25,26], selective trimethylsilylation of carboxamides on either the nitrogen or the oxygen has not yet been achieved.



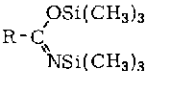
(20): R = C_2H_5
(21): R = CH_3

Silylation of acetamide and acrylamide with excess trimethylchlorosilane *(3)* yields the corresponding bistrimethylsilyl compounds *(22a)* or *(22b)* and *(23a)* or *(23b)*, respectively [30].

According to *Krüger, Rochow*, and *Wannagat* [31], *N,O*-bistrimethylsilylbenzamide can be obtained by a different route. An amide-type product *(a)* was ruled out by these authors, but should be given some consideration. Infrared spectra [25] and dipole moment data [13] support the imide form *(b)*, but the ^{1}H-NMR signals [25] do not indicate the presence of two non-equivalent trimethylsilyl groups, such as those in *(b)*. A splitting of about 5 cps below 0 °C in the methyl proton signal of the two trimethylsilyl groups might be due to a Chapman rearrangement [cf. [31]]. However, no corresponding effect is observed in the infrared spectrum of *(22a)* when recorded between −170 and +25 °C [32]. When heated in a sealed glass tube at 215 °C for 12 hours, bistrimethylsilylacetamide [*(22a)* or *(22b)*] is converted quantitatively into acetonitrile and hexamethyldisiloxane [25].



(22a): R = CH_3
(23a): R = CH_2=CH



(22b): R = CH_3
(23b): R = CH_2=CH

4. *N*-Alkylation of *O*-Silylated Carboxamides

Although the compounds mentioned in Section II.3 under 1. and 2. cannot be alkylated with methyl iodide, this alkylation does proceed with those listed under 3. and 4. Thus, *(24)* is alkylated to *(25)*, and *(26)* to *(27)*, (see Table 4). This method is preparatively valuable, since molecules with more than one amide group can be alkylated selectively, as shown by the examples *(20)* → *(28)*–*(31)* and *(32)* → *(33)*, *(34)*.

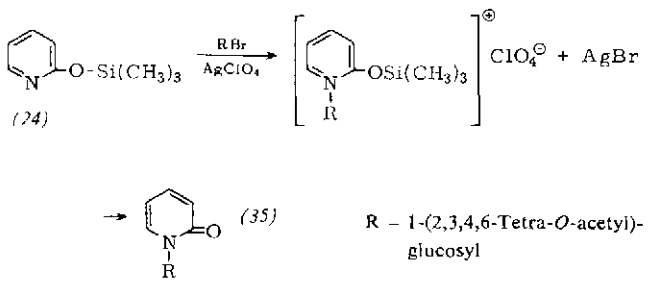
Acyl halogeno sugars react with *O*-silylated N-heterocyclic compounds (lactimethers) to form *N*-glycosides. *N*-Tetra-*O*-acetylglucosyl-α-pyridone *(35)*, which was prepared earlier in a different manner, is formed in 70% yield from *(24)* and acetobromoglucose [27,33].

[30] *L. Birkofer, A. Ritter*, and *W. Gießler*, Angew. Chem. *75*, 93 (1963); Angew. Chem. internat. Edit. 2, 96 (1963).

[31] *C. Krüger, E. G. Rochow*, and *U. Wannagat*, Chem. Ber. *96*, 2138 (1963).

[32] The authors wish to express their gratitude to Prof. *W. Lüttke*, Göttingen, for carrying out the measurements.

[33] Cf. *G. Wagner* and *H. Pischel*, Naturwissenschaften *48*, 454 (1961).

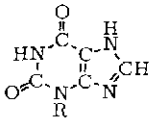


(24)

(35)

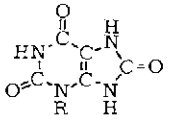
R = 1-(2,3,4,6-Tetra-*O*-acetyl)-glucosyl

Introduction of a glycosidic moiety into the 3-position of purine derivatives was first achieved using silyl compounds. Tristriethylsilylxanthine *(32)* and acetobromoglucose lead to 3-glucosylxanthine *(36)* [27], and tetrakistriethylsilyluric acid *(20)* and acetobromoglucose similarly to 3-glucosyluric acid *(37)* [27, 34].



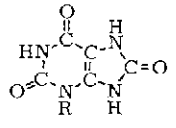
(36)

R = 1-Glucosyl



(37)

3-(1-Ribofuranosyl)uric acid *(38)*, which is present in ox blood [35, 36], was first synthesized starting from tetrakistriethylsilyluric acid *(20)* and 1-bromo-2,3,5-tri-*O*-benzoylribofuranose [34] (cf. Section VI.6).

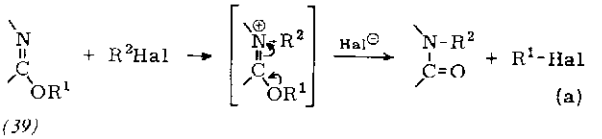


R = 1-Ribofuranosyl

(38)

5. The Course of *N*-Alkylation of *O*-Trialkylsilyl Lactims

The introduction of *N*-alkyl and *N* glycosyl groups *via* lactim ethers *(39)* was first described by *Hilbert* and *Johnson* [37] in 1930. Although no accurate studies appear to have been carried out, several authors believe that the course shown in Equation *(a)* is probable [38].



(39) (a)

There is no reason why this scheme should not also apply to *O*-silylated lactims.

This interpretation is unsatisfactory only for tetrakistriethylsilyluric acid *(20)* (Table 4), which can also be alkylated in the 7-position, although the five-membered ring of *(20)* has the lactam structure [25]. The alkylation in the 7-position observed with tristriethylsilylxanthine *(32)*, on the other hand, can be explained in a similar manner as the acylation of *N*-trimethylsilylimidazole *(1)*.

One disadvantage of the classical Hilbert-Johnson reaction [Equation (a)] is that the R^1-Hal present in the reaction medium increases in quantity as the reaction proceeds, and can react again. This competing reaction gives rise to a mixture of two products [37]. The side reaction is never observed when *O*-silyl lactims are used, since it would yield *N*-silylated compounds, and, in the case of six-membered heteroaromatic ring systems at least, these have never yet been detected.

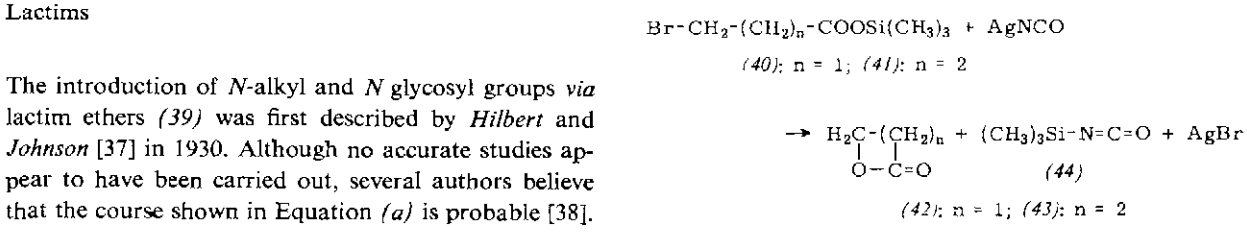
When carried out with *O*-silyl lactims, the Hilbert-Johnson reaction has two notable advantages over the classical procedure:

1. Ring systems which can undergo heteroaromatization can be converted in very good yields into *O*-silyl lactims by a one-step reaction, whereas *O*-alkyl or *O*-aryl lactims can generally be prepared only by multistage syntheses.

2. The yields are satisfactory (Table 4); this may be due to the uniform course of reaction and to the higher electrophilicity of the trialkylsilyl species compared to an alkyl group.

6. Cleavage of Si-O Bonds

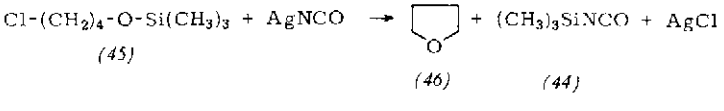
When trimethylsilyl bromoalkanoates such as *(40)* or *(41)* are treated with silver cyanate, lactones and trimethylsilyl isocyanate *(44)* are obtained instead of the expected trimethylsilyl isocyanato fatty esters [39] (cf. Section VI, 7 and 8).



(40): n = 1; *(41)*: n = 2

(42): n = 1; *(43)*: n = 2

Lactones are also obtained with silver perchlorate [39]. Trimethylsilyl perchlorate $(CH_3)_3SiClO_4$ [40] should not be isolated by distillation from the reaction medium, since a serious explosion once occurred during this operation. Similarly, ω-halogenoalkoxytrialkylsilanes, Hal-$(CH_2)_n$-O-SiR_3, give cyclic ethers [39]. Thus, the reaction of 1-chloro-4-trimethylsiloxybutane *(45)* with silver cyanate yields tetrahydrofuran *(46)* and the isocyanate *(44)*.



(45) (46) (44)

[34] *L. Birkofer, A. Ritter*, and *H. P. Kühlthau*, Angew. Chem. *75*, 209 (1963); Angew. Chem. internat. Edit. *2*, 155 (1963).

[35] *A. R. Davis, E. B. Newton*, and *St. R. Benedict*, J. biol. Chemistry *54*, 595 (1922).

[36] *H. S. Forrest, D. Hatfield*, and *J. M. Lagowski*, J. chem. Soc. (London) *1961*, 963.

[37] *G. E. Hilbert* and *T. B. Johnson*, J. Amer. chem. Soc. *52*, 4489 (1930).

[38] *K. Eichenberger, A. Staehlin*, and *J. Druey*, Helv. chim. Acta *37*, 837 (1954); *T. L. V. Ulbricht*, J. chem. Soc. (London) *1961*, 3345.

[39] *L. Birkofer, A. Ritter*, and *J. Schramm*, Chem. Ber. *95*, 426 (1962).

[40] *U. Wannagat, F. Brandmair, W. Liehr*, and *H. Niederprüm*, Z. anorg. allg. Chem. *302*, 185 (1959).

Intramolecular transesterification of chloromethyldimethylsilyl acetate *(47)* in the presence of silver cyanate leads to acetoxymethyldimethylsilyl isocyanate *(48)* [39].

$$H_3C\text{-}COOSi(CH_3)_2\text{-}CH_2Cl + AgNCO \quad (47)$$
$$\rightarrow H_3CCOOCH_2\text{-}Si(CH_3)_2\text{-}NCO + AgCl \quad (48)$$

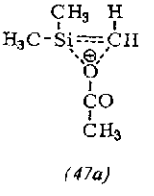
This rearrangement is the first Wagner-Meerwein reaction observed in the chemistry of organosilicon compounds [41].

7. The Course of Cyclization

The reaction of silver cyanate or silver perchlorate on the halogeno compounds *(40)*, *(41)*, *(45)*, and *(47)* probably results in the formation of the carbonium ions *(40a)*, *(41a)*, *(45a)*, and the bridged carbonium-siliconium ion *(47a)*, respectively; these then lead to the

$\overset{\oplus}{C}H_2\text{-}(CH_2)_n\text{-}COOSi(CH_3)_3$ *(40a)*: n = 1 *(41a)*: n = 2

$\overset{\oplus}{C}H_2\text{-}(CH_2)_3\text{-}O\text{-}Si(CH_3)_3$ *(45a)*



(47a)

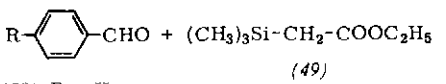
oxygenated cyclic compounds *(42)*, *(43)*, *(46)*, and the open-chain ester *(48)*, respectively.

8. Substitution at Si-C Bonds

The magnitude of the ionic component of the Si–C bond depends largely on the electronic effects of the neighboring groups. The value calculated for the Si–C bond in a normal C–C chain is 12% [42]. However, if electron-attracting substituents are present in the β-position with respect to the silicon, the susceptibility of the latter to nucleophilic attack will be considerably increased.

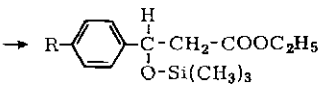
Gold, *Sommer*, and *Whitmore* [43] established that the Si–C bond in ethyl trimethylsilylacetate *(49)* can be cleaved even by absolute alcohol, ethoxytrimethylsilane and ethyl acetate being formed [44].

In the presence of basic catalysts such as solid NaOH and $K[Al(OCH_3)_4]$, *(49)* also reacts with aldehydes: the carbon chain is extended with formation of the ethyl β-trimethylsiloxycarboxylates [45]. With benzaldehyde *(50)*, anisaldehyde *(51)*, and *p*-nitrobenzaldehyde *(52)*, ethyl trimethylsilylacetate *(49)* gives the corresponding β-phenyl-β-trimethylsiloxypropionates *(53)*, *(54)*, and *(55)* (cf. Section VI.9).



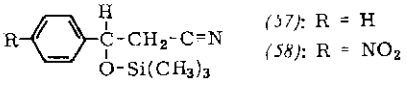
(49)

(50): R = H
(51): R = O-CH_3
(52): R = NO_2



(53): R = H
(54): R = O-CH_3
(55): R = NO_2

The yields decrease as follows: *(55)* ≫ *(53)* > *(54)*. Chain extension analogous to *(50)* → *(53)* also occurs when *(49)* is replaced by trimethylsilylacetonitrile $(CH_3)_3Si\text{–}CH_2\text{–}CN$ *(56)* [46, 45]. Compounds *(50)* and *(52)* form the β-phenyl-β-trimethylsiloxy propionitriles *(57)* and *(58)*, respectively.



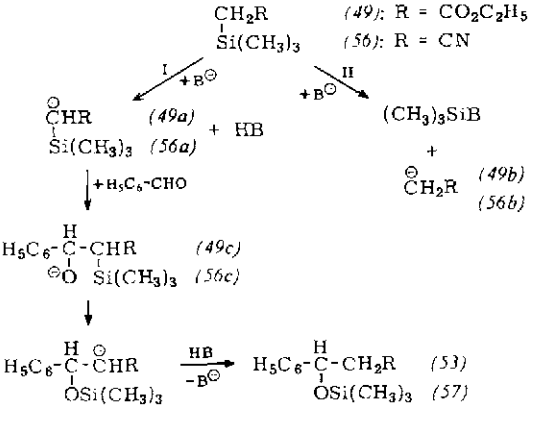
(57): R = H
(58): R = NO_2

p-Nitrobenzaldehyde *(52)* is again much more reactive than benzaldehyde *(50)*, as shown by the respective yields of 78 and 27% [45].

This method of chain lengthening is particularly useful when the required products are not obtained by the Reformatsky reaction, which often fails to give β-aryl-β-hydroxy esters, for example owing to dehydration during work-up of the reaction mixture, with consequent formation of α,β-unsaturated esters [47]. The free β-aryl-β-hydroxy esters or nitriles are obtained by alcoholysis of the trimethylsiloxy compounds *(53)*, *(54)*, *(55)*, *(57)*, and *(58)*. Although *(52)* does not undergo the Reformatsky reaction [48], it reacts almost quantitatively with ethyl trimethylsilyacetate *(49)* and trimethylsilylacetonitrile *(56)*.

9. The Mechanism of Substitution

The issue here is whether the catalytically active anion $B^{\ominus}$ splits off a proton from the α-methylene group in *(49)* and *(56)* to form a carbanion *(49a)* or *(56a)* [Reaction I], or whether the silyl group undergoes nucleophilic attack by $B^{\ominus}$, with cleavage of the Si–C bond and formation of a carbanion *(49b)* or *(56b)* [Reaction II].



(49): R = $CO_2C_2H_5$
(56): R = CN

[41] For references see: *H. Krauch* and *W. Kunz*: Organic Name Reactions. Wiley New York-London 1964, pp. 476, 557.

[42] Cf. [6], p. 89.

[43] *I. R. Gold*, *L. H. Sommer*, and *F. C. Whitmore*, J. Amer. chem. Soc. *70*, 2874 (1948).

[44] *L. H. Sommer* and *N. S. Marans*, J. Amer. chem. Soc. *72*, 1935 (1950).

[45] *L. Birkofer*, *A. Ritter*, and *H. Wieden*, Chem. Ber. *95*, 971 (1962).

[46] Prepared according to *M. Prober*, J. Amer. chem. Soc. *77*, 3224 (1955).

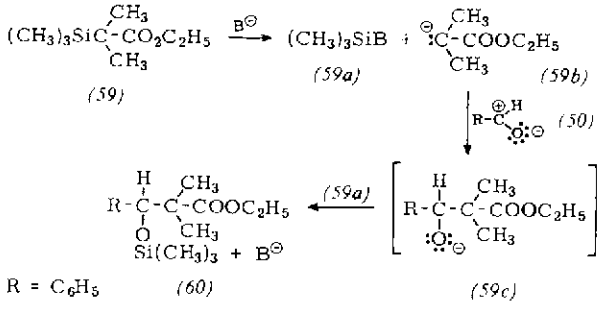
[47] *R. L. Shriner*: Organic Reactions. Wiley, New York 1947, Vol. I, 1, p. 11.

[48] *F. Bohlmann*, Chem. Ber. *90*, 1519 (1957).

Following Route I the carbanions *(49a)* or *(56a)* launch a nucleophilic attack on the aldehydic carbon atom to form a C-C bond. The resulting alkoxide anions *(49c)* or *(56c)* then give the corresponding β-siloxy compounds *(53)* or *(57)* by intramolecular "trans-silylation" and proton capture.

Since ethyl α-trimethylsilylisobutyrate *(59)*, which has no α-methylene group, also reacts with benzaldehyde *(50)* to form the β-trimethylsiloxy compound *(60)* [45], the reaction follows Route II in this case. The carbanion *(59b)* formed from *(59)* adds on as a nucleophile to the aldehyde carbonatom to form a C–C bond. Nucleophilic attack hy the resulting anion *(59c)* on *(59a)* gives *(60)*.

Route I [45] must be considered possible in the reaction with compounds *(49)* and *(56)* which contain α-methylene protons as well as the trimethylsilyl group.



R = C_6H_5 *(60)* *(59c)*

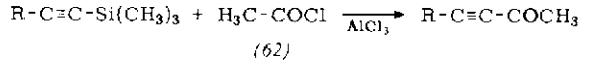
10. Substitution in Silylated Acetylenes

The Si–C bonds in ethyl trimethylsilylacetate *(49)*, trimethylsilylacetonitrile *(56)*, and ethyl trimethylsilylbutyrate *(59)* are easily broken, but –C≡C–Si– bonds are much less reactive [50], with only few exceptions [49].

The inertness of these bonds, even toward acyl chlorides, acid anhydrides, and α-chloroalkyl ethers, is readily overcome by using aluminum chloride as catalyst. Many new trimethylsilyl derivatives of acetylenic compounds containing ketonic or ether groups have been prepared in this way.

For example, bistrimethylsilylacetylene *(61)* reacts with acetyl chloride *(62)* or acetic anhydride to give 1-trimethylsilyl-1-butyn-3-one *(63)* in very good yield.

Similarly, the silyl group of unsymmetrically substituted trimethylsilylacetylenes, such as 1-phenyl-2-trimethylsilylacetylene *(64)*, can be replaced by an acyl group. Acetyl chloride reacts with *(64)* to give 1-phenyl-1-butyn-3-one *(65)* [51].

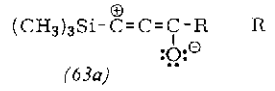


(62)

(61): R = $Si(CH_3)_3$ *(63)*: R = $Si(CH_3)_3$

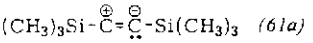
(64): R = C_6H_5 *(65)*: R = C_6H_5

It is remarkable that only one trimethylsilyl group in *(61)* can be replaced by an acyl group. The resonance structure *(63a)* of the 1-trimethylsilylalkynones apparently inhibits complete desilylation and acylation.

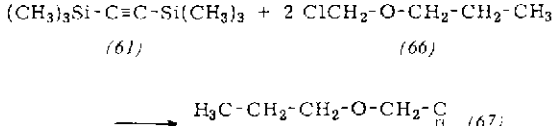


(63a)

The acylium ion $R-\overset{\oplus}{C}=O$ resulting from the reaction of the acyl chloride or acid anhydride with the Lewis acid aluminum chloride can no longer attack here as an electrophile, as it does *(61)*; instead, the latter presumably reacts with the acylating agent to form the resonance structure *(61a)*.



In the reaction with α-chloroalkyl ethers, *e.g.* chloromethyl n-propyl ether *(66)*, disubstitution of bistrimethylsilylacetylene *(61)* is no more difficult than monosubstitution. Formation of 1,4-dipropoxy-2-butyne *(67)* [52] supports this argument.

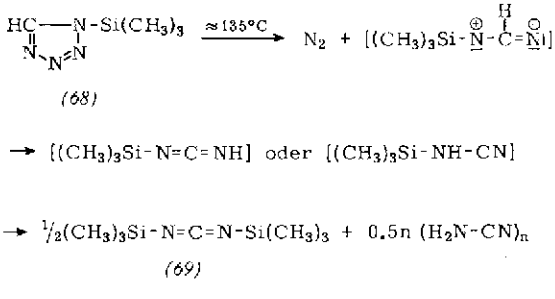


(61) *(66)* *(67)*

III. The Trimethylsilyl Group as an Electron Acceptor

1. Thermolysis of Silylated Tetrazoles

All the known *N*-trimethylsilyl derivatives of pyrrole, pyrazole, imidazole, and 1,2,4-triazole are thermally stable (see Section II.1), but silylated tetrazoles are decomposed by heat [53]. Thus at about 135 °C, 1-trimethylsilyltetrazole *(68)* loses one mole of nitrogen to form *N,N'*-bistrimethylsilylcarbodiimide *(69)* and polymeric cyanamide [54]. 2-Trimethylsilyl-5-phenyltetrazole *(70)* decomposes at about 190 °C to nitrogen and



(68)

3,5-diphenyl-1-bis(trimethylsilyl)amino-1,2,4-triazole *(72)*, hydrolysis of which yields 1-amino-3,5-diphenyl-1,2,4-triazole *(73)*. *C*-Phenyl-*N*-trimethylsilylnitrilimine *(71)*, the first known 1,3-dipolar organosilicon com-

[49] *Y. N. Volnow* and *A. Reutt*, Zhur. obshch. Khim. *10*, 1600 (1940); Chem. Abstr. *35*, 2853 (1941).

[50] *A. D. Petrov* and *L. L. Shchukovskaya*, Dokl. Akad. Nauk U.S.S.R. *86*, 551 (1952); Chem. Zbl. *1953*, 2103; Chem. Abstr. *47*, 12225 (1953).

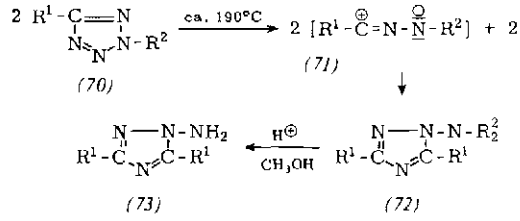
[51] *L. Birkofer*, *A. Ritter*, and *H. Uhlenbrauck*, Chem. Ber. *96*, 3280 (1963).

[52] Identical with the compound prepared hy another route by *A. L. Kranzfelder* and *R. R. Vogt*, J. Amer. chem. Soc. *60*, 1714 (1938).

[53] *L. Birkofer*, *A. Ritter*, and *P. Richter*, Chem. Ber. *96*, 2750 (1963).

[54] Cf. *L. Birkofer*, *A. Ritter*, and *P. Richter*, Tetrahedron Letters *1962*, 195; *J. Pump* and *U. Wannagat*, Liebigs Ann. Chem. *652*, 21 (1962).

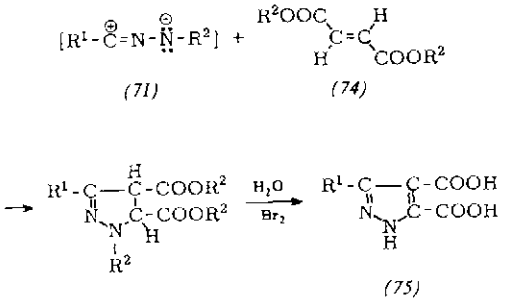
bound, can be trapped by 1,3-dipolar addition during the course of the complicated reaction [53].



(70) (71) (73) (72)

$R^1 = C_6H_5$; $R^2 = Si(CH_3)_3$

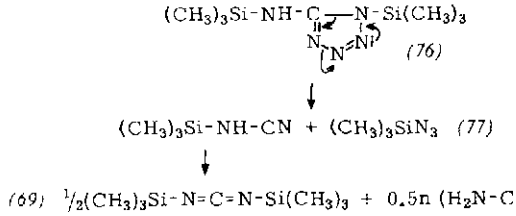
The formation of *(72)* during the thermolysis of *(70)* is prevented by the presence of compounds which react with 1,3-dipoles. Thermolysis of *(71)* in the presence of bistrimethylsilyl fumarate *(74)* followed by oxidation with bromine gives 3-phenylpyrazole-4,5-dicarboxylic acid *(75)*. This provides a general route for the preparation of pyrazole derivatives by reaction of 1,3-dipolarophiles with nitrilimines, *e.g. (71)* [55].



(71) (74) (75)

$R^1 = C_6H_5$; $R^2 = Si(CH_3)_3$

A third mode of decomposition of tetrazoles is illustrated by the thermolysis of 1-trimethylsilyl-5-(trimethylsilylamino)tetrazole *(76)* which yields trimethylsilyl azide *(77)*; compound *(77)* was first prepared by this method (cf. Section VI.10). In addition to *(77)* the carbodiimide *(69)*, which had previously been prepared by thermolysis of the tetrazole *(68)*, was also obtained. Other silyl azides have since been prepared [56, 57].



(76) (77) (69)

2. The Course of Thermolysis

The mechanism of the thermolysis of substituted tetrazoles has been elucidated by *Huisgen* [55]. The observation that silylated tetrazoles decompose at least as readily as correspondingly substituted phenyltetrazoles shows that by withdrawing electrons in the transition state the trimethylsilyl group favors the decomposition in the same way as does the phenyl group.

[55] Cf. *R. Huisgen, J. Sauer*, and *M. Seidel*, Chem. Ber. *94*, 2503 (1961); *R. Huisgen, M. Seidel, G. Wallbilich*, and *H. Knupfer*, Tetrahedron *17*, 3 (1962).

[56] *R. West* and *J. S. Thayer*, J. Amer. chem. Soc. *84*, 1763 (1962).

[57] *N. Wiberg, F. Raschig*, and *R. Sustmann*, Angew. Chem. *74*, 388 (1962); Angew. Chem. internat. Edit. *1*, 335 (1962).

IV. The Trimethylsilyl Moiety as a Protective Group

1. Reactions of Trimethylsilyl Azide

This azide can be conveniently prepared from trimethylchlorosilane *(3)* and sodium azide [53] (cf. Section VI.10) and distilled (b.p. 95 °C) at normal pressure without decomposition.

a) *Addition of Trimethylsilyl Azide onto C≡C Bonds*

Since it is not dangerous, trimethylsilyl azide *(77)* can be used in reactions which must otherwise be carried out with highly explosive hydrazoic acid. The trimethylsilyl group can again be subsequently replaced by a proton under mild conditions.

The azide *(77)* adds onto phenylacetylene *(78)* in the same way as hydrazoic acid [58], and after desilylation, 4-phenyl-1,2,3-triazole *(80)* [51, 53] can be isolated in 64 % yield. Reaction of the dimethyl acetylenedicarboxylate *(79)* with *(77)*, followed by replacement of the trimethylsilyl group by a proton, gives dimethyl 1,2,3-triazole-4,5-dicarboxylate *(81)* [53, 59].

(77)

(78): $R^1 = H$; $R^2 = C_6H_5$ *(80)*: $R^1 = H$; $R^2 = C_6H_5$

(79): $R^1 = R^2 = COOCH_3$ *(81)*: $R^1 = R^2 = COOCH_3$

R = $(CH_3)_3Si$

1,2,3-Triazole derivatives containing both *N*- and *C*-trimethylsilyl substituents can be selectively desilylated: methanol cleaves N-Si bonds, while methanol/HCl [60] cleaves C-Si bonds as well, both with protonation [51].

b) *Reaction of Trimethylsilyl Azide with Triphenylphosphine*

Like phenyl azide [61], trimethylsilyl azide *(77)* also reacts with triphenylphosphine; here the product is triphenylphosphine trimethylsilylimine *(82)* [53, 62] (cf. Section VI. 11.).

(77) (82)

Removal of the trimethylsilyl group from *(82)* with isopropanol yields triphenylphosphine imine *(83)* and isopropoxytrimethylsilane *(84)* without subsequent attack on the labile P–NH group [62].

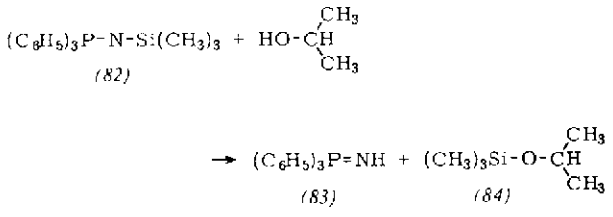
[58] *L. W. Hartzel* and *F. R. Benson*, J. Amer. chem. Soc. *76*, 667 (1954).

[59] Compound *(81)* is identical with the product obtained by another route by *S. Yamada, T. Mizoguchi*, and *A. Ayata*, J. pharmac. Soc. Japan (Yakugakuzasshi) *77*, 452 (1957); Chem. Abstr. *51*, 14697 (1957).

[60] *C. Eaborn*, J. chem. Soc. (London) *1956*, 4858.

[61] *H. Staudinger* and *J. Meyer*, Helv. chim. Acta *2*, 635 (1919).

[62] *L. Birkofer, A. Ritter*, and *S. M. Kim*, Chem. Ber. *96*, 3099 (1963).



(82) *(83)* *(84)*

Compound *(83)* can be prepared more simply and more safely in this way than from triphenylphosphine and chloramine [63]. The hitherto unknown trialkylphosphine imines can be obtained in a similar manner [64].

c) *Cause of the Thermal Stabilitiy of Trimethylsilyl Azide*

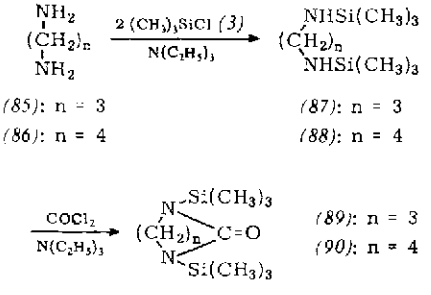
The thermal stability of trimethylsilyl azide *(77)* is unexpected when compared to organic azides, but may be due to its greater stabilization by resonance owing to $d_\pi - p_\pi$ bonding between the silicon and nitrogen atoms, which can occur provided the bond angle in the Si–NNN system is rather large.

Raman-spectroscopic measurements on trimethylsilyl isocyanate $(CH_3)_3Si-NCO$ *(44)* [66] and on trimethylsilyl azide *(77)* [65] indicate that the bond angle is over 120° in *(77)*, too. The trimethylsilyl azide molecule thus appears to be capable of resonance with participation of the silicon atom as well.

2. Carbamidation of Silylated Diamines; Cyclic Ureas and a New Uric Acid Synthesis

Cyclic ureas can be obtained from aliphatic ω,ω'-diamines such as trimethylenediamine *(85)* and tetramethylenediamine *(86)*, but only by way of the thioureas and subsequent replacement of sulfur by oxygen [67] and not by cyclization of the diamines with phosgene.

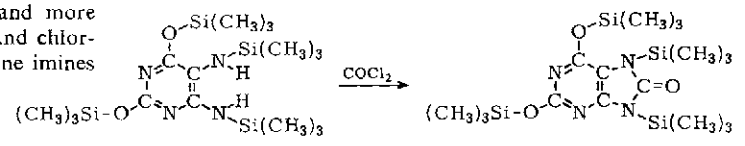
After conversion of *(85)* or *(86)* into the *N,N'*-bistrimethylsilyl compounds *(87)* and *(88)*, phosgene immediately brings about ring closure to *N,N'*-bistrimethylsilyltrimethyleneurea *(89)* or *N,N'*-bistrimethylsilyltetramethyleneurea *(90)*, which can be readily desilylated [8] (overall yields: 60 and 75%, respectively).



(85): n = 3 *(87)*: n = 3
(86): n = 4 *(88)*: n = 4

(89): n = 3
(90): n = 4

2,6-Bis-*O*-trimethylsilyl-4,5-bis(trimethylsilylamino)uracil *(91)*, which is obtained by silylation of 4,5 diaminouracil, reacts with phosgene in toluene by ring closure to form tetrakistrimethylsilyluric acid *(21)* [8] (cf. Sections VI.13 and VI.14). In this way, it has become possible for the first time to carry out syntheses with 4,5 diaminouracil in hydrocarbons as solvent. This is a typical example of a reaction in which the starting material becomes soluble in the organic phase only after silylation.

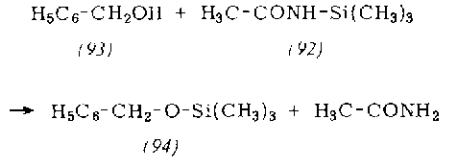


(91) *(21)*

The cylization of *(91)* to *(21)* can be effected even with CO_2 in 87% yield. Hydrolysis of *(21)* yields uric acid (cf. Section VI.15).

3. Preparation of Trimethylsilylalkoxy Compounds and Glucose Derivatives; Disaccharide Synthesis

The method regarded until now as the most suitable for the preparation of trimethylsilylalkoxy compounds was the alcoholysis of hexamethyldisilazane *(99)* [26,68]. However, hydroxy functions can be silylated quantitatively under milder conditions by mixing stoichiometric quantities of an alcohol and *N*-trimethylsilylacetamide *(92)*. Reaction of benzyl alcohol *(93)* and *(92)* yields benzoxytrimethylsilane *(94)* [4]. Isopropoxytrimethylsilane *(84)* [62] is equally easily obtainable.



(93) *(92)* *(94)*

Persilylated carbohydrates are best prepared by fusion of *(92)* with a carbohydrate for a short time. For example, glucose reacts in this way with *(92)* to give pentakis-*O*-trimethylsilylglucose [4] (cf. Section VI.16). The acetamide formed as by-product can be separated from the silylated sugar in a single operation by distillation or by addition of a solvent such as petroleum ether after the reaction, followed by filtration. The silylated carbohydrates are extremely soluble even in hydrocarbons. They can also be satisfactorily prepared from carbohydrates and *(92)* in solvents such as pyridine [4]. Until now, trialkylsilyl derivatives of carbohydrates were always prepared using trialkylchlorosilanes [69].

a) *Disaccharide Synthesis with 1,2,3,4-Tetrakis-O-trimethylsilylglucose*

Glucose can be selectively silylated with *N*-trimethylsilylacetamide in pyridine to give 1,2,3,4-tetrakis-*O*-trimethylsilylglucose *(95)* (cf. Section VI.17.). This reacts with α-

[63] *R. Appel* and *A. Hauss*, Chem. Ber. *93*, 405 (1960).

[64] *L. Birkofer* and *S. M. Kim*, Chem. Ber. *97*, 2100 (1964).

[65] The authors are indebted to Prof. *F. Fehér* and Dr. *M. Gottauf*, Köln, for recording and interpreting the Raman spectrum of *(77)*.

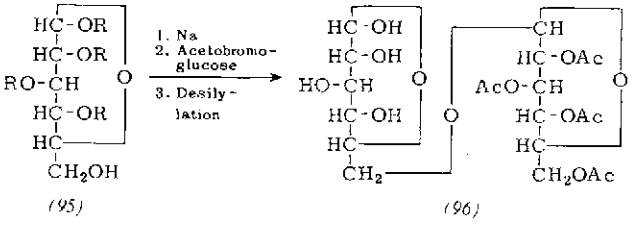
[66] *J. Goubeau, E. Heubach, D. Paulin*, and *I. Widmaier*, Z. anorg. allg. Chem. *300*, 194 (1959).

[67] *R. Mecke jr.* and *R. Mecke*, Chem. Ber. *89*, 343 (1956).

[68] *St. H. Langer, S. Connell*, and *I. Wender*, J. org. Chemistry *23*, 50 (1958).

[69] *F. A. Henglein* and *K. Scheinost*, Makromolekulare Chem. *21*, 59 (1956); *E. J. Hedgley* and *W. G. Overend*, Chem. and Ind. *14*, 378 (1960); *R. Schwarz, E. Baronetzky*, and *K. Schoeller*, Angew. Chem. *68*, 335 (1956).

acetobromoglucose to form 1,2,3,4-tetrakis-*O*-trimethylsilyl-2′,3′,4′,6′-tetra-*O*-acetyl-β-gentiobiose, which yields tetra-*O*-acetyl-β-gentiobiose on desilylation *(96)* [70]. Acetylation of the latter leads to octaacetyl-β-gentiobiose [71].



(95) *(96)*

4. Peptide Syntheses Using Silylated Amino Acids and Peptides

Owing to the ease of removal of the silyl groups, trimethylsilyl esters of *N*-trimethylsilylamino acids [3,7] are more suitable for peptide syntheses than alkyl esters of amino acids.

a) *Trimethylsilyl Esters of N-Trimethylsilylamino Acids*

Trimethylsilyl esters of *N*-trimethylsilylamino acids are easy to prepare. An amino acid or its hydrochloride is heated in excess hexamethyldisilazane *(99)* together with a few drops of concentrated sulfuric acid [3,7,72] (cf. Section VI.18.).

Experiments with L-alanine, L-valine, and L-leucine show that no racemization occurs during silylation (see Table 5).

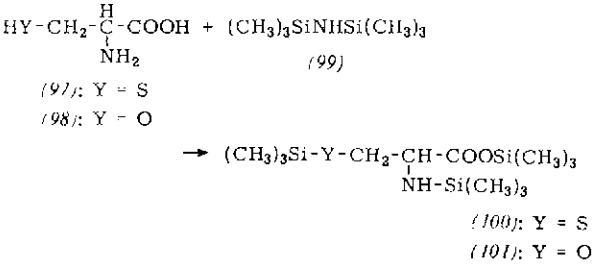
Table 5. Specific rotations of unsilylated and desilylated amino acids.

Amino acids	$[\alpha]_D^{20}$	
	Unsilylated	Desilylated
L-Alanine	+ 14.1 ± 1°	+ 13.5 ± 1°
L-Valine	+ 6.4 ± 1°	+ 6.0 ± 1°
L-Leucine	− 10.4 ± 1°	− 10.3 ± 1°

Triethylsilyl esters of *N*-triethylsilylamino acids are obtained in high yields by treatment of amino acids with triethylsilane and $PdCl_2$ catalyst in the presence of a little triethylaminosilane [73]. Silyl derivatives of amino acids have also been obtained [74] by reaction of the sodium salts of the amino acids with trimethylchlorosilane *(3)*. Free amino acids cannot be silylated with *(3)*, owing to their zwitterionic character [2].

b) *Trimethylsilyl Derivatives of Polyfunctional Amino Acids*

The trimethylsilyl residue has been used as a protective group for the SH and OH functions in peptide syntheses with cysteine *(97)* and serine *(98)*, since it can be removed simply by hydrolysis. The reactions of *(97)* and *(98)* with hexamethylsilazane *(99)* yield the trimethylsilyl esters of *N,S*-bistrimethylsilylcysteine *(100)* and *N,O*-bistrimethylsilylserine *(101)*, respectively [75].



(97): Y = S
(98): Y = O

(99)

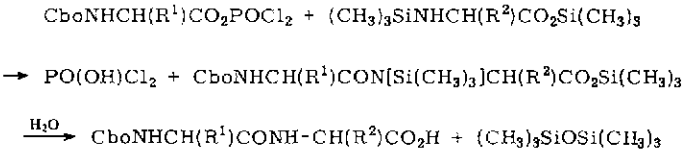
(100): Y = S
(101): Y = O

c) *Peptide Syntheses with Trimethylsilyl Esters of N-Trimethylsilylamino Acids* [75]

Trimethylsilyl esters of *N*-trimethylsilylamino acids are preferable to alkyl esters of amino acids for peptide syntheses, *e.g.* by the phosphorus oxychloride [76] or imidazolide methods [77]. Unlike the alkyl esters of *N*-carbobenzoxy dipeptides, the resulting silyl esters of *N*-carbobenzoxy dipeptides need not be isolated and hydrolyzed in a separate operation, since they are hydrolyzed to the free carbobenzoxy dipeptides during the normal work-up.

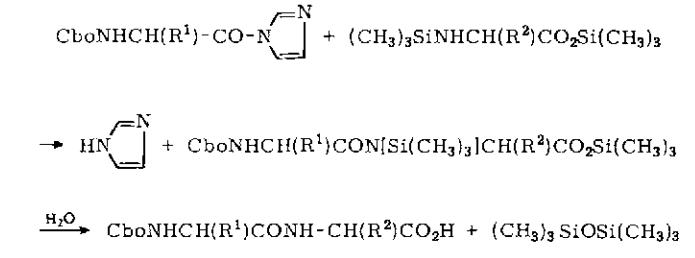
Silylated amino acids can also be used in syntheses by the *p*-nitrophenyl ester [78] and ethyl chloroformate methods [79]. To prepare dipeptides by the *p*-nitrophenyl ester method in a one-step reaction [80], the *p*-nitrophenyl ester of the carbobenzoxy amino acid is fused with the desired amino acid and *N*-trimethylsilylacetamide *(92)*. After work-up, the yield of carbobenzoxy dipeptide is 80–95 %.

Phosphorus Oxychloride Method:

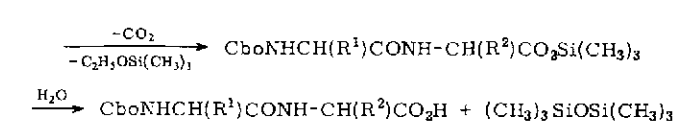


Cbo = H_5C_6-CH_2-O-CO-

Imidazolide Method:



Mixed Anhydride Method:



[75] *L. Birkofer, W. Konkol,* and *A. Ritter,* Chem. Ber. *94,* 1263 (1961).

[76] *Th. Wieland* and *B. Heinke,* Liebigs Ann. Chem. *599,* 70 (1956).

[77] *G. W. Anderson* and *R. Paul,* J. Amer. chem. Soc. *80,* 4423 (1958); *R. Paul* and *G. W. Anderson,* ibid. *82,* 4596 (1960).

[78] *M. Bodansky,* Nature (London) *175,* 685 (1955).

[79] *Th. Wieland* and *H. Bernhard,* Liebigs Ann. Chem. *572,* 190 (1951); *R. A. Boissonas,* Helv. chim. Acta *34,* 874 (1951).

[80] *L. Birkofer, F. Müller,* and *J. Biedermann,* unpublished work.

[70] Identical with a product prepared by *A. Klemer,* Chem. Ber. *92,* 218 (1959).

[71] *H. Bredereck, A. Wagner, G. Faber, H. Ott,* and *J. Rauther,* Chem. Ber. *92,* 1135 (1959).

[72] *L. Birkofer* and *F. Müller,* unpublished work.

[73] *L. Birkofer, E. Bierwirth,* and *A. Ritter,* Chem. Ber. *94,* 821 (1961).

[74] *K. Rühlmann,* J. prakt. Chem. *281,* 68 (1959).

p-Nitrophenyl Ester Method:

$$CbzNHCH(R^1)COO\text{-}C_6H_4\text{-}NO_2 + H_2NCH(R^2)CO_2H + 2\ H_3C\text{-}CONHSi(CH_3)_3 \quad (92)$$

$$\rightarrow CbzNHCH(R^1)CONH\text{-}CH(R^2)CO_2H + HO\text{-}C_6H_4\text{-}NO_2 + 2\ H_3C\text{-}CONH_2 + (CH_3)_3SiOSi(CH_3)_3$$

Tripeptides in One Step-Reaction

Mixed anhydrides obtained from *N*-carbobenzoxyamino acids and ethyl chloroformate react with silyl esters of *N*-silylamino acids to form silyl esters of *N*-carbobenzoxy dipeptides. It is possible, without isolating the latter, to convert them once again into mixed anhydrides using ethyl chloroformate. Renewed addition of silylated amino acids to the mixed anhydrides of the preceding step yields the silyl esters of *N*-carbobenzoxy tripeptides, hydrolysis of which gives *N*-carbobenzoxy tripeptides [81].

Syntheses Using Silylated Di- and Tri-peptides

Like amino acids, di- and tri-peptides can also be silylated by hexamethyldisilazane *(99)*. However, the silyl esters of di- or tri-peptides cannot be distilled without undergoing side-reactions or decomposing. Nevertheless, they will react without previous isolation with *N*-carbobenzoxyamino acids or *N*-carbobenzoxy peptides by several methods to give higher peptides [81].

V. Removal of Carbobenzoxy Groups with Triethylsilane

The protective group can be removed from *N*-carbobenzoxyamino acids or peptides using triethylsilane with $PdCl_2$ as catalyst [73]. The resulting *N*-silylamino acid esters or *N*-silyl peptides are then converted into the free compounds by methanolysis. This method is particularly suitable for compounds containing sulfur: for example, *N*-carbobenzoxy-*S*-benzylcysteine gives *S*-benzylcysteine.

The trimethylsilyl ester of *N*-carbobenzoxyglycine, which contains no free carboxyl group, is also decarbobenzoxylated on reaction with triethylsilane; this shows that the cleavage is not brought about by the hydrogen initially liberated by silylation of carboxyl groups, but by the triethylsilane

$$R\text{-}\underset{\underset{HNCO_2CH_2C_6H_5}{|}}{CH}CO_2H \xrightarrow[PdCl_2]{(C_2H_5)_3SiH} H_2 + R\text{-}\underset{\underset{HNCO_2CH_2C_6H_5}{|}}{CH}CO_2Si(CH_3)_3$$

$$\xrightarrow{(C_2H_5)_3SiH} CO_2 + H_5C_6\text{-}CH_3 + R\text{-}\underset{\underset{HNSi(CH_3)_3}{|}}{CH}\text{-}CO_2Si(CH_3)_3$$

$$\xrightarrow{2\ CH_3OH} R\text{-}CH(NH_2)CO_2H + 2\ (C_2H_5)_3SiOCH_3$$

VI. Practical Procedures

1. *N- Trimethylsilylimidazole (1)* [9]

All reactions must be carried out in the absence of moisture. Imidazole (13.6 g) is heated under reflux in an oil bath for 2 h with 24.2 g of hexamethyldisilazane *(99)* plus 2 drops of concentrated sulfuric acid. On fractional distillation 23.8 g of *(1)* is obtained (b.p. 91 °C/12 mm; 85 % yield; $n_D^{20} = 1.4756$).

2. *N-Acetylimidazole (2)* [9]

N-Trimethylsilylimidazole *(1)* (0.1 mole) is dissolved in 25 ml of dry benzene, and 0.1 mole of acetyl chloride in 25 ml of dry benzene is added dropwise with stirring at 0 °C. After stirring for 15 min, the trimethylchlorosilane *(3)* formed and the benzene are removed *in vacuo*, leaving 10.5 g of *(2)*, 96 % yield; m.p. 105 °C.

3. *N,N'-Carbonyldiimidazole (6)* [9]

Phosgene (0.05 mole) is passed into a solution of 0.1 mole of *(1)* in 100 ml of dry benzene at 0 °C; 7.9 g of analytically pure *(6)*, m.p. 115 °C (98 % yield), is precipitated.

4. *Tetrakistriethylsilyluric Acid (20)* [7]

Uric acid (6.3 g) is boiled for 16 h with triethylsilylamine; excess triethylsilylamine and its condensation product, hexaethyldisilazane, are then removed by distillation at 12 mm. Afterwards 21 g of *(20)*, m.p. 43 °C (91 % yield), distils out of the residue at 200–205 °C/0.04 mm.

5. *1-Methyluric Acid (28)* [27]

Tetrakistriethylsilyluric acid *(20)* (5 g) is dissolved in 15 g of methyl iodide, 1.6 g of $AgClO_4$ is added, and the mixture is left standing for 10 min. Silver iodide precipitates out with liberation of heat, and is filtered off. Hydrolysis of the filtrate with aqueous ethanol gives 1.25 g of *(28)* (85 % yield) which decomposes at 400 °C. Small quantities of more highly methylated uric acids can be readily removed owing to their poor solubility in water.

6. *3-(1-Furanosyl)uric Acid (38)* [27,34]

Tetrakistriethyluric acid *(20)* (12 g) is dissolved in 50 ml of toluene and mixed with 4 g of $AgClO_4$. 1-Bromo-2,3,5-tribenzoylribofuranose (10 g) in 60 ml of toluene is added dropwise over 10 min with constant stirring. The AgBr precipitate is centrifuged out in a moisture-free atmosphere and the solution is poured into 500 ml of petroleum ether. The resulting precipitate is dissolved in a little toluene and hydrolyzed with methanol, to give 10 g (90 % yield) of 3-(tribenzoylribofuranosyl)uric acid. This is filtered off and redissolved in 200 ml of methanol. Ammonia is passed in until the solution is saturated, and the latter is left standing for 2 days at 20 °C. The solvent is then removed and the 3-ribofuranosyluric acid *(38)* is recrystallized from methanol. The yield is quantitative; the product decomposes at 220 °C.

7. *Trimethylsilyl β-Bromopropionate (40)* [39]

β-Bromopropionic acid (0.22 mole) in 100 ml of benzene is placed in a flask fitted with a reflux condenser and a dropping funnel, and 0.23 mole of trimethylchlorosilane *(3)* is added. A solution of 0.23 mole of triethylamine in 50 ml of benzene is added dropwise to this mixture. After heating on the water bath for 2–3 h with stirring, triethylamine hydrochloride is filtered off, the benzene is removed, and the ester *(40)* is distilled (b.p. 85.7 °C/13 mm; yield 66 %).

8. *β-Propiolactone (42)*

A suspension of 50 g of AgNCO in 30 ml of toluene is heated with stirring in an oil bath at 130–140 °C, and 68 g of *(40)* are added dropwise. After heating and stirring for a further hour,

[81] *L. Birkofer, A. Ritter*, and *P. Neuhausen*, Liebigs Ann. Chem. *659*, 190 (1962).

the AgBr formed is filtered off and the filtrate is distilled at normal pressure. Trimethylsilyl isocyanate *(44)* and toluene distil over, and fractionation of the residue gives 11 g (or 50 %) of *(42)*, b.p. 56 °C/14 mm. It is not advisable to replace the silver cyanate by silver perchlorate and to isolate the resulting trimethylsilyl perchlorate, owing to the danger of explosions (cf. Section II.6.).

9. *Ethyl β-Trimethylsiloxy-β-(p-nitrophenyl)-propionate (55)* [45]

A mixture containing 22.7 g of *p*-nitrobenzaldehyde, 30 g of ethyl trimethylsilylacetate *(48)* and 330 mg of $KAl(OCH_3)_4$ as catalyst is heated under reflux for 9 h at 160–180 °C in an oil-bath in the absence of moisture. The catalyst is filtered off, and the filtrate is fractionated using a spinning-band column. An 81 % yield (37.6 g) of *(55)*, b.p. 126 °C/0.1 mm, is obtained; recrystallization from ethanol/water furnishes yellow crystals melting at 44 °C.

10. *Trimethylsilyl Azide (77)* [53]

Sodium azide (9.8 g) and 16.3 g of trimethylchlorosilane *(3)* in 75 ml of tetrahydrofuran are refluxed with stirring for 48 h. The solution is filtered to remove NaCl and distilled at normal pressure in a spinning-band column to give an 87 % yield of *(77)*, b.p. 95 °C.

11. *Triphenylphosphine N-Trimethylsilylimine (82)* [53]

When 6.9 g of *(77)* is heated with 14.5 g of triphenylphosphine, vigorous evolution of nitrogen occurs at a bath temperature of 110 °C. As the temperature is raised gradually to 140 °C over a period of 4 h, 1320 ml of nitrogen is liberated. On distillation of the reaction mixture, *(82)* distils over at 170–171 °C/0.06 mm. The yield is 18.7 g (97 %). Compound *(82)* recrystallizes from acetonitrile to give colorless crystals, m.p. 76–77 °C.

12. *Triphenylphosphinimine (83)* [62]

Compound *(82)* (17.5 g) is mixed with two-thirds of a solution of 3 drops of concentrated sulfuric acid in 50 ml of absolute isopropanol in a 100-ml two-necked flask fitted with a dropping funnel and a column with a descending condenser. The solution is heated to boiling, and the remaining isopropanol solution is added dropwise at the same rate as the isopropoxytrimethysilane *(84)* (b.p. 75 °C) formed distils off. When *(84)* has distilled over completely (after about 1 h), excess isopropanol is removed *in vacuo*. Absolute petroleum ether (b.p. 40–70 °C) (40 ml) is added, and *(83)* precipitates out in crystalline form. Recrystallization from cyclohexane gives colorless plates, m.p. 127.5 °C; the yield is 14.8 g (85 %).

13. *2,6-Bis-O-trimethylsilyl-4,5-bis(trimethylsilylamino)uracil (91)* [8]

4,5-Diaminouracil (10 g) is refluxed for 2 h with 30 g hexamethyldisilazane *(99)* containing 2 drops of sulfuric acid. Fractional distillation gives a 90 % yield (29 g) of *(91)*, b.p. 105 °C/10^{-4} mm, which solidifies to give needles, m.p. 60 °C.

14. *Tetrakistrimethylsilyluric Acid (21)* [8]

Triethylamine (8.5 g) is added to 16.5 g of *(91)* in 100 ml of toluene, and the mixture is cooled to 0 °C. Phosgene (4 g) in 50 ml of toluene is added dropwise with stirring. After a few hours, the triethylammoniumchloride formed is filtered off, and the solution is fractionated. Distillation gives an 80 % yield (14.0 g) of *(21)*, b.p. 135–140 °C/0.02 mm. Recrystallization from acetonitrile gives needles, m.p. 114 °C.

15. *Uric Acid*

Trituration of *(21)* with ethanol gives a quantitative yield of uric acid.

16. *Pentakis-O-trimethylsilylglucose* [4]

D-Glucose (10 mmoles) is mixed with 70 mmoles of *N*-trimethylsilylacetamide *(92)*, and the mixture is heated for 15 min at 180 °C. Acetamide and excess *(92)* are removed by vacuum distillation. On fractionation, pentakis-*O*-trimethylsilylglucose distils over at 115 °C/0.08 mm in 98 % yield.

17. *1,2,3,4-Tetrakis-O-trimethylsilylglucose (95)* [4]

D-Glucose (50 mmoles) and 220 mmoles of *(92)* are dissolved in 100 ml of pyridine and boiled for 2.5 h. The pyridine and acetamide are distilled off, and the residue is fractionated to give a 73 % yield of *(95)*, b.p. 117 °C/0.01 mm.

18. *Trimethylsilyl Ester of N-Trimethylsilyl-L-leucine* [3, 7, 72]

L-Leucine (10 g) is heated in 45 g of refluxing hexamethyldisilazane *(99)* containing 2 drops of concentrated sulfuric acid (bath temperature 130–140 °C) until dissolved, and is then boiled for further 30 min. After cooling, 150 ml of benzene, 2.6 g of triethylamine, and 2.7 g of trimethylchlorosilane *(3)* are added and the mixture is allowed to stand at room temperature for 12 h. The precipitate is filtered off. On distillation of the filtrate at 12 mm, the excess *(99)* comes off first, followed by the ester. A 92 % yield (19.5 g) of the trimethylsilyl ester of *N*-trimethylsilyl-L-leucine, b.p. 104 °C/12 mm, is obtained.

19. *Peptide Syntheses*

a) *By the Phosphorus Oxychloride Method* [75]

A solution of 0.02 mole of *N*-carbobenzoxyglycine in 100 ml of tetrahydrofuran is cooled to −15 °C. A solution of 0.02 mole (1.84 ml) of pure phosphorus oxychloride in 10 ml of tetrahydrofuran is added dropwise with stirring. Next 0.02 mole (2.8 ml) of triethylamine is added; this is followed by dropwise addition of a solution of 0.02 mole of the trimethylsilyl ester of *N*-trimethylsilyl-DL-leucine and 0.02 mole of triethylamine in 20 ml of tetrahydrofuran, the rate of addition being adjusted so that the temperature does not exceed −10 °C. Stirring is continued for further 5–10 min. The reaction mixture is kept for 2 h at −10 °C, and the product is hydrolyzed by dropwise addition with stirring of 50 ml of water. On removal of the tetrahydrofuran at room temperature (12 mm) *N*-carbobenzoxyglycyl-DL-leucine precipitates out. After recrystallization from methanol/water, the product melts at 127 °C (yield = 85 %).

b) *By the Imidazolide Method* [81]

N-Carbobenzoxy-DL-valine (0.01 mole) and 1.75 g of *N,N'*-carbonyldiimidazole *(6)* are dissolved in 100 ml of tetrahydrofuran and heated at 50 °C for 1 h. After dropwise addition of 0.011 mole of the trimethylsilyl ester of *N*-trimethylsilylglycyl-β-alanine to the cooled solution, the mixture is refluxed for 3 h, and the tetrahydrofuran is then distilled off at 11 mm. The residue is decomposed with 40 ml of water, the hexamethyldisiloxane is removed, and the aqueous filtrate is

acidified to Congo red with 6 N HCl. The *N*-carbobenzoxy-DL-valylglycyl-β-alanine precipitates as crystals in 87 % yield. Recrystallization from water gives clusters of needles, m.p. 175 °C.

c) *By the Ethyl Chloroformate Method* [81]

N-Carbobenzoxy-Gly-Gly-Gly-β-Ala (0.01 mole) and 0.01 mole (1.4 ml) of triethylamine are dissolved in 100 ml of a 1:1 mixture of tetrahydrofuran and dimethyl sulfoxide. The solution is cooled to −5 °C, and 0.01 mole (0.96 ml) of ethyl chloroformate in 15 ml of tetrahydrofuran is added dropwise with stirring. Stirring is continued for further 30 min at this temperature, and 0.012 mole of the trimethylsilyl ester of *N*-trimethylsilyl-Gly-Gly-β-Ala in 30 ml of tetrahydrofuran is then added. The mixture is stirred for 90 min at −5 °C and then for 90 min at room temperature and finally boiled for a short time. The tetrahydrofuran is evaporated off at 12 mm on a water-bath at 40 °C, and then the dimethyl sulfoxide at 0.1 mm. The residue is hydrolyzed by addition of 40 ml of water containing 1 g of $NaHCO_3$. *N*-Carbobenzoxy-Gly-Gly-Gly-β-Ala-Gly-Gly-β-Ala is obtained in 92 % yield; after recrystallization from methanol/water (4:1 v/v), it melts at 276 °C (decomp.).

d) *By the p-Nitrophenyl Ester Method* [80]

The *p*-nitrophenyl ester of *N*-carbobenzoxy-L-proline (29.6 g), 10.1 g of L-proline, and 23 g of *N*-trimethylsilylacetamide *(92)* are fused together at 65 °C on a water-bath and heated with stirring for further 6 h. After cooling, 100 ml of saturated $KHCO_3$ solution are added, and the solution is extracted with three 40-ml portions of acetic acid/ether (1:2). After removal of the remaining organic solvent at 12 mm, the aqueous solution is filtered through active charcoal and acidified to pH 2 with 18 % HCl. Carbobenzoxyprolylproline precipitates as crystals, which recrystallize from methanol/water to give 25 g (90 % yield) of a product with m.p. 190 °C; $[\alpha]_D^{27} = -103° \pm 1$ (c = 1 in methanol).

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COMMUNICATIONS

Photocatalysed Cycloaddition of Dihalogenomaleimides and Dihalogenomaleic Anhydrides onto Olefins and Acetylenes [1]

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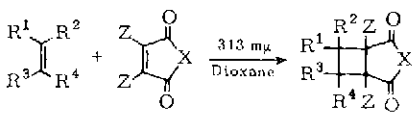
Dedicated to Professor Rudolf Tschesche on the occasion of his 60th birthday

The imides and anhydrides of dichloro- and dibromomaleic acids *(1)* can be added photochemically onto C—C double and triple bonds to form C_4 rings in good yields. The reactions proceed on irradiation of 2 moles of olefin or acetylene and 1 mole of *(1)* in dioxane with light of 302–313 mμ wavelength. Whereas the reactions with *(1)*, Z = Cl and X = O, only go to completion in the presence of benzophenone [**] as sensitizer, reactions with *(1)*, Z = Cl or Br and X = NH, are only slightly promoted by benzophenone.

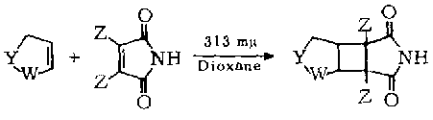
The imide adducts can be obtained in crystalline form by evaporation of the solvent after irradiation. Purification by chromatography on SiO_2 was occasionally necessary. The anhydride adducts were isolated in the form of *cis*-cyclobutane-1,2-dicarboxylic acids, which are easier to handle and which can subsequently be reconverted into the anhydrides with thionyl chloride.

The method has been used to prepare the following compounds:

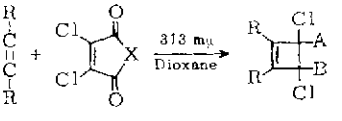


(1)

R^1	R^2	R^3	R^4	Z	X	M.p. [°C] or b.p. [°C/mm]	Yield [%] [1]
CH_3	CH_3	H	H	Cl	NH	153	95
H	H	H	$C_{10}H_{21}$	Cl	O	115/0.01 [2]	92
H	H	H	H	Br	O	104 [*]	96
H	H	H	C_6H_{13}	Cl	NH	62–63	84
Cl	Cl	Cl	Cl	Cl	NH	303	42
CH_3	CH_3	H	$COCH_3$	Cl	NH	174	25



Y	W	Z'	M.p. [°C]	Yield [%] [1]
SO_2	CH_2	Cl	two isomers: 286 and 245	54
O	CO	Cl	283 (decomp.)	85 3]
$PO(OC_2H_5)$	CH_2	Cl	281	65
CH_2	$PO(OC_2H_5)$	Cl	two isomers: 296 and 281 [4]	60
CH_2	CH_2	Br	200	85



R	X	A	B	M.p. [°C]	Yield [%] [1]
$CO_2C_2H_5$	NH	−CO−NH−	−CO−	182	54
CH_3	O	CO_2H	CO_2H [5]	213	73

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Publication deferred until now at the authors' request
German version: Angew. Chem. 77, 452 (1965)

[*] Part II.—Part I: *H. D. Scharf* and *F. Korte*, Chem. Ber. *98*, 764 (1965).

[**] *G. O. Schenk* et. al., Naturwissenschaften *49*, 36 (1962).

[1] Pure product obtained after irradiation of 0.1 mole of *(1)* for 15–18 h with a Philips HPK 125 W lamp (radiation output about 8×10^{-3} molar quanta/h at 302 mμ and about 2.8×10^{-2} molar quanta/h at 313 mμ.

[2] n 1.4780.

[3] The product contains 1 mole of dioxane.

[4] Melting point of a mixture with the product made from 1-oxo-1-ethoxy-3-phospholine: 252–260 °C.

[5] After hydrolysis.

N-Sulfonyl Isothiocyanates [1]

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We have found that *N*-sulfonyl isothiocyanates *(2)* [2–4] are obtained in good yields when potassium salts of *N*-(dithiomethylene)sulfonamides [potassium sulfonylimidocarbonates *(1)* [5], are treated with equimolar amounts of phosgene at room temperature.

$$R\text{-}SO_2\text{-}N{=}C(SK)_2 + COCl_2 \longrightarrow R\text{-}SO_2\text{-}NCS + COS + 2\,KCl$$
(1) *(2)*

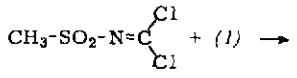
(2), R	B.p. [°C/mm] (M.p. [°C])	n_D^{20}	Yield [%]
(a), CH_3	104/18	1.5449	66
(b), C_4H_9	72/0.2	1.5171	85
(c), Cyclohexyl	92/0.2	1.5489	60
(d), $C_6H_5CH_2$	120/0.5 (38)		64
(e), C_6H_5	100/0.3	1.6012	75
(f), *o*-$CH_3C_6H_4$	114/0.15	1.6010	84
(g), *p*-$CH_3C_6H_5$	109/0.4	1.5938	88
(h), *o*-ClC_6H_4	127/0.4	1.6168	73
(i), *m*-ClC_6H_4	90/0.01	1.6132	66
(j), *p*-ClC_6H_4	105/0.6	1.6173	65
(k), 3,4-$Cl_2C_6H_4$	102/0.01 (33)		70
(l), α-Thienyl	93/0.02	1.6139	63
(m), *p*-$CH_3CONH\text{-}C_6H_4$	(130–132)		67

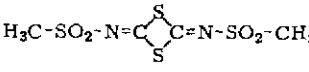
The reaction is exothermal and is conducted with suspensions of the anhydrous salts *(1)* in inert solvents (dichloromethane, benzene, or carbon tetrachloride) with cooling. The products *(2)* usually can be purified by distillation after removal of the potassium chloride by suction filtration and evaporation of the solvent.

Instead of phosgene, 2 moles of ethyl chloroformate [here ethyl pyrothiocarbonate is formed alongside *(2)*], phosphorus pentachloride, or less advantageously even thionyl or sulfuryl chloride can be used.

The *N*-sulfonyl isothiocyanates *(2)* are highly reactive acylating agents and react smoothly at room temperature with NH, alcoholic OH, or SH groups. Phenolic hydroxyl groups require longer reaction times or catalysis with tertiary amines.

Some *N*-sulfonyl isothiocyanates, *e.g. (2a)*, *(2j)*, and especially *(2i)*, tend to dimerize on standing. The structures *(3)* of the dimers were inferred from their formation from sulfonyl isocyanide dichlorides and *(1)*.





(3)

Compounds of type *(3)* dissociate completely into 2 moles of *(2)* on heating above their melting points.

Received: January 29th and March 19th, 1965 [Z 938/764 IE]
German version: Angew. Chem. 77, 429 (1965)

[1] German Patent Application No. 1 183 492 (May 28th, 1963).

[2] *H. Ulrich* and *A. A. R. Sayich*, Angew. Chem. *76*, 781 (1964); Angew. Chem. internat. Edit. *3*, 639 (1964).

[3] *W. Gauss*, Wissenschaftliches Hauptlaboratorium der Farbenfabriken Bayer AG., unpublished experiments (1953).

[4] *W. Hägele*, Ph. D. Thesis, Technische Hochschule Stuttgart, 1963, p. 18.

[5] *R. Gompper* and *W. Hägele*, Angew. Chem. *74*, 753 (1962); Angew. Chem. internat. Edit. *1*, 553 (1962).

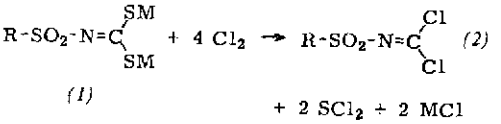
[6] *B. Anders* and *E. Kühle*, Angew. Chem. *77*, 430 (1965); Angew. Chem. internat. Edit. *4*, 430 (1965).

Sulfonyl Isocyanide Dichlorides and Sulfonyl Carbodiimides [1]

By Dr. B. Anders and Dr. E. Kühle

Wissenschaftliches Hauptlaboratorium
der Farbenfabriken Bayer AG., Leverkusen (Germany)

Sulfonyl isocyanide dichlorides *(2)* are obtained in good yields on chlorination of salts of *N*-(dithiomethylene)sulfonamides [sulfonylimides of dithiocarbonates] *(1)*, M = K.



(1) *(2)*

$$+ 2\,SCl_2 + 2\,MCl$$

(2), R =	M.p. [°C]	Yield [%] after recrystallization
CH_3	76–78	73
$Cl\text{-}C_6H_5$	75–77	52
$CH_3\text{-}C_6H_5$	80–85	89

The salt is suspended in a solvent resistant to chlorine, *e.g.* carbon tetrachloride, the equivalent amount of Cl_2 is passed in, keeping the temperature at about 25 °C by cooling with ice. The potassium chloride formed is filtered off. After evaporation of the solvent, the sulfonyl isocyanide dichlorides *(2)* are obtained as crystalline or oily residues which can be crystallized from hydrocarbons.

The infrared spectra of *(2)* contain the C=N band at 1650 cm^{-1} (alkyl or aryl isocyanide dichlorides: 1600–1610 cm^{-1}). The presence of the sulfonyl group in *(2)* makes these compounds much more reactive than alkyl or aryl isocyanide dichlorides [2].

N-Sulfonylcarbodiimides *(3)*, a group of compounds recently described [3], are obtained in very good yields (often 95 to 100 %) when sulfonyl isocyanide dichlorides *(2)* are heated to 100–140 °C with hydrochlorides of primary amines in inert solvents (*e.g.* toluene). The *N*-sulfonylcarbodiimides *(3)* are obtained in the form of crystals or oils. They are often

$$(2) + R'\text{-}NH_2\text{·}HCl \rightarrow R\text{-}SO_2\text{-}N{=}C{=}N\text{-}R' + 3\,HCl$$
(3)

quite stable, but some tend to polymerize. They add on water very rapidly, even without addition of acids, to form *N*-sulfonylureas. For example, after about 4 min in water/dioxane (7:3), *N*-cyclohexyl-*N'*-tosylcarbodiimide is converted to about 50 % into the corresponding urea derivative.

Received: January 29th and March 19th, 1965 [Z 940/766 IE]
German version: Angew. Chem. 77, 430 (1965)

[1] German Patent Application No. F 41 550 4b XII O (Dec. 11th, 1963); F 43707 4c XII O (August 8th, 1964), Farbenfabriken Bayer AG., inventors: *B. Anders* and *E. Kühle*.

[2] *E. Kühle*, Angew. Chem. *74*, 361 (1962); Angew. Chem. internat. Edit. *1*, 647 (1962).

[3] *H. Ulrich* and *A. A. R. Sayigh*, Angew. Chem. *76*, 781 (1964); Angew. Chem. internat. Edit. *3*, 639 (1964).

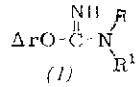
On the Addition of Amines to Cyanic Esters

By Dr. E. Grigat and Dr. R. Pütter

Wissenschaftliches Laboratorium der Zwischenproduktenabteilung der Farbenfabriken Bayer AG, Leverkusen (Germany)

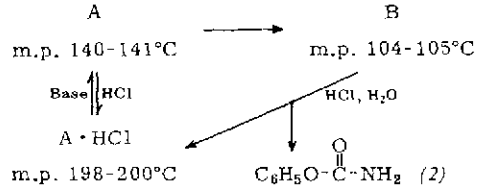
Martin et al. [1] recently reported on the formation of isoureas *(1)* from phenyl cyanate and amines. For the product *(1a)*, which we had described previously [2], they obtained a

melting point of 104–105 °C, which differs considerably from our value (140–141 °C) [3].



(1) *(1a)*, R = H, R^1 = C_6H_5, Ar = C_6H_5

We therefore carried out both syntheses and found that the product obtained by the procedure of *Martin* et al. (substance B) is composed of two moles of phenyl cyanate and one mole of aniline, whereas our method gave a mole ratio of 1:1 (substance A). Substance A can be converted into substance B with phenyl cyanate, and on treatment of B with aqueous HCl, the hydrochloride of A and phenyl carbamide *(2)* are obtained.



This proves that the compound with m.p. 140–141 °C is the iso-urea *(1a)*. The formation of the 2:1 adduct by the procedure of *Martin* et al. [1] confirms our observation [2] that free primary amines (in contrast to their salts) add on 2 moles of cyanic ester with the formation of iminobiscarbamidic esters.

Received: February 22nd, 1965 [Z 961/787 IE]
German version: Angew. Chem. 77, 452 (1965)

[1] *D. Martin, H.-G. Herrmann, S. Rackow,* and *K. Nadolski,* Angew. Chem. 77, 96 (1965); Angew. Chem. internat. Edit. 4, 73 (1965).

[2] *E. Grigat* and *R. Pütter,* Chem. Ber. 97, 3027 (1964). The compound is listed in the table on p. 3032.

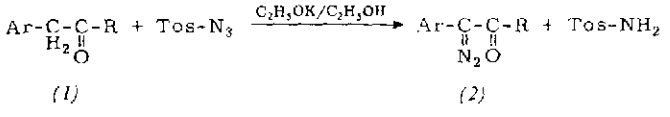
[3] From ligroin, m.p. 142–143 °C.

Synthesis of v-Triazolo[3,4-a]pyridines and 1,2,3-Triazoles by Diazo Group Transfer with Tosyl Azide [1]

By Dr. M. Regitz

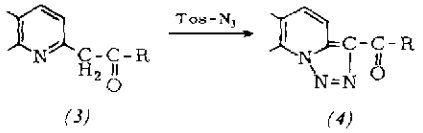
Institut für Organische Chemie der Universität des Saarlandes, Saarbrücken (Germany)

Arylmethyl ketones *(1)* react with *p*-toluenesulfonyl azide and potassium ethoxide in ethanol at −10 to 0 °C to yield α-diazoarylmethyl ketones *(2)* plus tosyl amide [2].



(1) *(2)*

If the aryl residue in *(1)* is replaced by 2-pyridyl, 6-picolyl, or 2-quinolyl *(3)*, an analogous reaction occurs, leading to high yields of *v*-triazolo[3,4-*a*]pyridine derivatives *(4)*, whose structures are indicated by their elemental analyses and ultraviolet and infrared spectra (no diazo band).



(3) *(4)*

(3)		*(4)*	
Heteroaromatic group	R	Yield [%]	M.p. [°C]
2-Pyridyl	Phenyl	88	111–112 [3]
2-Pyridyl	t-Butyl	90	95–96
2-Pyridyl	n-Propyl	79	98
2-Pyridyl	2-Furyl	94	215
6-Picolyl	Methyl	84	147–148
2-Quinolyl	2-Thienyl	85	213
2-Quinolyl	Methyl	85	170
2-Quinolyl	Isopropyl	87	157–158
2-Quinolyl	Phenyl	85	167–168 [3]
2-Quinolyl	3-Pyridyl	65	208–209

Compounds that are structurally related with *(3)* and in which the azomethine grouping is not part of a pyridine ring, *e.g.* monoanils of cyclic β-diketones, also react with tosyl azide in ethanol/C_2H_5OK at about 25 °C to give 1,2,3-triazole derivatives in yields of 70–90 %.

Received: February 22nd, 1965 [Z 924/748 IE]
German version: Angew. Chem. 77, 428 (1965)

[1] Reactions of Compounds Containing Active Methylene Groups with Azides, Part IX. – Part VIII: *M. Regitz* and *D. Stadler,* Liebigs Ann. Chem. *1965*, in the press.

[2] *M. Regitz,* Tetrahedron Letters *1964*, 1403; Chem. Ber. *98*, 1210 (1965).

[3] Cf. *E. Enders,* Ph. D. Thesis, Universität Saarbrücken, 1962.

Ammoniates of Uranium Trichloride and Tetrachloride

By Priv.-Doz. Dr. H. J. Berthold and Dr. H. Knecht

Institut für Anorganische Chemie und Kernchemie der Universität Mainz (Germany)

UCl_3 and UCl_4 react with gaseous ammonia at room temperature and with liquid ammonia at ≤ -34 °C to form ammoniates with the compositions $UCl_3 \cdot (6.8–6.9)NH_3$ and $UCl_4 \cdot (7.3–7.5)NH_3$ at 22–23 °C and 760–790 mm. If the reaction is conducted in liquid ammonia under pressure at room temperature and the excess ammonia is subsequently allowed to evaporate, UCl_3 gives the same ammoniate, but UCl_4 then binds 9–10 moles of NH_3.

In liquid ammonia, in addition to ammoniate formation, a small amount of ammonolysis also occurs, detectable from the reduction in chlorine content to 2.8 with UCl_3 and to 3.5 with UCl_4.

Isothermal decomposition of the ammoniates in a stream of nitrogen (70 ml/min) at ca. 20 °C leads to $UCl_3 \cdot 3NH_3$ and $UCl_4 \cdot 4NH_3$, which are both stable up to approximately 45 °C. Decomposition at higher temperatures leads without detectable intermediates to $UCl_3 \cdot NH_3$ and $UCl_4 \cdot NH_3$. These two ammoniates are stable up to about 300 °C. They decompose above 350 °C with partial ammonolysis.

With the exception of $UCl_4 \cdot NH_3$, all the ammoniates are crystalline and have characteristic X-ray diagrams. Ammoniates claimed to be stable above room temperature, namely $UCl_4 \cdot 12NH_3$, $UCl_4 \cdot 8NH_3$ [2], $UCl_4 \cdot 5NH_3$ [3], $UCl_4 \cdot 3NH_3$ [1,3], and $UCl_4 \cdot 2NH_3$ [4], could not be detected.

The higher ammoniates of uranium(III) and uranium(IV) chlorides absorb gaseous carbon dioxide with great rapidity; the CO_2 reacts with part of the bonded ammonia to form ammonium carbamate, which does not occur as a separate phase but is built into the lattices of the higher ammoniates without significant alterations of their spacious structures.

Comparison of these ammoniate-carbamates with the ammoniates obtained on pyrolysis reveals that only that portion of the ammonia reacts with CO_2 which is readily released at room temperature, and which is apparently only loosely bound inside the large hollows of the ammoniate lattices.

Consequently, by analogy to compounds containing water of crystallization, it seems as though a distinction must be made with ammoniates between "structural ammonia" and "coordinated ammonia". Since the coordinatively bonded ammonia ought not to react with carbon dioxide, the reaction of ammoniates with carbon dioxide should provide a means for differentiating between structural and coordinated ammonia.

Received: February 26th, 1965 [Z 937/763 IE]
German version: Angew. Chem. 77, 453 (1965)

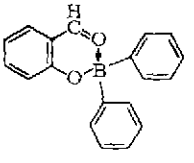
[1] *W. Peters*, Ber. dtsch. chem. Ges. *42*, 4826 (1909); Z. anorg. Chem. *77*, 159 (1912).
[2] *G. Beck*, Z. anorg. allg. Chem. *206*, 416 (1932).
[3] *P. Spacu*, Z. anorg. allg. Chem. *230*, 181 (1936).
[4] *J. Kalnine* and *G. Gibson*, J. inorg. nucl. Chem. *7*, 55 (1958).

Benzoboradioxacyclohexadienes and Benzoazaboraoxacyclohexadienes

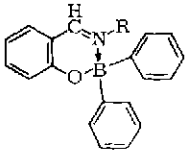
By Prof. Dr. F. Umland and Dipl.-Chem. C. Schleyerbach

Anorganisch-Chemisches Institut der Universität Münster
and
Institut für Anorganische Chemie der Technischen Hochschule Hannover (Germany)

The reaction of equimolar amounts of salicylaldehyde and diphenylborinic acid or its anhydride (tetraphenyldiboron oxide) leads to 3,3-diphenyl-3-bora-2,4-dioxabenzocyclohexa-1,5-diene *(1)*, which has the same basic skeleton as a complex prepared from acetophenone and boron trifluoride by *Kästner* [1].



(1)



(2)

When the reaction is conducted in the presence of amines or, preferably, when azomethine derivatives of salicylaldehyde are condensed with diphenylborinic acid, derivatives of the hitherto unknown ring system 3,3-diphenyl-2-aza-3-bora-4-oxabenzocyclohexa-1,5-diene *(2)* are formed.

	R	M.p. [°C]	UV [mμ] [a]	ε × 10⁻³	Color of solid
(1)	—	151	M 236	13.0	bright yellow
			M 325	2.7	
			S 370	1.0	
(2a)	H—	193	M 280	8.0	pale yellow
			M 375	2.5	
(2b)	HO—	157	M 259	10.0	white
			M 305	3.0	
(2c)	C_3H_7—	103	M 239	11.0	pale yellow
			M 360	2.0	
			S 402	1.0	
(2d)	C_4H_9—	104	M 239	12.0	yellow
			M 360	2.5	
			S 402	1.0	
(2e)	HOC_2H_4—	145	M 280	10.0	pale yellow
			M 370	3.5	
(2f)	C_6H_5—	154	M 269	10.0	ochre yellow
			M 337	8.0	
(2g)	o-HOC_6H_4—	159	M 355	9.5	lemon yellow
			M 418	9.5	

[a] In methanol; M = maximum, S = shoulder.

Equimolar amounts of the azomethines and tetraphenyldiboron oxide were dissolved separately in ethanol or ethanol/benzene (1:1 v/v), and the solutions were mixed and boiled briefly. The products crystallize out on cooling, generally in yields of about 70%, and can be recrystallized from ethanol/benzene (about 1:1). They melt without decomposition and are stable in air, in the solid state and in solution, even in neutral or weakly acidic aqueous solutions. They are decomposed by aqueous alkalies.

If the azomethines of salicylaldehyde obtained with aniline or *o*-aminophenol are treated with Flavognost® (β-aminoethyl diphenylborinate) instead of with tetraphenyldiboron oxide, then *(2e)* is formed instead of *(2f)* or *(2g)*.

Received: March 1st, 1965 [Z 926/752 IE]
German version: Angew. Chem. 77, 426 (1965)

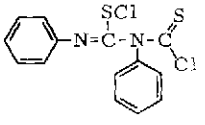
[1] *D. Kästner*, Angew. Chem. *54*, 273, 296 (1941).

Synthesis of N-Phenyl-S-chloroisothiocarbamoyl Chlorides by Chlorination of Isothiocyanates [*]

By Dr. G. Ottmann and H. Hooks, Jr.

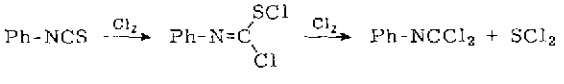
Olin Mathieson Chemical Corporation, Chemicals Division, New Haven, Conn. (U. S. A.)

During the preparation of phenyl isocyanide dichloride from the corresponding isothiocyanate and chlorine, *Helmers* [1] isolated an unstable adduct, to which *Dyson* and *Harrington*[2] assigned the structure *(1)*.



(1)

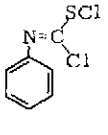
We have now found that the first step of the chlorination of phenyl isothiocyanates consists of the addition of one mole of chlorine onto one isothiocyanato group to form *N*-phenyl-*S*-chloroisothiocarbamoyl chlorides *(2)*, a hitherto unknown class of compounds. The compound *(1)* is merely a by-product formed in a side reaction.



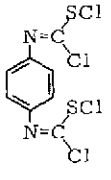
(2)

N-Phenyl-*S*-chloroisothiocarbamoyl chlorides *(2)* can be prepared in a pure state and in high yields by treating aromatic isothiocyanates in an indifferent solvent at 0–10 °C with one mole of chlorine per –NCS group. The solid representatives can be purified by recrystallization from pentane or hexane.

We have prepared the following derivatives: *N*-phenyl-*S*-chloroisothiocarbamoyl chloride *(3)* [yellow oil, $n_D^{24} = 1.6291$; 91.5% yield], *N,N'*-phenylene-1,4-bis-(*S*-chloroisothiocarbamoyl chloride) *(4)* [yellow crystals, m.p. 82–83 °C; 97.8%], and *N,N'*-toluylene-2,4-bis-(*S*-chloroisothiocarbamoyl chloride) *(5)* [yellow crystals, m.p. 75–75.5 °C; 65%].



(3)



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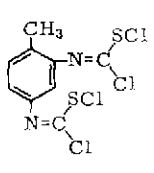


(5)

Their structures are supported by combustion analysis, molecular weight determination, infrared and NMR spectroscopy, and by their chemical reactions which will be the subject of forthcoming publications. The *N*-phenyl-*S*-chloroisothio-

carbamoyl chlorides are sensitive to moisture and heat but remain unchanged for a long time when stored in a pure state below 0 °C in a completely dry nitrogen atmosphere.

Received: March 1st, 1965 [Z 927/749 IE]
German version: Angew. Chem. 77, 427 (1965)

[*] Chlorination of Isothiocyanates. First communication.

[1] *O. Helmers*, Chem. Ber. *20*, 786 (1887).

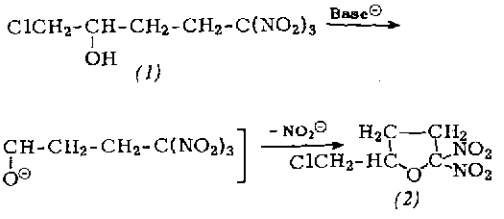
[2] *G. M. Dyson* and *T. Harrington*, J. chem. Soc. (London) *1940*, 191; *1942*, 150.

Synthesis of 5-Chloromethyl-2,2-dinitrotetrahydrofuran

By Dr. E. Steininger

Battelle Institut, Frankfurt/Main (Germany)

The reaction of 1-chloro-5,5,5-trinitropentan-2-ol *(1)* with triethylamine, sodium hydrogen carbonate, potassium hydroxide, or preferably sodium t-butoxide or sodium hydroxide in ether at 0 °C does not lead as expected to 1,2-epoxy-5,5,5-trinitropentane, but instead to 5-chloromethyl-2,2-dinitrotetrahydrofuran *(2)*. The yield is up to 86 %.



The starting material *(1)* is obtained in 90 % yield by reduction of 1-chloro-5,5,5-trinitropentan-2-one *(3)* with sodium borohydride in methanol, while *(3)* is produced in 85 % yield by addition of nitroform $CH(NO_2)_3$ onto chloromethyl vinyl ketone.

The structure of *(2)*, b.p. 104–105 °C/0.01 mm, $n_D^{20} = 1.4893$, was proved by elemental analysis and infrared and NMR spectroscopy (proton signals in ratios of 1:2:2:2 at 5.1, 3.9, 2.4, and 3.2 ppm).

This reaction appears to be the first example of the cyclization of a nitro compound by elimination of a nitrite ion.

Received: March 4th, 1965 [Z 936/762 IE]
German version: Angew. Chem. 77, 427 (1965)

Preparation of Azo Compounds from N,N'-Dialkylsulfamides

By Dr. R. Ohme and Prof. Dr. Ernst Schmitz

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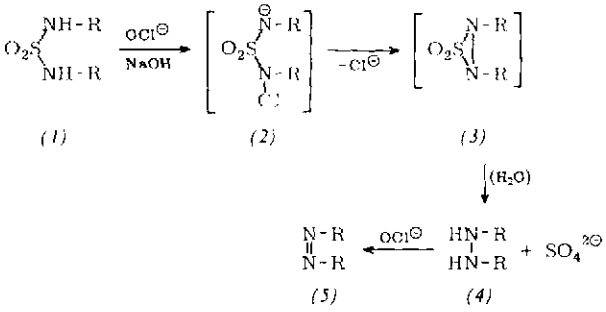
We have found that *N,N'*-dialkylsulfamides *(1)* react in 1 N alkaline solution with sodium hypochlorite in a molar ratio of 1:2 at 20–60 °C to form aliphatic azo compounds *(5)*, *e.g.* azopropane *(5a)*, azo-n-butane *(5b)*, and azocyclohexane *(5c)* in yields of 100, 54, and 80 % respectively.

Cross experiments indicated that the reaction proceeds intramolecularly *via* the *N*-chloro anion *(2)* and the cyclic compound *(3)*: if a mixture of *N,N'*-dipropylsulfamide [1] and *N,N'*-di-n-butylsulfamide is subjected to the reaction, only azo-n-propane *(5a)* and azo-n-butane *(5b)* are obtained, none of the mixed azo compound $C_3H_7-N=N-C_4H_9$ being



formed. The isolation of di-n-propylhydrazine (m.p. of dihydrochloride 172 °C) in 50 % yield when insufficient hypochlorite was taken forms evidence for the intermediate occurrence of *N,N'*-dialkylhydrazines.

The azo compounds *(5a)* and *(5b)* were shown by gas chromatography to be identical with products obtained from *N,N'*-dialkylhydrazines by oxidation with hypochlorite; *(5c)*, m.p. 33 °C, was identified by comparing its infrared spectrum with that of a sample prepared according to [2]. The azo compounds *(5a)–(5c)* were rearranged by acids to alkylhydrazones [3], which were then hydrolysed to the parent carbonyl compounds and alkylhydrazines. Identification of the alkylhydrazines was accomplished by treatment with potassium cyanate [4] and precipitation of the 2-alkylsemicarbazides with *p*-nitrobenzaldehyde.

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German version: Angew. Chem. 77, 429 (1965)

[1] *R. Sowada*, J. prakt. Chem. *20*, 318 (1963).

[2] *H. H. Harkins* and *H. L. Lochte*, J. Amer. chem. Soc. *46*, 450 (1924).

[3] *E. Fischer*, Ber. dtsch. chem. Ges. *29*, 795 (1896).

[4] *G. Gever* and *H. Hayes*, J. org. Chemistry *14*, 813 (1949).

High-Temperature Ammonolysis of Uranium Trichloride and Tetrachloride

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UCl_3 and UCl_4 undergo ammonolysis above 350 °C. Between 450 and 500 °C, UCl_3 gives rise to NH_4Cl and a mixture of amorphous amido-compounds [UNH_2Cl_2 plus $U(NH_2)_2Cl$]. At higher temperatures the latter are transformed *via* crystalline uranium imidochloride, U(NH)Cl, into uranium nitride with the composition $UN_{1.73-1.75}$. The uranium mononitride, UN, expected as a final product of the ammonolysis, is not formed. 1 g of UCl_3 is completely ammonolized after 15 min. at 800 °C.

UCl_4 reacts with ammonia at about 450 °C to form amorphous uranium(IV) amidotrichloride UNH_2Cl_3. At about 475 °C, this compound is reduced to crystalline UCl_3, which was detected analytically and by its X-ray diffraction pattern. The ammonolysis then continues as for UCl_3. Attention was first called to a reduction of UCl_4 to UCl_3 by NH_3 at higher temperatures by *Rammelsberg* [1].

U(NH)Cl obtained by various routes between 500 and 550 °C crystallizes in a PbFCl layer lattice (space group D_{4h}^7-P4/nmm) with two molecules in the tetragonal unit cell. The lattice constants are $a = 3.972 \pm 0.005$ Å and $c = 6.810 \pm 0.010$ Å. Intensity calculations gave the parameter $u = 0.168 \pm 0.002$ for uranium and the parameter $v = 0.63 \pm 0.01$ for chlorine. The distance between the $NH^{2\ominus}$ anions (2.809 Å) is remarkably short and suggests the occurrence of hydrogen bridges between the $NH^{2\ominus}$ ion layers. Other nearest neighbors are $U^{3\oplus}$–4 $NH^{2\ominus}$ = 2.292 Å, $U^{3\oplus}$–4 $Cl^{\ominus}$ = 3.127 Å, $U^{3\oplus}$–$Cl^{\ominus}$ = 3.146 Å. The chlorine-chlorine distance between neighboring layers is 3.32 Å.

Powder photographs of the chlorine-free nitrides $UN_{1.73\ 1.75}$ reveal only lines due to a face-centered cubic lattice such as occurs in UN_2 (CaF_2-type structure) [2]. The lattice constants correspond to those of nitrides of the same composition obtained by the reaction either of finely divided uranium (prepared from UH_3) with nitrogen at 350 °C or of UH_3 with ammonia at 250 °C. Measurements with a diffractometer gave a lattice constant of a = 5.287 ± 0.002 Å. The weak lines reported for nitrides of composition up to $UN_{1.75}$ [2], which require a body-centered cubic unit cell with doubled lattice constant (phase of $UN_{1.5} = U_2N_3$ crystallizing with the α-Mn_2O_3-type structure), were not observed.

Received: March 10th, 1965 [Z 932/758 IE]
German version: Angew. Chem. 77, 428 (1965)

[1] *C. Rammelsberg*, Pogg. Ann. Phys. Chem. *55*, 318 (1842); *56*, 125 (1842).

[2] *R. E. Rundle, N. C. Baenziger, A. S. Wilson*, and *R. A. McDonald*, J. Amer. chem. Soc. *70*, 99 (1948).

Sensitivity of Pyrimidines and Purines towards Neutron Irradiation

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Pyrimidines are much more sensitive towards X-rays than purines, among which adenine exhibits the highest resistance [1]. On the other hand, when aqueous solutions of pyrimidines and purines are irradiated with thermal neutrons, the bases are decomposed to an extent directly proportional to their nitrogen content – here the purines are more labile, and adenine is most extensively destroyed.

Base [a]	Reduction [%] of the UV extinction of the bases at λ_{max} following irradiation with neutron doses of				Nitrogen content of the bases [%]
	0.18×10^{14} n	0.54×10^{14} n	1.62×10^{14} n	2.7×10^{14} n	
Thymine		9		45	22.2
Uracil	4	12	23	50	24.9
Azauracil	12		29		39.0
Cytosine		17			37.8
Guanine	13	57	52	93	46.3
Azaguanine	22		53		55.0
Adenine		75		97	51.8

Polynucleotide [b]	Amino acid	Inhibition [%] of the incorporation of the amino acid into a polypeptide after irradiation of the polynucleotide with a neutron dose of			
		1.8×10^{13} n	3.6×10^{13} n	7.2×10^{13} n	16.2×10^{13} n
Poly(uridylic acid)	Phenylalanine	18	(10) [c]	38	(12) [c]
Poly(cytidylic acid)	Proline	17	53 (12)		(17)
Poly(adenylic acid)	Lysine	42	75 (27)		(36)

[a] Concentration of base = 50 µg/ml in water at pH 5.6 in a quartz tube; neutron flux = 3.0×10^{11} n/cm²/sec.

[b] Concentration of polynucleotide during irradiation = 1 mg/ml, during protein synthesis = 80 µg of poly-U per ml, 350 µg of poly-C per ml, and 120 µg of poly-A per ml. The incorporation of the amino acids was determined according to [2].

[c] The figures in parentheses indicate the decrease [%] in the ultraviolet optical density of the polynucleotides at λ_{max} in water at pH 5.6.

Whereas the destructive action of X-rays is probably due to the formation of oxygen-containing free radicals, that of the neutrons is proabably due to the nuclear reaction $^{14}N(n,p)^{14}C$.

If the pyrimidines and purines are part of a nucleic acid, they are more resistant to neutrons. However, polynucleotides irradiated with neutrons possess less activity in cell-free protein synthesis [2] than untreated specimens; poly-A is much more labile in this respect than poly-U or poly-C.

Received: March 17th, 1965 [Z 933/759 IE]
German version: Angew. Chem. 77, 428 (1965)

[1] *A. Wacker*, Dtsch. med. Wschr. *86*, 735 (1961); *E. R. Lochmann, D. Weinblum*, and *A. Wacker*, Biophysik *1*, 396 (1964).

[2] *M. W. Nirenberg* and *J. H. Matthei*, Proc. nat. Acad. Sci. U.S.A. *47*, 1588 (1961).

Synthesis of 2,5-Dibromo-1,2,4-triazole by Bromination of 1,2,4-Triazole [1]

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With the exception of the hydroxymethylation with formalin [2], no electrophilic C-substitution of 1,2,4-triazole is known [3]. Moreover, direct halogenation of 1,2,4-triazoles was hitherto considered to be impossible [4].

We have found that, like 1,2,3-triazole [5], 1,2,4-triazole can be brominated even in aqueous solution at room temperature, only one equivalent of bromine being required to lead directly to the dibromo derivative. The yield obtained after treatment with two equivalents of bromine is 24–29 %. The strong acidifying effect of the bromine atoms manifests itself in a pK_a value of 5.23 for 3,5-dibromo-1,2,4-triazole, compared with the value of 10.26 for 1,2,4-triazole.

1,2,4-Triazole (1.4 g or 0.02 mole) is dissolved in 10 ml of water, and 3.2 g (0.02 mole) of bromine is slowly added. At first crystals are formed, but then an oil is deposited from which crystals separate out again after 5–6 h. The solid is filtered off, and the filtrate is treated with further 0.02 mole of bromine. After 2 days, further crops of crystals of the same product can be isolated. The total yield is 1.1 g or 24 %. If the reaction mixture is heated on a water bath right from the start for 24 h or longer, the yield increases to 29 %. 2,5-Dibromo-1,2,4-triazole crystallizes from chloroform as colorless needles, m.p. 211–212 °C.

Received: March 18th, 1965 [Z 934/760 IE]
German version: Angew. Chem. 77, 429 (1965)

[1] Communication No. VIII on 1,2,4-triazoles. – Communication No. VII: *E. Tenor* and *C.-F. Kröger*, Chem. Ber. 97, 1373 (1964).

[2] *R. G. Jones* and *C. Ainsworth*, J. Amer. chem. Soc. *77*, 1538 (1955).

[3] Cf. *J. H. Boyer* in *R. C. Elderfield*: Heterocyclic Compounds. Wiley, New York 1961, Vol. 7, p. 446; *A. Albert*: Heterocyclic Chemistry. Athlone Press, London 1959, pp. 136, 165.

[4] Cf. *A. Étienne* and *V. Grignard*: Traité de Chemie Organique. Masson, Paris 1953, Vol. 21, p. 896.

[5] *R. Hüttel* and *A. Gebhardt*, Liebigs Ann. Chem. *558*, 43 (1947).

(1,3,4,6-Tetra-O-acetyl-β-D-glucos-2-yl)-carbodiimides

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(1,3,4,6-Tetra-*O*-acetyl-β-D-glucos-2-yl)thioureas [1] can be desulfurized with yellow HgO to give (1,3,4,6-tetra-*O*-acetyl-β-D-glucos-2-yl)carbodiimides, which are very stable compounds that exhibit no mutarotation. Five grams of the thiourea were shaken with 2.5 molar equivalents of HgO [DAB 6 quality, from E. Merck, Darmstadt (Germany)] in 50 ml of chloroform plus 25 ml of carbon disulfide at room temperature until the suspension turned black (often only after 20–30 h). The solution was filtered and the solvent evaporated; the residual syrup was crystallized from ether/petroleum ether [*(1)* from benzene/petroleum ether, *(5)* from ethanol/petroleum ether]. The structures of the carbodiimides were inferred from their infrared spectra and for *(2)* from hydrogenation to the formamidine stage [2].

(1,3,4,6-Tetra-*O*-acetyl-β-D-glucos-2-yl)carbodiimides, R–N=C=N–R'

	R'	M.p. [°C]	$[\alpha]_D^{20}$ [a]	Yield [%]
(1)	1,3,4,6-Tetra-*O*-acetyl-β-D-glucos-2-yl [3]	from 72	25.4°	89
(2)	*p*-Tolyl	62–64	25.7	62
(3)	Cyclohexyl	78–79	17.4	93
(4)	Benzyl	72–73	19.9	88
(5)	9-Fluorenyl	171–172 (decomp.)	9.0	83
(6)	Diphenylmethyl	95–97	11.5	87

[a] c = 1 in dimethylformamide.

Bis-(1,3,4,6-tetra-*O*-acetyl-β-D-glucos-2-yl)carbodiimide *(1)* [3] crystallizes only after standing for several weeks in a refrigerator. It is recovered unchanged after boiling for 12 h in benzene with a molar equivalent of 1,3,4,6-tetra-*O*-acetyl-β-D-glucosamine; no trisubstituted guanidine derivative is formed.

During the formation of *(2)*, *N*-(1,3,4,6-tetra-*O*-acetyl-β-D-glucos-2-yl)-*N'*-(*p*-tolyl)urea is produced as a by-product.

Desulfuration of *N*-cyclohexyl-*N*-hydroxy-*N'*-(1,3,4,6-tetra-*O*-acetyl-β-D-glucos-2-yl)-thiourea [1] afforded a 90 % yield of the carbodiimide *(3)* and elemental sulfur. Carbodiimide *N*-oxide formed as an intermediate appears to oxidize unreacted starting material [4]. *N*-(1,3,4,6-*O*-Tetraacetyl-β-D-glucos-2-yl)-*N''*-phenylthiosemicarbazide cannot be desulfurated with HgO to an aminocarbodiimide.

Received: March 18th, 1965 [Z 939/765 IE]
German version: Angew. Chem. *77*, 454 (1965)

[1] *J. C. Jochims* and *A. Seeliger*, Tetrahedron *1965*, in the press.

[2] *J. C. Jochims*, Chem. Ber. *97* (1965), in the press.

[3] Bis-(2,3,4,6-tetra-*O*-acetyl-β-D-glucos-1-yl)carbodiimide has recently been described: *A. Messmer, J. Pinter*, and *F. Szegö*, Angew. Chem. *76*, 227 (1964); Angew. Chem. internat. Edit. *3*, 228 (1964).

[4] *E. Schmidt* and *M. Seefelder*, Liebigs Ann. Chem. *571*, 83 (1950).

Proton Activity of the 1,3-Dithiolium System

By Doz. Dr. H. Prinzbach, Dipl.-Chem. H. Berger, and Prof. Dr. A. Lüttringhaus

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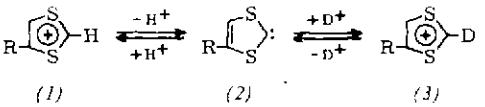
Like their thiazolium [2], oxazolium [3], and imidazolium [4] analogues, 1,3-dithiolium cations *(1)* [1] have a considerable C–H acidity in the 2-position. On determining the half-lives of hydrogen-deuterium exchange by measuring the NMR spectra of *(1)* in 60 % v/v CF_3COOD/D_2O at 34 ± 2 °C we have obtained the following results:

	Concn. [mole/l]	$t_{1/2}$ [min]	$\tau_{H(2)}$ (TMS = 10)
(1a)	1.85	166 ± 15	−1.12
(1b)	0.91	36 ± 5	−1.19
(1c)	0.91	34 ± 5	−1.31

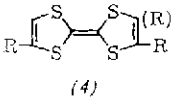
It can be noticed that the half-life decreases with the magnetic shielding of the 2-position. The rate of H/D exchange decreases with increasing activity of the CF_3COOD, parallel with the acid-base equilibrium below.



(1) *(2)* *(3)*

(a), R = CH_3 (ClO_4^-)
(b), R = C_6H_4–OCH_3(p) (HSO_4^-)
(c), R = C_6H_5 (HSO_4^-)

When the acids *(1a)*–*(1c)* are dissolved in acetonitrile and treated at 20 °C with an excess of *N*-ethyldiisopropylamine, the 1,4,5,8-tetrathiafulvalenes *(4a)*–*(4c)* [5] are immediately formed in 30–40 % yields as mixtures of the geometrical isomers.



(4)

(4a): yellow needles from ethanol, m.p. 96–100 °C; λ_{max} in tetrahydrofuran: 453 mμ (ε = 180), 298 (7500); NMR in CS_2: 4.28 τ [2 H, S]; 7.97 τ [6 H, S].

(4b): orange-yellow needles from benzene/ethanol, m.p. 254–256 °C; λ_{max} in tetrahydrofuran: 392 mμ (ε = 5100), 332 (12100); 270 (22700).

(4c): orange-yellow needles from benzene, m.p. 202–206 °C; λ_{max} in tetrahydrofuran: 403 mμ (ε = 2700); 329 (9000); 259 (12100); NMR in CS_2: 3.61 τ [2 H, S]; 2.71 τ [10 H, M]. The mass spectrum of the dimethyl derivative *(4a)* [Hitachi RMU-6A instrument, glass inlet system at 120 °C; 2000 V accelerating voltage, 80 eV electron voltage] contains the peak of the molecular ion (m/e = 232) and in comparable abundance the peak of the dithiacarbene *(2)* (m/e = 116) [6]. To our knowledge, this is the first time that such a carbene has been detected by mass spectrometry.

Received: March 19th, 1965 [Z. 948/775 IE]
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[1] For the preparation of *(1a)* and *(1b)*, see *A. Lüttringhaus, H. Berger*, and *H. Prinzbach*, Tetrahedron Letters *1965*, in the press; *(1c)* was made according to *D. Leaver, W. A. H. Robertson*, and *D. M. McKinnon*, J. chem. Soc. (London) *1962*, 5104.

[2] *R. Breslow*, J. Amer. chem. Soc. *80*, 3719 (1958); *H. W. Wanzlick* and *H. J. Kleiner*, Angew. Chem. *75*, 1204 (1963); Angew. Chem. internat. Edit. *3*, 65 (1964); *H. Quast* and *S. Hünig*, Angew. Chem. *76*, 989 (1964); Angew. Chem. internat. Edit. *3*, 800 (1964); *H. Balli*, Angew. Chem. *76*, 995 (1964); Angew. Chem. internat. Edit. *3*, 809 (1964).

[3] *P. Haake* and *W. B. Miller*, J. Amer. chem. Soc. *85*, 4044 (1963); *H. A. Staab, M. Th. Wu, A. Mannschreck*, and *G. Schwalbach*, Tetrahedron Letters *1964*, 845.

[4] *R. A. Olofson, W. R. Thompson*, and *J. S. Michelman*, J. Amer. chem. Soc. *86*, 1865 (1964).

[5] *W. R. H. Hurtley* and *S. Smiles*, J. chem. Soc. (London) *1926*, 2263.

[6] The mass spectrum was kindly measured by Dr. *J. Seibl*, Eidgenössische Technische Hochschule, Zürich (Switzerland).

Nitryl Nitrato Complexes of Indium and Thorium

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The synthesis of anhydrous nitrates using chlorine nitrate and chlorides or bromides [1] has been applied to indium halides. On treatment of $InBr_3$ with excess $ClNO_3$ at 20 °C, a quantitative yield of nitryl tetranitratoindate(III) *(1)* was obtained as a white, readily hydrolysable solid:

$$2\,InBr_3 + 10\,ClNO_3 \rightarrow 2\,NO_2[In(NO_3)_4] + 3\,Br_2 + 5\,Cl_2 + O_2$$
(1)

The structure of the complex is supported by the fact that equimolar amounts of *(1)* and $CsNO_3$ react together in anhydrous nitric acid at 20 °C to give a quantitative yield of white crystals of cesium tetranitratoindate(III) *(2)*, which is also very sensitive towards hydrolysis.

$$NO_2[In(NO_3)_4] + CsNO_3 \rightarrow Cs[In(NO_3)_4] + N_2O_5$$
(1) *(2)*

The infrared spectrum of *(2)* does not contain a band for the nitryl cation, which occurs at 2360 cm^{-1} in the spectrum of *(1)* [2], nor the bands characteristic of $CsNO_3$.

Reaction of *(1)* with excess N_2O_4 at 20 °C proceeds quantitatively to white, easily hydrolysable nitrosyl tetranitratoindate(III) *(3)*:

$$NO_2[In(NO_3)_4] + N_2O_4 \rightarrow NO[In(NO_3)_4] + N_2O_5$$
(1) *(3)*

Instead of the band of the nitryl cation at 2360 cm^{-1}, the infrared spectrum of *(3)* contains a band due to the nitrosyl cation [3] at 2270 cm^{-1}.

At 135 °C in a high vacuum, compound *(1)* gives a clear, volatile, colorless melt, with partial decomposition to white, easily hydrolysable crystals of indium oxide nitrate *(4)*:

$$NO_2[In(NO_3)_4] \rightarrow InONO_3 + 2\,N_2O_4 + O_2$$
(1) *(4)*

Compound *(3)* decomposes at 90 °C to white, readily hydrolysable indium nitrate *(5)*:

$$NO[In(NO_3)_4] \rightarrow In(NO_3)_3 + N_2O_4$$
(3) *(5)*

The infrared spectra of compounds *(1)–(3)* and *(5)* contain bands characteristic of covalent nitrates with $-ONO_2$ groupings [4].

By analogy to the preparation of the new indium compounds, the following thorium compounds were obtained:

$$ThCl_4 + 8\,ClNO_3 \xrightarrow[-O_2]{-6\,Cl_2} (NO_2)_2[Th(NO_3)_6]$$
(6), white, readily hydrolysable

$$(NO_2)_2[Th(NO_3)_6] + 2\,CsNO_3 \xrightarrow{-2\,N_2O_5} Cs_2[Th(NO_3)_6]$$
(6) *(7)*, white, readily hydrolysable

$$(NO_2)_2[Th(NO_3)_6] + 2\,N_2O_4 \xrightarrow{2\,N_2O_5} (NO)_2[Th(NO_3)_6]$$
(6) *(8)*, white, readily hydrolysable

$$2\,(NO_2)_2[Th(NO_3)_6] \xrightarrow[-6\,N_2O_4,\,-3\,O_2]{190\,^\circ C,\ high\ vacuum} 2\,ThO(NO_3)_2$$
(6) *(9)*, white, readily hydrolysable

$$(NO_2)_2[Th(NO_3)_6] \xrightarrow[-2\,N_2O_4]{90\,^\circ C,\ high\ vacuum} Th(NO_3)_4$$
(8) *(10)*, white, readily hydrolysable

The infrared spectra of *(6)–(8)* and *(10)* also contain the bands characteristic of covalently bonded nitrate groups.

Received: March 22nd, 1965 [Z 945/771 IE]
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[1] *M. Schmeisser* and *K. Brändle*, Angew. Chem. *69*, 781 (1957); cf. *G. Brauer*: Handbuch der präparativen anorganischen Chemie. Verlag Enke, Stuttgart 1960, Vol. 1, p. 298.

[2] *R. A. Marcus* and *J. M. Fresco*, J. chem. Physics *27*, 564 (1957).

[3] *D. W. A. Sharp* and *J. Thorley*, J. chem. Soc. (London) *1963*, 3557.

[4] *C. C. Addison* and *B. M. Gatehouse*, J. chem. Soc. (London) *1960*, 613.

Photochemical Isomerization of the Tricyclo[3,2,1,$0^{2,4}$]octene System – a Homovinylcyclopropane System

By Doz. Dr. H. Prinzbach, Dipl.-Chem. W. Eberbach, and Dipl.-Chem. G. von Veh

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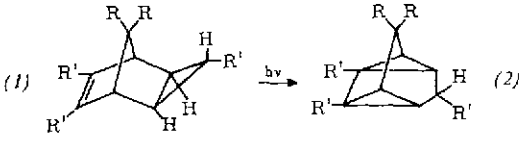
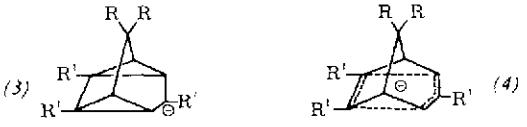
The *exo*-tricyclo[3,2,1,$0^{2,4}$]octene derivatives *(1a)*, b.p. 136–140 °C/10^{-3} mm, *(1b)*, m.p. 235 °C, *(1c)*, m.p. 80.5 °C, and *(1d)*, m.p. 240–241 °C, can be isomerized photochemically (Hanau Q-81 lamp fitted with a Uviol filter) to the tetracyclo[3,3,0,$0^{2,8}$,$0^{4,6}$]octane compounds *(2a)–(2d)* [1]. Whereas the photoisomerization of the esters *(1a)* [λ_{max} = 230.2 mμ (ε = 6770)] and *(1c)* [λ_{max} = 240.8 mμ (ε = 5170)] [3] produces compounds *(2a)* and *(2c)* in yields of 40 % at the most together with at least three other products, the valence isomerization of the acids *(1b)* [λ_{max} = 254.3 mμ (ε = 6700)] and *(1d)* [λ_{max} = 261.5 mμ (ε = 5330)] [4] proceeds uniformly and in at least 90 % yield [5].





(a), R = H, R' = CO_2CH_3 *(b)*, R = H, R' = CO_2H
(c), R/R = C_2H_4, R' = CO_2CH_3 *(d)*, R/R = C_2H_4, R' = CO_2H

(2a): m.p. 59 °C; IR: no C=C valence vibration bands; UV in ethanol: only terminal absorption (ε_{220} = 440); NMR in CCl_4: 6.25 τ; 6.34 τ [CH_3O; $(CH_3O)_2$]; 7.27 τ [1 H, S]; 7.5–8.5 τ [6 H, M]; molecular weight: 280 (mass spectrum [6]).

(2b): m.p. 228 °C.

(2c): m.p. 92.5 °C; IR: no C=C valence vibration bands; UV in ethanol: only terminal absorption (ε_{220} = 570); NMR in CCl_4: 6.25 τ; 6.31 τ [CH_3O; $(CH_3O)_2$]; 7.05 τ [1 H, S]; 7.98 τ [4 H, AB spectrum; $\delta^A - \delta^B$ = 46.5 cps; J_{AB} = 9.0 cps]; 9.33 τ [4 H, S]; molecular weight: 306 (mass spectrum [6]).

(2d): m.p. 244–245 °C.

The tetracycles *(2a)* and *(2c)* are very stable towards heat; no isomerization or fragmentation is observed up to 250 °C. The mass spectra [6] (CEC Zl-103 C instrument; temperature

of the inlet system 125 °C; temperature of the ion source 250 °C) of the pairs of valence isomers *(1)/(2)* have approximately equal abundances of the various fragments [7]. The carbanion *(3a)* formed from *(2a)* with sodium methoxide reacts with methanol to yield at least four products in proportions of about 68:18:13:1; their structures are at present being investigated.

The carbanion *(3a)* can be formulated as a non-classical bishomocyclopentadienyl anion *(4a)* [8]. Compounds of type *(2)* are therefore representatives of a system which permits the study of such non-classical anions.

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[1] Unsubstituted tetracyclo[3,3,0,$0^{2,8}$,$0^{4,6}$]octane *(2a)*, R′ = H, and its 7-methoxycarbonyl derivative cannot be obtained directly by irradiation of the corresponding *exo*-tricyclo[3,2,1,$0^{2,4}$]octene compounds [2]. The possibility of photosensitized energy transfer is currently being examined.

[2] *G. von Veh*, Ph. D. Thesis, Universität Freiburg/Breisgau 1965; *R. R. Sauers* and *P. E. Sonnet*, Chem. and Ind. *1963*, 786; Tetrahedron *20*, 1029 (1964).

[3] Irradiation of 1 g of ester in 300 ml of ether at 5 °C for 3 h.

[4] Irradiation of 1 g of acid in 300 ml of water at 5 °C for 6.5 h.

[5] It is remarkable that the photoisomerization in water of the *endo*-compounds corresponding to *(1b)* and *(1d)* is much less specific; in addition to the tetracycles epimeric with *(2)* in the 7-position, comparable yields of a second, as yet unidentified product are obtained.

[6] The mass spectra were kindly measured by Dr. *W. Benz*, Badische Anilin- & Soda-Fabrik, Ludwigshafen (Germany).

[7] *Z. Dolejšek*, *V. Hanuš*, and *H. Prinzbach*, Angew. Chem. *74*, 902 (1962); Angew. Chem. internat. Edit. *1*, 598 (1962).

[8] *S. Winstein*, *P. Bruck*, *P. Radlick*, and *R. Baker*, J. Amer. chem. Soc. *86*, 1867 (1964); *N. A. Le Bel*, *A. G. Phillips*, and *R. N. Liesemer*, J. Amer. chem. Soc. *86*, 1876 (1964).

Detection of Atomic Sulfur and Phenylphosphinidene (C_6H_5P:) in Solution

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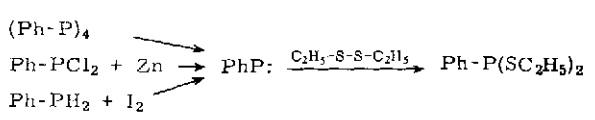
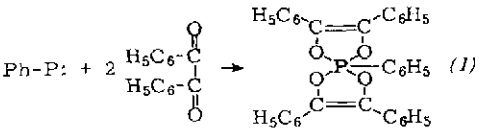
While searching for electronic states of elements of the second group of the periodic table corresponding to those of the carbenes and imenes (nitrenes, azenes), we have succeeded in detecting both atomic (electrophilic) sulfur and phenylphosphinidene (C_6H_5P:) in their solutions.

Atomic sulfur [1] is formed during the photochemical formation of isonitriles [2] from isothiocyanates with light of 254 mμ wavelength and was detected by its addition onto cyclohexene to form cyclohexene episulfide.

Phenylphosphinidene [3] is produced on heating tetraphenylcyclotetraphosphine $(C_6H_5-P)_4$ above 160 °C, or from phenyldichlorophosphine and zinc dust at 25 °C, or on oxidation of phenylphosphine with iodine in the presence of triethylamine. It was trapped by insertion into the $p_\pi-d_\pi$ double bond of disulfides, a reaction leading to phenylphosphonodithioites. This reaction is analogous to the formation of mercaptals on trapping of carbenes with disulfides [4].



Phenylphoshinidene made from phenyldichlorophosphine reacts with benzil to yield the 1,1′-spirobis(phosphadioxole) *(1)*.



Procedure: Nine grams of phenyldichlorophosphine are stirred for 2 h at 25 °C with 10 ml of tetrahydrofuran, 50 ml of diethyl disulfide, and 4 g of zinc dust. After extraction of the reaction mixture with water, distillation of the organic phase yields 7 g of diethyl phenylphosphonodithioite.

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[1] The formation of atomic sulfur in the gaseous state on irradiation of COS is described by *A. R. Knight*, *O. P. Strausz*, and *H. E. Gunning*, J. Amer. chem. Soc. *85*, 2349 (1963).

[2] *U. Schmidt* and *K. H. Kabbitzke*, Angew. Chem. *76*, 687 (1964); Angew. Chem. internat. Edit. *3*, 641 (1964).

[3] Unsuccessful attempts to detect phenylphosphinidene by addition onto olefins, dienes, and tolane are mentioned by *W. Henderson*, *M. Epstein*, and *F. S. Seichter*, J. Amer. chem. Soc. *85*, 2462 (1963) in reference [10].

[4] *A. Schönberg*, *O. Schutz*, and *J. Peter*, Ber. dtsch. chem. Ges. *62*, 440 (1929).

Synthesis and Polymerization of 1,5-Dioxaspiro[2,4]heptane

By Dr. E. Steininger

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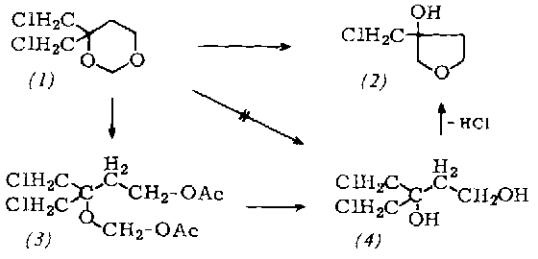
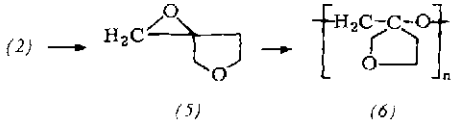
On heating 4,4-bis(chlormethyl)-*m*-dioxane *(1)* [1] with 5 % by weight of conc. H_2SO_4 in ethanol in a sealed tube at 120 °C for 5 hours, 3-chlormethyl-3-hydroxytetrahydrofuran *(2)*, b.p. 109,5 °C, $n_D^{20} = 1{,}4868$, is formed in 73 % yield. Another synthesis of *(2)* is the transformation of *(1)* with acetic anhydride [molar ratio 1:7 in the presence of 10 % by weight referred to *(1)* of conc. H_2SO_4, 2 hours at 100 °C, addition of sodium acetate, filtration and distillation] into 3,3-bis(chloromethyl)-1,5-diacetoxy-2-oxapentane *(3)*, b.p. 135 to 137 °C/0.9 mm, yield 83 %. On alcoholysis (refluxing for 12 hours in excess ethanol with addition of small amounts of H_2SO_4) this gives in 76 % yield 4-chloro-3-chloromethylbutane-1,3-diol *(4)*, b.p. 90 °C/10^{-3} mm (molecular distillation), which on heating to 160 °C is quantitatively converted into *(2)*. It was not possible to obtain *(4)* directly from *(1)*.



Treatment of *(2)* with NaOH or sodium t-butoxide (molar ratio 1:1.1) in ether at 20–30 °C gives 1,5-dioxaspiro[2,4]-heptane *(5)*, b.p. 46 % C/14 mm, $n_D^{20} = 1{,}4423$, with a yield of over 80 %. With catalysts conventionally used in epoxide polymerization [*e.g.* $BF_3{\cdot}(C_2H_5)_2O$], *(5)* polymerizes in CH_2Cl_2 to give a polyglycol *(6)*, which is a viscous oil or a low-melting resin, depending on its molecular weight.



The compound *(5)* can also be copolymerized with ethylene oxide or propylene oxide.

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[1] The compound *(1)* is obtained from 3-chloro-2-chloromethylpropene and formaldehyde (molar ratio 1:3) in 80% H_2SO_4 by a Prins reaction [2] in 68% yield; b.p. 120 °C/12 mm, $n_D^{20} = 1{,}4927$. The byproduct 3-chloro-4-chloromethyl-4-hydroxytetrahydropyran, m.p. 104.5 °C, is formed with a yield of 11%.

[2] *E. Arundale* and *C. A. Mikeska*, Chem. Rev. *51*, 505 (1952).

Gold Complexes of Cycloalkenes and Cycloalkadienes

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Gold complexes of olefins were recently described for the first time [1]. We have found that cyclopentene, cyclohexene, *cis*-cyclooctene, and *trans*-cyclodecene react with aqueous solutions of $HAuCl_4$ or $NaAuCl_4$ or with finely pulverized $HAuCl_4 \cdot 4\,H_2O$ to form gold(I) complexes. These are colorless crystalline substances. When aqueous solutions of the inorganic gold compounds are used, they precipitate only slowly because their formation is preceded by the reduction of Au(III) to Au(I). They decompose at relatively low temperatures, *e.g.* the cyclopentene complex at 55–60 °C, and the cyclooctene complex at 81–85 °C. The olefin evaporates off to a considerable extent from the cyclopentene and cyclohexene complexes even during drying.

Cyclooctenegold(I) chloride is obtained in 74% yield with aqueous solutions of $HAuCl_4$ or in practically quantitative yield from the dry tetrahydrate. It crystallizes in rectangular prisms ($C_8H_{14}AuCl$, molecular weight = 308 by cryoscopy in bromoform). Its infrared spectrum resembles that of $(C_8H_{14}PdCl_2)_2$ [2] and exhibits a characteristic shift of the double-bond absorption of the cyclooctene moiety from 1655 to 1512 cm^{-1}.

Cyclodecenegold(I) chloride ($C_{10}H_{18}AuCl$) separates in 78% yield in the form of needles, m.p. 75–80 °C (decomp.), on shaking an aqueous solution of $HAuCl_4$ with excess olefin. Its molecular weight measured in a vapor pressure osmometer in chloroform is 386.

1,5-Cyclooctadiene reacts immediately with $HAuCl_4$ or $NaAuCl_4$ in water to give a 68% yield of yellow quadratic platelets or cubes of a substance $(C_8H_{12}AuCl)_n$, m.p. 85–90 °C (decomp.), which does not resemble the compound described by *Chalk* [1] in color, melting point, or composition. The compound is so insoluble that its molecular weight could not be determined. On reduction with methanolic sodium hydroxide solution [3], it reaffords 1,5-cyclooctadiene. Here, too, the infrared spectrum contains the double-bond absorption at 1515 cm^{-1}.

Received: March 24th, 1965 [Z 947/773 IE]
German version: Angew. Chem. 77, 456 (1965)

[1] *A. J. Chalk*, J. Amer. chem. Soc. *86*, 4733 (1964).

[2] *R. Hüttel, H. Dietl*, and *H. Christ*, Chem. Ber. *97*, 2037 (1964).

[3] *H. Christ* and *R. Hüttel*, Angew. Chem. *75*, 921 (1963); Angew. Chem. internat. Edit. *2*, 626 (1963).

New N-Silylimidazolidinones

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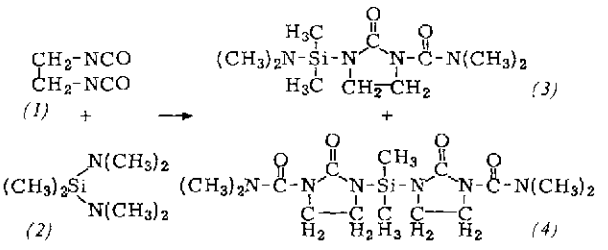
Cyclic ureas can be directly silylated [1]. Other *N*-silylimidazolidinones are accessible by ring extension [2]. We have found a simple new route to this little-known class of compounds: ethylene diisocyanate *(1)* reacts with dimethylbis(dimethylamino)silane *(2)* to give 1-dimethylcarbamoyl-3-[dimethyl(dimethylamino)silyl]imidazolidinone *(3)* and dimethylbis(1-dimethylcarbamoyl-2-oxoimidazolidin-3-yl)silane *(4)*.



After slow, dropwise addition of a solution of *(1)* in ether to an etheral solution of the stoichiometric amount of *(2)* at −10 °C and removal of the solvent, *(3)* can be distilled in about 70% yield from *(4)* (yield about 20%); *(3)* has m.p. 67–69 °C, b.p. 108–109 °C/0,1 mm, *(4)* has m.p. 172 to 175 °C. Both compounds crystallize well and are sensitive to solvolysis. They were characterized by analysis and infrared and proton magnetic resonance spectra.

On reversing the order of adding the reagents, *i.e.* on adding *(2)* to *(1)*, only little *(3)* can be isolated, and apart from *(4)* polymers are formed, which have not yet been finally characterized. The relative yields of *(3)*, *(4)*, and polymer depend strongly on the conditions of reaction.

With anhydrous ethanol, *(3)* and *(4)* react quantitatively at room temperature with formation of 1-dimethylcarbamoylimidazolidin-2-one, m.p. 126–128 °C.

The reaction of bis(trimethylsilyl)methylamine with *(1)* is similar to that of *(2)* with *(1)*.

Received: March 25th, 1965 [Z 963/789 IE]
German version: Angew. Chem. 77, 456 (1965)

[1] *P. L. De Benneville* and *M. J. Hurwitz*, U.S. Pat. 2876209 (1959).

[2] *O. J. Scherer* and *M. Schmidt*, Chem. Ber., in the press.

Reaction of Sodium Bistrimethylsilylamide with Carbon Monoxide and Metal Carbonyls [1]

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der Technischen Hochschule Graz (Austria)

Carbon monoxide reacts with sodium bistrimethylsilylamide *(1)* in petroleum ether or benzene at 80 °C and 100 atm to give sodium cyanide and bistrimethylsilyl ether in yields of over 80%. The same products are formed in 95% yield in the reaction of trimethylsilyl cyanide *(2)* and sodium trimethylsiloxide *(3)* in benzene at 80 °C. It is therefore possible that the reaction of *(1)* and CO proceeds *via (2)* and *(3)* as intermediates, *(2)* reacting as trimethylsilyl isocyanide.

$$CO + NaN[Si(CH_3)_3]_2 \rightarrow NaCN + O[Si(CH_3)_3]_2 \leftarrow (CH_3)_3SiCN + NaOSi(CH_3)_3$$
$$(1) \qquad\qquad (2) \qquad (3)$$

The reaction of carbon dioxide with *(1)* rapidly leads *via* several stages to bistrimethylsilylcarbodiimide $(CH_3)_3SiN{=}C{=}N{-}Si(CH_3)_3$, bistrimethylsilyl ether, and NaOCN [2]. Here, trimethylsilyl isocyanate occurs as an intermediate; this was shown by passing CO_2 over molten *(1)* at 200 °C and distilling off the trimethylsilyl isocyanate before it could react with *(1)* or *(3)*, which is also formed as an intermediate.

Both iron pentacarbonyl and nickel tetracarbonyl react vigorously with *(1)*, bistrimethylsilyl ether being produced

together with silicon-free carbonylcyano complexes of nickel and iron, which are decomposed by oxygen or moisture and whose structures have not yet been elucidated. The reaction is suspected to follow the overall equation:

$$M(CO) + NaN[Si(CH_3)_3]_2 \rightarrow [M(CN)]^{\oplus}Na^{\ominus} + O[Si(CH_3)_3]_2$$

M = $(OC)_4Fe$ or $(OC)_3Ni$

This was confirmed indirectly by trapping sodium trimethylsiloxide formed as an intermediate with trimethylchlorosilane (→ sodium chloride and bistrimethylsilyl ether) and by isolating tetracarbonyltrimethylsilylisonitriloiron *(4)*, which proved to be identical with the compound prepared by *Seyferth* [3].

$$(OC)_4Fe{=}C{=}N{-}Si(CH_3)_3 \qquad (4)$$

To our knowledge, the reactions of *(1)* with $Fe(CO)_5$ and $Ni(CO)_4$ are the first reactions of metal carbonyls in which substitution of the carbonyl oxygen occurs without cleavage of the metal-carbon bond. The isolation of *(4)* also implies that trimethylsilyl cyanide reacts in the form of trimethylsilyl isonitrile in the synthesis [3] of *(4)* from $Fe(CO)_5$ and $(CH_3)_3SiCN$ and that, although the latter compound is currently generally formulated as the nitrile, it is at least in equilibrium with the isonitrile form

$$(CH_3)_3Si{-}C{\equiv}N: \rightleftharpoons (CH_3)_3Si{-}\overset{\oplus}{N}{\equiv}\overset{\ominus}{C}:$$

Received: March 26th, 1965 [Z 952/777 IE]
German version: Angew. Chem. 77, 457 (1965)

[1] The Chemistry of Si–N Compounds, Part 49. – Part 48: *U. Wannagat, W. Veigl*, and *H. Bürger*, Mh. Chem. *96* (1965), in the press.

[2] *U. Wannagat, H. Kuckertz, C. Krüger*, and *J. Pump*, Z. anorg. allg. Chem. *333*, 54 (1964).

[3] *D. Seyferth* and *N. Kahlen*, J. Amer. chem. Soc. *82*, 1080 (1960).

Organocarboranes from Alkyldiboranes

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In the preparation of alkali borohydrides MBH_4 from alkyldiboranes and alkali metals [1], organocarboranes are obtained as by-products.

Sodium (2.3 g; 0.1 g-atom) is simmered with tetraethyldiborane (28 g; 0.2 mole) with stirring (1–2 hours). The $NaBH_4$ is filtered off, washed several times with hexane, and the combined filtrate and washings are fractionally distilled. After removal of the solvent and triethylborane, about 1.5 g of a yellow fraction, b.p. 37–49 °C/10^{-3} mm, is obtained, which consists of about 15 % organocarboranes and of organoboranes which are sensitive to oxidation.

The composition of the carboranes here is similar to those obtained in the hydroboration of acetylene [2, 5] and in the pyrolysis of alkyldiboranes [3]. Mainly *C,C*-dimethyl-*B*-ethyl derivatives of the $C_2B_5H_7$ carboranes [2] with molecular weights of 254, 226 and 198 are present. The retention volumes in gas chromatography agree with those of the carboranes prepared by the hydroboration of acetylene. Compounds with molecular weights [4] of 230 and 202, which are alkyl derivates of $C_2B_5H_{11}$ [2], are also found. A carborane with three B atoms (molecular weight [4] 174) with a gas-chromatographic retention volume agreeing with that of 1,5-dimethyl-2,3,4-triethyl-1,5-dicarbaclovopentaborane(5) [5], appears as well.

In the formation of the carboranes from alkyldiboranes, the removal of hydrogen from the borohydrides is thought to be the initial step – in analogy to the dehalogenation of dialkylhaloboranes [6]:

$$2\ (C_2H_5)_2BH + Na \rightarrow (C_2H_5)_2B\cdot + Na[BH_2(C_2H_5)_2]$$

The formation of the B_3C group *via* radical intermediates [6] and all further steps in the synthesis should take place as in the dehalogenation. *C*-Dimethyl-*B*-pentaethyldicarbaclovoheptaborane(7) (with a molecular weight of 254) then results from tetraethyldiborane and sodium according to the equation:

$$44\ (C_2H_5)_2BH + 12\ Na \rightarrow 12\ NaBH_4 + 27\ B(C_2H_5)_3 + C_{14}H_{31}B_5$$

The reaction of alkyldiboranes with lithium is significantly slower than that with sodium. The same carboranes are obtained, but in lower yields. Carboranates could in no case be detected. Whereas the metal borohydrides – as described earlier [1] – are obtained in the pure state, evidently no "colloidal boron" [1] is formed.

Received: March 29th, 1965 [Z 955/782 IE]
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[1] *R. Köster*, German Pat. 1062227 (March 28th, 1956), Studiengesellschaft Kohle m.b.H.; Chem. Abstr. *55*, 7776c (1961).

[2] *R. Köster* and *G. W. Rotermund*, Tetrahedron Letters *1965*, 777.

[3] *R. Köster, W. Larbig*, and *G. W. Rotermund*, Liebigs Ann. Chem. *682*, 21 (1965).

[4] The molecular weights were determined by mass spectrometry (*D. Henneberg*, Mülheim/Ruhr).

[5] *R. Köster* and *G. W. Rotermund*, Tetrahedron Letters *1964*, 1667.

[6] *R. Köster* and *G. Benedikt*, Angew. Chem. *76*, 650 (1964); Angew. Chem. internat. Edit. *3*, 515 (1964).

Azido Complexes of Manganese(II) and Palladium(II) [1]

By Priv.-Doz. Dr. W. Beck, Dipl.-Chem. K. Feldl, and Dr. E. Schuierer

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So far only few homogeneous azido compounds of transition elements have been isolated [2]. The reaction of silver azide with $[(C_2H_5)_4N]_2[MnBr_4]$ in acetone has now led to colorless tetraethylammonium tetra-azidomanganate(II) $[(C_2H_5)_4N]_2[Mn(N_3)_4]$. This compound is readily soluble in water and acetone and is not detonated by mechanical shock. In agreement with its tetrahedral structure, the compound shows paramagnetism corresponding to five unpaired electrons, and an asymmetric azide valence vibration ν_3 from the $[Mn(N_3)_4]^{2\ominus}$ anion occurs at 2062 cm^{-1} in the infrared spectrum (solution in acetone).

Tetraphenylarsonium triazidopalladate(II) $[(C_6H_5)_4As][Pd(N_3)_3]$ can be precipitated from aqueous solutions of $Pd(NO_3)_2$ and NaN_3 (in a molar ratio of 1:4) with tetraphenylarsonium chloride; with the divalent cation $[Fe(phen)_3]^{2\oplus}$, the red, insoluble tetraazidopalladate(II) $[Fe(phen)_3][Pd(N_3)_4]$ can be precipitated. These compounds are diamagnetic and do not explode, although they deflagrate in a flame. On the other hand, the brown insoluble $Pd(N_3)_2$ that is formed as the initial product on adding sodium azide to aqueous solutions of palladium nitrate does detonate upon mere touch [3]. $[(C_6H_5)_4As][Pd(N_3)_3]$ crystallizes in brown needles and dissolves readily in acetone or chloroform to give orange-red solutions. The salt-like character of the compound is demonstrated by its conductivity in acetone (129 Ω^{-1} cm^2/mole). Two ν_3 azide bands

are observed in the infrared spectrum at 2069 and 2025 cm^{-1} (solution in acetone); accordingly, the $[Pd(N_3)_3]^{\ominus}$ anion cannot have a trigonal planar structure [*].

Triphenylphosphine reacts with aqueous solutions of $Pd(NO_3)_2$ and NaN_3, which were already suspected to contain the ions $[Pd(N_3)_3]^{\ominus}$ and $[Pd(N_3)_4]^{2\ominus}$ [4], by substitution of the azido ligands and formation of the yellow diamagnetic compound $[(C_6H_5)_3P]_2Pd(N_3)_2$. The occurrence of only one azide band at 2033 cm^{-1} (solution in chloroform) suggests that this non-ionic complex has a *trans*-planar structure.

Received: March 29th, 1965 [Z 954/779 IE]
German version: Angew. Chem. 77, 458 (1965)

[1] Pseudohalogenometal Compounds, Part 9. – Part 8: *W. Beck*, and *K. Feldl*, Z. Naturforsch. *20b*, 272 (1965).

[2] *F. A. Cotton* and *M. Goodgame*, J. Amer. chem. Soc. *83*, *1777* (1961); *F. Kröhnke* and *B. Sander*, Z. anorg. allg. Chem. *334*, 66 (1964).

[3] Cf. also *R. G. Clem* and *E. H. Huffman*, J. inorg. nucl. Chem. *27*, *365* (1965).

[*] Note added in proof: Ionic weight measurements in nitrobenzene indicate a dimeric structure.

[4] *F. G. Sherif* and *K. F. Michail*, J. inorg. nucl. Chem. *25*, 999 (1963).

Preparation and Properties of Tris(trifluoromethanesulfenyl)amine

By Dr. Dr. A. Haas, Dr. M. E. Peach, and cand. chem. P. Schott

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By the reaction of stoichiometric quantities of CF_3SCl and ammonia in Carius tubes at −45 °C and 20 °C, CF_3SNH_2 and $(CF_3S)_2NH$, respectively, are obtained [1]. This method is not satisfactory for the preparation of large amounts.

We found that CF_3SNH_2 is formed in 80 % yield when CF_3SCl is bubbled into liquid ammonia at −80 °C. By the reaction of CF_3SSCF_3 with ammonia in a Carius tube at room temperature, NH_4SCN and NH_4F are formed as well as CF_3SNH_2:

$$CF_3SSCF_3 + 6\ NH_3 \rightarrow CF_3SNH_2 + NH_4SCN + 3\ NH_4F.$$

Stoichiometric quantities of CF_3SNH_2 and CF_3SCl, in the presence of trimethylamine as an HCl scavenger, react to form $(CF_3S)_2NH$.

Similarly it was possible to prepare tris(trifluoromethanesulfenyl)amine *(1)* for the first time from CF_3SCl and CF_3SNH_2 or $(CF_3S)_2NH$:

$$CF_3SNH_2 + 2CF_3SCl + 2(CH_3)_3N \rightarrow (CF_3S)_3N + 2(CH_3)_3N{\cdot}HCl \qquad (1)$$

The compound *(1)* is a yellow liquid, stable in air, soluble in benzene and nitrobenzene, and was identified by elementary analysis and molecular-weight determination. The vapor pressure obeys the equation

$$\log p = 7{,}55 - 1740/T$$

Extrapolation gives a b.p. of 99,6 °C/760 mm; this is in good agreement with the experimentally determined value of 99,0 °C/754 mm. The heat of evaporation was calculated to be 7960 cal/mole. The Trouton constant was found to be 21.36 $cal{\cdot}deg^{-1}{\cdot}mole^{-1}$.

The infrared spectrum in the NaCl and KBr regions showed the following strong absorptions: 1184 cm^{-1} (vs) [2], 1166 (vs), 1135 (sh), 1120 (vs), 844 (s), 757 (s), and 479 (m).

Received: April 7th, 1965 [Z 958/781 IE]
German version: Angew. Chem. 77, 458 (1965)

[1] *H. J. Emeléus* and *S. N. Nabi*, J. chem. Soc. (London) *1960*, 1103.

[2] vs = very strong, s = strong, m = medium, sh = shoulder.

CONFERENCE REPORTS

Symposium on Reaction Mechanisms

The Winter Assembly of the Swiss Chemical Society took place in Berne (Switzerland) on February 20th, 1965. The following papers were among those presented:

The Mechanism of Catalysed Reactions of Formaldehyde with Amines and Amides

B. Glutz and *H. Zollinger*, Zurich (Switzerland)

The reaction of formaldehyde with semicarbazide and with urea in aqueous solution is general acid and base catalysed, as are most reactions of ketones and aldehydes with compounds containing amino groups. Whereas the reaction with semicarbazide is of 1st order relative to the formaldehyde concentration and independent of the semicarbazide concentration, the rate of reaction of urea is directly proportional to the concentration of both reactants. It appears that in the reaction with semicarbazide the rate-limiting step is the dehydration of methyleneglycol $CH_2(OH)_2$, whereas in the urea reaction it is the conversion of free formaldehyde. From the dependence of the rate of the urea reaction upon the concentration of numerous acids and bases (carboxylic acids and their anions, phosphoric acid and phosphates, HCO_3^- and CO_3^{2-}, tertiary amines and conjugate acids, H_3O^+, H_2O and OH^-) the Brönsted parameters were determined (acid catalysis: $\alpha = 0.28$, base catalysis: $\beta = 0.37$). The possibility of differentiating between a two-stage mechanism with an initial termolecular or quasi-termolecular multi-centered step and a three-stage mechanism consisting of purely bimolecular stages was discussed. The non-linear dependence of the reaction rate at pH > 11 is kinetically consistent with the two-stage mechanism and the preceding methyleneglycol ⇌ methyleneglycolate equilibrium. Moreover an acidity constant is obtained for methyleneglycol (pK_a 13.1) which corresponds to the expected value. Several bases exhibit markedly weaker $[N(CH_2CH_2OH)_3]$ or stronger $[HCO_3^-, H_2PO_4^-]$ catalytic activities than expected from the Brönsted relationship. Possible causes are solvation effects or bifunctional catalysis. The selection of catalysts is of importance in the preparation of macromolecular compounds (plastics) and in cross-linking reactions of textile fibers (cotton and other cellulosic fibers).

Mechanism and Stereochemistry of Fragmentation Reactions

C. A. Grob, Basel (Switzerland)

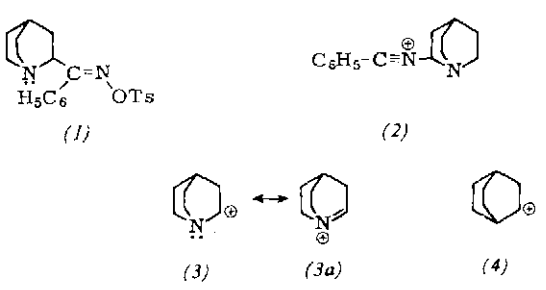
In a fragmentation reaction a molecule a–b–c–d–X breaks down into an electrofugal fragment $a–b^{\oplus}$, a nucleofugal fragment $X^{\ominus}$, and an unsaturated fragment c=d (the symbols a to d signify the atoms C, N, O, and in some cases S, in

variable sequence and with differing bond order). A large number of seemingly different reactions can thus be traced back to a single reaction type. Three basic mechanisms for fragmentations are possible: (a) the three fragments separate from one another simultaneously, (b) the nucleofugal fragment $X^{\ominus}$ separates first or (c) the electrofugal fragment $a\text{-}b^{\oplus}$ separates first from the molecule a–b–c–d–X. As yet only the first two mechanisms have been unequivocably established.

3-Aminoalkyl halides such as $(CH_3)_2N\text{-}CH_2\text{-}CH_2\text{-}C(CH_3)_2Cl$ undergo solvolysis reactions *via* carbonium ions $(CH_3)_2N\text{–}CH_2\text{–}CH_2\text{–}C(CH_3)_2^{\oplus}$, as can be seen from the substitution, elimination, ring-closure, and fragmentation products and from the fact that homomorphous alkyl halides [$(CH_3)_2CH$– in place of $(CH_3)_2N$–] exhibit practically the same reaction rate. In contrast, 3-aminoalkyl halides or 3-aminoaryl sulfonates $R_2N\text{–}C\gamma\text{–}C\beta\text{–}C\alpha\text{–}X$ (X = halogen or $ArSO_3$ respectively), in which the Cα–X bond and the axis of the free electron pair on the nitrogen are anti-coplanar to the Cβ–Cγ bond, react according to the first mechanism, *i.e.* with simultaneous separation of $R_2\overset{\oplus}{N}{=}C$ and $X^{\ominus}$. This mechanism is only observed with relatively rigid mono- and bicyclic 3-amino alcohols which meet the stereoelectronic requirement mentioned above. Examples are: 1-amino-4-bromoadamantane, 4-bromoquinuclidine, 3β-chlorotropane, 4α- and 5α-tosyloxydecahydroquinolines (tosyloxy groups equatorial). The solvolysis rate of these compounds in ethanol (80 % by vol.) is some 50 to 50000 times greater than that of the homomorphous compounds.

If, on account of configuration, the anti-coplanar orientation of the Cα–X bond or of the free electron pair relative to the Cβ–Cγ bond is prevented, fragmentation either does not occur or follows the non-accelerated two-step mechanism. This is the case for example with 3α-chlorotropane, decahydroquinolines with axial 4β- or 5β-tosyloxy groups, and with 7α- and 7β-tosyloxydecahydroquinolines.

Both the anti- and the syn-forms of α-aminoketoxime esters $R_2N\text{–}CH_2\text{–}C(R^1){=}N\text{–}X$ fragment completely by the synchronous mechanism to give carbimonium salts $R_2\overset{\oplus}{N}{=}CH_2X^{\ominus}$ and nitriles; the reaction is about 10^3 times as fast with the anti-form as with the syn-form. Moreover, the fragmentation proceeds 10^3 to 10^8 times as fast as the Beckmann rearrangement of corresponding ketoxime derivatives in which the amino group is replaced by a homomorphous alkyl group. If however the free electron pair is turned out of the stereoelectronically favored anti-coplanar orientation, as in (2-quinuclidyl)phenylketoxime tosylate *(1)*, a Beckmann rearrangement to the *N*-(2-quinuclidyl)phenylnitrilium ion *(2)* occurs, in place of the synchronous fragmentation. In aqueous media the ion *(2)* is 80 % converted into *N*-(2-quinuclidyl)benzamide, but it also gives the 2-quinuclidyl cation *(3)*, or secondary products, in 20 % yield by fragmentation. Since the homomorphous (2-bicyclo[2.2.2]octyl)-phenylketoxime tosylate [CH in place of N in *(1)*] reacts



(1) *(2)* *(3)* *(3a)* *(4)*

somewhat more slowly under these conditions to yield exclusively *N*-(2-bicyclo[2.2.2]octyl)benzamide, the 2-quinuclidyl cation must be slightly stabilized by mesomerism *(3)* ↔ *(3a)* which is impossible with the 2-bicyclo[2.2.2]octyl cation *(4)*. It follows, therefore, that the N–C(2) bond in the cation *(3)* ↔ *(3a)* assumes double-bond character and that Bredt's rule may not apply in the case of energy-rich intermediates.

Influence of the Nucleophile on Competing β-Elimination and S_N2 Substitution

R. F. Hudson and *G. Klopman*, Geneva (Switzerland)

The reaction between β-phenethyl bromide and sodium phenoxide in the presence of phenol in ethanolic solution gives approximately equal yields of ether *(1)* and olefin *(2)*.

$$ArO^{-} + Ar\text{-}CH_2\text{-}CH_2Br \rightarrow \begin{matrix} Ar\text{-}CH_2\text{-}CH_2\text{-}OAr\ (1) \\ + \\ Ar\text{-}CH{=}CH_2\ (2) + Br^{-} \end{matrix}$$

The elimination is shown to be general base catalysed (as required by a synchronous E_2 mechanism) [1]. When relatively high concentrations of phenol are used, the olefin produced by ethoxide ions present in the solution may be neglected, and the simultaneous S_N2 and E_2 reactions of the phenoxide ions may be followed. The yield of olefin is found to increase regularly with the pK_a of the *p*-substituted phenol used.

By measuring the total rate, constants (k) for the substitution and elimination reactions of several alkyl bromides were obtained and related to the pK_a of the corresponding phenol by the Brönsted equation ($\log k = \alpha pK_a + \text{const.}$) to give α for substitution (α_S) and for elimination (α_E) (cf. Table 1). We consider these coefficients to give a measure of the extent of bond formation in the transition state.

Table 1. α_S and α_E [*] for reactions of several alkyl bromides with *p*-substituted phenolate ions (*p*-R–C_6H_5OH, R–CH_3O, CH_3, H, Br, CH_3CO, and NO_2) in methanol.

	$(C_3H_7)_2CHBr$	$C_8H_{17}Br$	C_4H_9Br	$C_6H_5\text{–}CH_2CH_2Br$	$p\text{-}NO_2\text{–}C_6H_4\text{–}CH_2CH_2Br$
α_S	0.27	0.36	0.37	0.35	–
α_E	0.39	–	–	0.56	0.72

[*] Calculated from total rate constants for 0.1 M solutions.

Whereas α_S is not very sensitive to substitution at the β-carbon atom, α_E and hence the extent of bond formation at hydrogen in the β-elimination increases with conjugation in the incipient carbanion. This change in α_E is in the same direction as the primary isotope effect for the Hofmann elimination of the corresponding tetra-alkylammonium salts [2]. The present kinetic work and primary isotope effects thus lead to a consistent description of the transition states of β-elimination reactions.

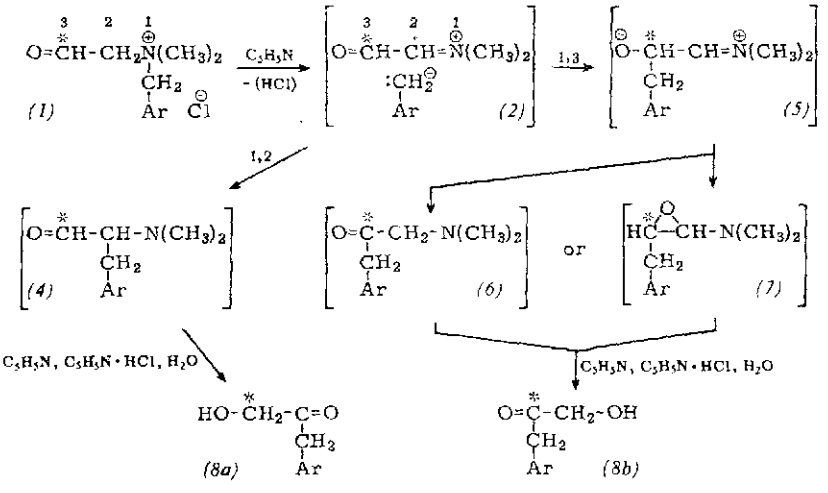
The Mechanism of Anionic Rearrangements. — A Stevens-1,3-Rearrangement

E. F. Jenny and *K. Schenker*, Basel (Switzerland)

Heating the ammonium salt *(1)*, labelled in the carbonyl group with ^{14}C, in moist pyridine affords the radioisomeric hydroxy ketones *(8a)* and *(8b)* in the ratio 57:43. The unusual course of this rearrangement is explained by the intermediate occurrence of the ion pair *(2)* [1]. The carbanion of *(2)* can add onto both electrophilic centers, C-2 and C-3, of the cation. In the first case the normal Stevens-1,2-rearrangement product, the amino aldehyde *(4)*, results; in the second case the amino ketone *(6)* or the oxide *(7)* is formed by a 1,3-shift *via* the zwitterion *(5)*. Compounds of type *(4)*, *(6)*, or *(7)* cannot be isolated, however, since they react further with pyridine and other amines [2]. Thus in the presence of aniline, *p*-nitrobenzyl anilinomethyl ketone[*(6)*,

[1] *R. F. Hudson* and *G. Klopman*, J. chem. Soc. (London) *1964*, 5.
[2] *H. Simon* and *G. Müllhofer*, Chem. Ber. *97*, 2202 (1964).

Ar = p-NO_2–C_6H_4 and –NH–C_6H_5 in place of –$N(CH_3)_2$] is obtained, which is relatively stable under the reaction conditions. In the absence of primary amines water can adopt their role: the hydroxy ketone *(8)* results in 40–50 % yield. In all these rearrangements the carbon skeleton remains intact. It can thus be concluded from the distribution of ^{14}C in compound *(8)* that the usual Stevens-1,2-rearrangement is accompanied by a hitherto unobserved Stevens-1,3-rearrangement. A subsequent isomerization of the end-

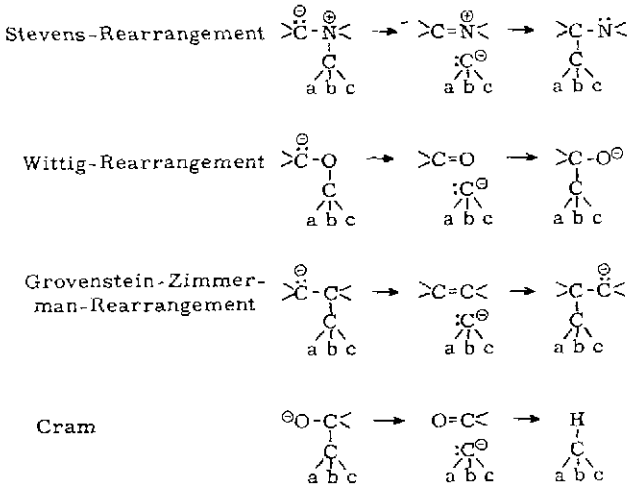


Ar = p-Nitrophenyl-

products *(8a)* and *(8b)* was experimentally excluded. An irreversible protonation of the carbanion in *(2)* yields p-nitrotoluene *(3)* as a by-product (12 %, estimated from the isotope dilution).

The ion-pair mechanism of the Stevens rearrangement clearly places it in the same class as other anionic 1,2-rearrangements. Like the Wittig rearrangement [3, 7], the Grovenstein-Zimmerman rearrangement [4, 5], and the thermal decomposition of alcoholates investigated by *Cram* [6], the Stevens rearrangement follows an S_Ei mechanism.

The nature of the intermediates satisfactorily explains the stereochemical course of these reactions. An S_Ni mechanism for anionic 1,2-migrations has until now only been found in the case of aryl shifts [4]. If a saturated carbon atom migrates, however, fragmentation and recombination (S_Ei) appear to be preferred.



[1] *E. F. Jenny* and *J. Druey*, Angew. Chem. *74*, 152 (1962); Angew. Chem. internat. Edit. *1*, 155 (1962).

[2] *K. L. Nelson, J. C. Robertson*, and *J. J. Duvall*, J. Amer. chem. Soc. *86*, 684 (1964); *C. L. Stevens, R. D. Elliot, B. L. Winch*, and *I. L. Klundt*, ibid. *84*, 2272 (1962).

[3] *U. Schoellkopf* and *W. Fabian*, Liebigs Ann. Chem. *642*, 1 (1961); *U. Schoellkopf* and *D. Walter*, ibid. *654*, 27 (1962); *P. T. Lansbury* and *V. A. Pattison*, J. Amer. chem. Soc. *84*, 4295 (1962); J. org. Chemistry *27*, 1933 (1962).

[4] *E. Grovenstein, Jr.* and *G. Wentworth*, J. Amer. chem. Soc. *85*, 3305 (1963); *E. Grovenstein, Jr.* and *L. C. Rogers*, ibid. *86*, 854 (1964).

[5] *H. E. Zimmerman* and *F. J. Smentowski*, J. Amer. chem. Soc. *79*, 5455 (1957); *H. E. Zimmerman* and *A. Zweig*, ibid. *83*, 1196 (1961).

Hydrogen- and Electron-Transfer in Reactions with Molecular Oxygen

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Vanadium(III) and vanadium(IV) ions oxidize extremely slowly in acidic aqueous solution. A measurable autoxidation is observed only with the appearance of hydrolyzed species such as $V(OH)^{2+}$ in the case of vanadium(III). It must therefore be assumed that a hydrogen transfer to the oxidizing oxygen occurs, giving VO^{2+} or VO_2^+ respectively in one step.

$$V(OH)^{2+} + O_2 \rightarrow VO^{2+} + HO_2$$
$$VO(OH)^{+} + O_2 \rightarrow VO_2^{+} + HO_2$$

A detailed study of the autoxidation of a VO^{2+} chelate with α-picolinic acid in various pH regions gave the following results: in weakly acidic solutions there exists the chelate $VO(Pi)_2$ (Pi = α-picolinate), whose reactivity towards molecular oxygen is extremely low. An upper limit can be given for the apparent bimolecular rate constant: $k \leqslant 0.14$ mole^{-1} l min^{-1} (25 °C). Hydrogen transfer is impossible. It can be seen that an oxidation by electron transfer must also be slow, if it is assumed (the VO-bond axis being defined as the z-axis) that a d-electron of the central ion is located in d_{xy}. A direct electron transfer to the oxygen molecule coordinated in the *trans*-position to the VO-group is then difficult for reasons of symmetry.

Likewise the hydrolyzed ion $[VO(Pi)_2OH]^-$ can react only slowly with oxygen ($k \leqslant 1.4$ mole^{-1} l min^{-1}), for here all six coordination positions are occupied. On progressive hydrolysis in weakly alkaline solution, the rate of autoxidation increases in proportion to the concentration of hydroxyl ions. The structure and composition of the products are not yet conclusively proved. The dissociation of at least one ligand Pi^- creates free coordination positions, so that both H- and electron-transfer to a coordinately bound oxygen molecule are possible in principle.

$$VO(Pi)_2OH^- + OH^- \rightarrow VO(Pi)(OH)_2^- + Pi^- \qquad (a)$$

[6] *D. J. Cram* et al., J. Amer. chem. Soc. *81*, 5785 (1959) and previous publications.

[7] Alkyl ethers may rearrange by a free-radical mechanism: *P. T. Landsbury* and *J. D. Sidler*, Tetrahedron Letters *1965*, 691.

For the reaction of the hydrolyzed ion formed in (a) with O_2, an apparent rate constant k = 840 mole^{-1} l min^{-1} (25 °C) was found. To decide whether the oxidation with oxygen occurs by H- or e$^-$-transfer, the reaction kinetics in D_2O were investigated. Under conditions where the hydrolysis (a) remains incomplete, the isotope factor k_{H_2O}/k_{D_2O} is 4.1. Since however the oxidation rate is independent of the oxygen concentration under these conditions, it must be assumed that the rate-determining step occurs before the actual reaction with oxygen, and that the measured isotope effect is hence not kinetic but must be due to a hydrolysis reaction of type (a).

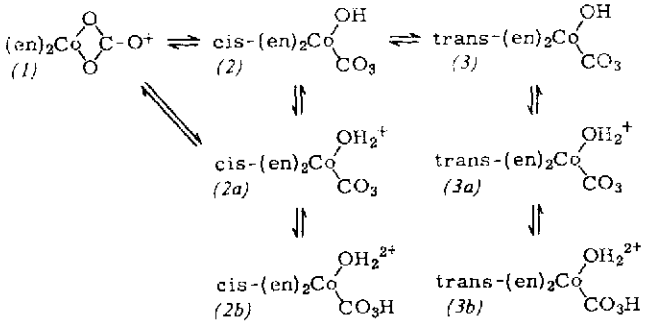
If, on the other hand, the hydrolysis (a) is complete, the rate of autoxidation is independent of pH but proportional to oxygen concentration. Under these conditions we determined the isotope factor k_{H_2O}/k_{D_2O} to be 0.92 (25 °C). The redox reaction between vanadium(IV) and molecular oxygen therefore very probably occurs by electron transfer.

Opening of the Four-Membered Chelate Ring of the Tetraamminecarbonatocobalt(III)Ion

H. Scheidegger and *G. Schwarzenbach*, Zurich (Switzerland)

According to *Werner*, tetramminecarbonatocobalt(III) complexes with the cation $N_4CoCO_3^+$ [1] (N signifies the N-atom of ammonia or amines such as ethylenediamine, "en") contain a four-membered chelate ring, as has recently been proved by X-ray analysis in the case of one of the solid salts [2]. On the basis of the expected (and now established) ring strain the view has often been expressed that the complex may be hydrated in solution and exist as $N_4Co(OH_2)OCO_2^+$. In particular the kinetics of isotope exchange with [^{14}C]-hydrogen carbonate seemed to confirm this [3].

It was now shown, however, that the ring is closed even in solution, for the complex *(1)* is aprotic between pH 3 and 11, while the aquocarbonato complex *(2a)* is transformed by OH^- into the hydroxo complex *(2)*, and by H^+ into the hydrogen carbonato complex *(2b)*. We employed a flow apparatus [4] in which the solutions of complex and acid can be mixed very rapidly and the pH-value measured within 10^{-2} sec at the most (a rapid decomposition occurs with CO_2 evolution). With NaOH *(1)* reacts slowly with ring opening; using the flow apparatus, the concentration of the complex *(2)* which is formed can be estimated acidimetrically. The rates and equilibrium constants given in the Table were obtained in this way. The *cis*-hydroxo complex *(2)* is slowly converted into the *trans*-isomer *(3)*. This conversion can be followed optically. The uncharged hydroxocarbonato complexes *(2)* and *(3)* can be separated from the other species by ion-exchange.



[1] *H. Scheidegger* and *G. Schwarzenbach*, Chimia (1965), in thepress.

[2] *G. A. Barclay* and *B. F. Hoskins*, J. chem. Soc. (London) *1962*, 586.

[3] *G. Lapidus* and *G. M. Harris*, J. Amer. chem. Soc. *85*, 1223 (1963).

[4] *G. Schwarzenbach*, Pure appl. Chem. *5*, 377 (1962).

Equilibrium constants K and half lives $\tau_{1/2}$ of tetraamminecarbonatocobalt(III) complex at 20 °C.

Reaction	$\tau_{1/2}$ →	$\tau_{1/2}$ ←	K
(1) ⇌ *(2)*	90 min [a]	180 min [a]	$10^{2.2}$
(1) ⇌ *(2a)*	—	1 min [b]	10^{-3}
(2) ⇌ *(3)*	9 days [c]	19 days [c]	2.1
(2) ⇌ *(2a)*	0	0	$10^{8.7}$
(2a) ⇌ *(2b)*	0	0	$10^{5.3}$
(3) ⇌ *(3a)*	0	0	$10^{7.2}$
(3a) ⇌ *(3b)*	0	0	$< 10^6$

[a] about pH 12; [b] about pH 8.7; [c] about pH 11.

Geometry of the Transition State of the Claisen Rearrangement

H. Schmid, *A. Habich*, and *G. Frater*, Zurich (Switzerland)

Many experiments led to the postulate that the thermal Claisen and Cope rearrangements proceed *via* quasi-cyclic transition states. The geometry of these transition states may be similar to either a chair or a boat form. *Doering* and *Roth* have recently shown [1] that the stereochemistry of the Cope rearrangement of non-cyclic systems requires a chair-like transition state. Despite many investigations little is yet known about the stereochemistry of the Claisen rearrangement [1]. New experiments were therefore devised to obtain more information.

On heating in *N,N*-diethylaniline at 186 °C, both *cis*- and *trans*-4-methylphenyl crotyl ether yield 2-(α-methylallyl)-4-methylphenol exclusively. If, on the other hand, *cis*- and *trans*-3,5-dimethylphenyl crotyl ether are heated, the products are mixtures of 2-(α-methylallyl)-3,5-dimethylphenol and 4-crotyl-3,5-dimethylphenol [2], in the ratios 9.8:1 from the *cis*-ether and 3.1:1 from the *trans*-ether. The 4-crotyl-3,5-dimethylphenol formed from both ethers consists of over 95 % *trans*-isomer. The thermal rearrangement of *cis*- and *trans*-2,6-dimethylphenyl crotyl ethers affords mixtures of the stereoisomeric 4-crotyl-2,6-dimethylphenols, that from the *cis*-ether having a *trans*/*cis*-ratio of 2.2, that from the *trans*-ether a ratio of 9.6. 2,6-Dimethyl crotyl ether recovered from an experiment in which 90 % of the *cis*-ether had reacted contained only 7–8 % *trans*-ether. From these experiments it can be concluded that the rearrangements of allyl- and crotyl phenyl ethers to the *ortho*-phenols are essentially stereospecific and proceed *via* chair- or boat-like transition states. The subsequent *ortho* → *para* rearrangement is not necessarily stereospecific. Very probably all the compounds investigated have a chair-type transition state in the ether ⇌ *ortho*-phenol rearrangement, which also applies to the *ortho* → *para* rearrangement in the case of the *trans*-compounds.

[VB 918/223 IE]

German version: Angew. Chem. *77*, 459 (1965)

[1] *W. v. E. Doering* and *W. R. Roth*, Angew. Chem. *75*, 27 (1963); Angew. Chem. internat. Edit. *2*, 115 (1963).

[2] *H. Schmid*, Österr. Chem.-Ztg. *65*, 109 (1964).

Recent Developments in the Chemistry of Phosphorus

Marianne Baudler, Köln (Germany)

An apparatus for preparing higher phosphorus hydrides (phosphanes) has been developed in which, by controlled hydrolysis of calcium phosphide, 150 ml of crude liquid phosphanes can be obtained in a few days, from which solid white products seperate at −78 °C. After distilling off the P_2H_4, a pale yellow, viscous residue, decomposing at room temperature, remains which consists of a mixture of higher phosphanes: by gas chromatography five compounds, in

addition to P_2H_4, can be detected which belong to the homologous series of open-chain phosphanes P_nH_{n+2} and cyclic phosphanes P_nH_n.

For the analysis of mixtures of mono-, di-, and triphosphoric acids having phosphorus in different oxidation states, thin-layer chromatography on cellulose powder is preferable to paper chromatography. With a weakly acidic and an ammoniacal solvent a two-dimentional separation of the acids into three "branches" [*] according to the number of phosphorus atoms can be achieved. In the system containing ammonia the following relationships between R_f-values and structures of the acids are found:

1. The R_f-value decreases with increasing number of phosphorus atoms.

2. The R_f-value decreases with increasing oxidation state.

3. With acids of equal composition [*e.g.* acids of type P(II)–P(IV) and P(III)–O–P(III)] the R_f-value is higher for acids containing P–O–P bonds than for isomeric acids containing P–P bonds. The R_f-value also increases on passing from a P–P acid to a P–O–P acid containing an additional oxygen atom [*e.g.* P(II)–P(IV) → P(III)-O-P(V), or P(IV)-P(IV) → P(V)-O-P(V)].

The ultraviolet absorbtion of the aqueous solutions of these acids occurs at very short wavelengths. Only the long-wavelength ends of the bands are seen at about 450 mμ. The extinction coefficients of the acids with a P–P chain are always greater than those of the isomeric acids with a P–O–P skeleton. They increase markedly with the number of P–H bonds.

[GDCh-Ortsverband Frankfurt/Main (Germany), December 17th, 1964] [VB 900/207 IE]

German version: Angew. Chem. 77, 433 (1965)

The Hydrolysis of Terpenyl Phosphates, Model Reactions of Terpene Biosynthesis

W. Rittersdorf, Göttingen (Germany)

In order to clarify the part played by geranyl phosphate in the biosynthesis of squalene [1] and to obtain a model for the biosynthesis of monoterpenes, the hydrolysis of geranyl phosphate and similar phosphates was studied.

The ortho- and pyro-phosphate monoesters of geraniol *(1)*, nerol *(2)*, linalool *(3)*, and α-terpineol *(4)* (prepared according to [2]) were hydrolysed with 1 N H_2SO_4 at room temperature. The terpenes formed were analysed by capillary gas chromatography on polyglycol columns (see Table 1). The mixtures formed from terpenyl phosphate and pyrophosphate were very similar, qualitatively and quantitatively. This indicates an S_N1 mechanism for the hydrolysis. Bicyclic terpenes were not detected.

Table 1. Composition of the mixtures formed by hydrolysis of the phosphate esters of some terpene alcohols.

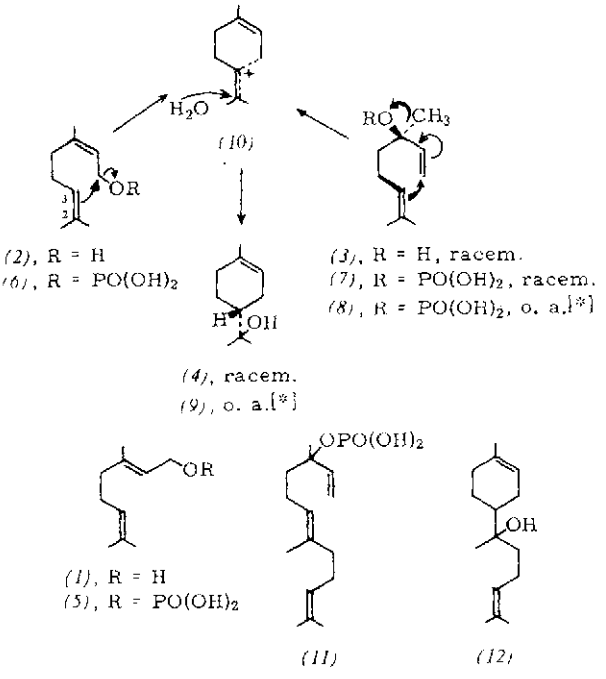
Phosphate	Hydrocarbon [%]	*(3)* [%]	*(4)* [%]	*(2)* [%]	*(1)* [%]
Geranyl	2	75	—	—	20
Neryl	3	28	60	7	—
Linaloyl	2	65	15	6	10
Terpinyl	15	—	80	—	—

The results of the hydrolysis of geranyl *(5)* and neryl phosphate *(6)* show that the configuration of the intermediate geranyl and neryl cations is stable. Cyclization of *(6)* and of linaloyl phosphate *(7)* to yield *(4)* takes place by nucleophilic displacement of the phosphate group by the 2,3-double bonds. This was concluded from the following data:

a) Comparison of the rate of hydrolysis of *(6)* and of 2,3-dihydroneryl phosphate showed anchimeric acceleration of the reaction by the double bond by a factor of about 2.

b) (−)-(*R*)-Linaloyl phosphate *(8)* yielded (+)-(*R*)-terpineol *(9)* 40 % optically pure, in conformity with the stereochemistry of S_N2' reactions of allyl compounds [3].

The addition of water to the intermediate cyclic cation *(10)* seems not to be stereospecific, because preliminary experiments indicate that the hydrolysis of *trans*-nerolidyl phosphate *(11)* yields both diastereomers of bisabolol *(12)*. The diastereomers were separated gas-chromatographically after their conversion into the trimethylsilyl ethers.



[GDCh-Ortsverband Göttingen (Germany), December 17th, 1964] [VB 903/210 IE]

German version: Angew. Chem. 77, 432 (1965)

[1] *F. Lynen, B. W. Agranoff, H. Eggerer, U. Henning*, and *E. M. Möslein*, Angew. Chem. *71*, 657 (1959).

[2] *F. Cramer, W. Rittersdorf*, and *W. Böhm*, Liebigs Ann. Chem. *654*, 180 (1962).

[3] *G. Stork* and *W. N. White*, J. Amer. chem. Soc. *78*, 4609 (1956).

[*] Branch I: monoacids; branch II: diacids; branch III: acids of type P(IV)-P(III)-P(IV), P(III)-O-P(IV)-P(IV), and P(III)-O-P(V)-O-P(V).

[*] o. a. = optically active.

Ageing of Precipitates by Ostwald Ripening

M. Kahlweit, Göttingen (Germany)

The theory of the ageing of precipitates by ripening is based on the Gibbs-Thomson equation, the initial size distribution of the precipitate and the kinetics of its growth in a nearly saturated solution. Growth kinetics, in the simplest case, is diffusion-controlled. Accordingly, it is necessary to know the surface tension σ and the diffusion coefficient D of the disperse phase, if theoretical and experimental results are to be compared.

For testing the theory, a system was chosen, in which diffusion-controlled growth may be assumed and σ and D are known, *viz.* an emulsion of amyl alcohol droplets in aqueous solution. Droplet growth in an emulsion of this type may be easily traced with an optical microscope, and quantitative agreement with theory was observed.

The second example to be studied was the ripening of crystalline TlI-precipitates in aqueous solution. It proceeds

much more slowly than would be expected according to theory. The reason is that the growth of crystalline precipitates at concentrations close to saturation is generally not diffusion-controlled.

A third example is the kinetics of phase separation in quenched supersaturated metal alloys, such as Ag-Pb. An interpretation of this separation as ripening of the clusters formed on quenching is suggested. The change in particle number and size may be traced by resistance measurements and with an electron microscope. Measurements have so far shown qualitative agreement with theory. Independent measurements of the diffusion coefficient in heterogeneous crystals are necessary, however, for reliable evaluation, especially with regard to a calculation of the interfacial tension between two solid phases.

[GDCh-Ortsverband Göttingen (Germany),
December 17th, 1964] [VB 899/204 IE]
German version: Angew. Chem. 77, 431 (1965)

Dehydration of Hydroxides

F. Freund, Göttingen (Germany)

A mechanism for the dehydration of $Mg(OH)_2$ and similar compounds has been suggested by *Taylor* [1], in which protons and cations are assumed to diffuse in opposite directions. Due to the high activation energy for the lattice diffusion of cations, this mechanism is, however, improbable or limited to special cases. More likely, the hydroxy groups must be assumed to be stationary, and water molecules to be formed at OH lattice positions by transfer of protons:

$$OH^- + OH^- \rightleftharpoons H_2O + O^{2-} \quad (a)$$

The water molecules then diffuse out of the lattice:

$$H_2O \longrightarrow + H_2O \text{ gas} \quad (b)$$

The diffusion process according to (b) is dependent on direction owing to the anisotropy of the lattice [2]. To form a water molecule, two OH groups must react with one another. The activation energy required for the proton transfer is less for adjacent, than for non-adjacent OH groups. At a given temperature, reaction (a) will therefore come to a standstill when all adjacent OH groups have reacted. Due to the statistical nature of the reaction, some OH groups will remain unreacted; thus the isothermal dehydration of such a hydroxide cannot be complete. Similarly, an oxide surface densely covered with OH groups cannot be freed of the last traces of water by merely evacuating at constant temperature, but only by simultaneously raising the temperature.

Statistical calculations of the number of OH groups remaining behind on a surface showed degrees of dehydration of around 90 %. Preliminary model calculations for three-dimensional lattices (hydroxides with layer structure) gave similar results.

[GDCh-Ortsverband Göttingen (Germany).,
December 17th, 1964] [VB 896/202 IE]
German version: Angew. Chem. 77, 431 (1965)

[1] *M. C. Ball* and *H. F. Taylor*, Mineralog. Mag. J. mineralog. Soc. *32*, 754 (1961).

[2] *F. Freund*, Ber. dtsch. keram. Ges. *42* (1965), in the press.

The Influence of Alpha-Radiation on Metal Surfaces

D. Frenzel, Göttingen (Germany)

Single crystals were prepared by the Bridgman method from lead which had been purified by zone melting. All samples were handled *in vacuo* and irradiated at 22 °C and at pressures below 10^{-8} mm Hg with a 3 curie polonium-210 source. Platinum-shadowed carbon matrices were prepared from the surfaces for electron microphotography. The linear magnification was 40000.

The single-crystal surfaces, even before irradiation, proved to be relatively smooth. Apart from numerous small and irregularly occurring discontinuities [*], grooves separated by an average distance of about 500 Å were observed in the majority of samples. The samples were then irradiated with total doses of between 10^{14} and 10^{16} α-particles/cm², *i.e.* each surface atom, on the average, was hit by one α-particle. Surprisingly, the surfaces were levelled to a large extent, the degree of levelling being about 80 % for the largest dose. This corresponds to a rearrangement of about 5 lead atoms per incident α-particle.

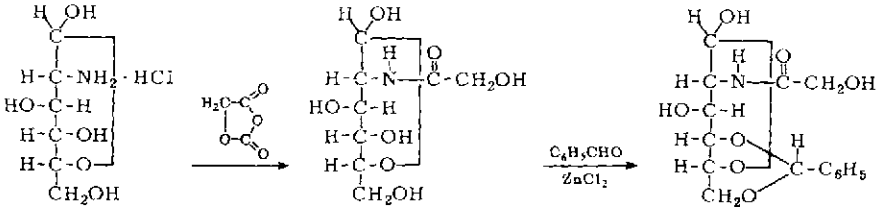
It is reasonable to assume a diffusion mechanism for the movement of the atoms. Surface tension may be regarded as the driving force. It can be shown, with the aid of models permitting the calculation of these effects, that volume diffusion is negligible compared to surface diffusion, for a surface roughness with a periodicity of about 500 Å.

[GDCh-Ortsverband Göttingen (Germany),
December 17th, 1964] [VB 894/199 IE]
German version: Angew. Chem. 77, 431 (1965)

The Synthesis of N-Glycolylneuraminic Acid and the Biochemistry of Glycoproteins Containing Neuraminic Acid

H. Faillard, Köln (Germany)

N-Glycolyl-D-glucosamine *(1)* was obtained by the reaction of D-glucosamine hydrochloride with 1,3-dioxolane-2,4-dione, prepared from glycollic acid and phosgene in dioxane [1] (in collaboration with *M. Blohm*). In analogy to the method of *Okujama* and *Sinohara* [2] the *N*-glycolyl-D-glucosamine could be converted into the 4,6-benzylidene derivative *(2)* by reaction with benzaldehyde and zinc chloride.



(1) *(2)*

The 4,6-benzylidene-*N*-glycolylglucosamine *(2)* condenses with potassium di-t-butyl enoloxaloacetate to yield the corresponding t-butoxycarbonyl lactone [3]. Elimination of CO_2 and isobutylene from this compound and hydrogenolytic removal of the benzylidene residue afford the γ-lactone of *N*-glycolylneuraminic acid, which opens in alkaline media to give the free acid *(3)*. Both the 4,6-benzylidene-*N*-glycolyl-

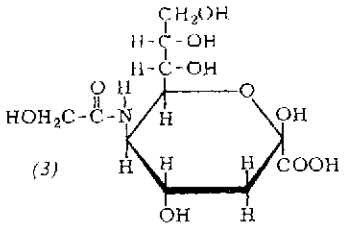
[*] Size about 50 Å.

[1] *G. W. Jourdian* and *S. Roseman*, J. biol. Chemistry *237*, 2442 (1962).

[2] *T. H. Okujama* and *H. Sinohara*, Tohoku J. expt. Med. *68*, 181 (1958).

[3] *R. Kuhn* and *G. Baschang*, Liebigs Ann. Chem. *659*, 156 (1962).

glucosamine ($[\alpha]_D^{20} = +32.3°$) and the *N*-glycolylneuraminic acid ($[\alpha]_D^{20} = -33.5°$) can be obtained in crystalline from.



(3)

The intrinsic factor, a glycoprotein of human gastric mucosa, contains *N*-acetylneuraminic acid, which protects the biologically active protein portion of this molecule from attack by trypsin in the digestive tract (research in collaboration with *W. Pribilla*). If *N*-acetylneuraminic acid is eliminated with neuraminidase, the intrinsic factor is attacked by trypsin and loses its power to promote the resorption of vitamin B_{12} in the intestine. Protection against trypsin is also obtained if *N*-acetylneuraminic acid in the intrinsic factor is replaced by the cation exchanger poly(acrylic acid vinyl pyrrolidone).

[GDCh-Ortsverband Mülheim/Ruhr (Germany), January 6th, 1965] [VB 904/209 IE]
German version: Angew. Chem. 77, 432 (1965)

Nuclear Magnetic Relaxation Times and the Microdynamic Structure of Liquid Mixtures

H. G. Hertz, Münster (Germany)

There is relatively little knowledge, mostly from spectroscopic investigations, about the preferred spatial arrangement of molecules in liquid mixtures, *i.e.* about the "structure" of mixtures. The "microdynamic structure" of a liquid is characterized by dividing the liquid into microscopic regions and ascribing to each of these regions a molecular reorientation and residence time. Thus it is possible, for example, to correlate changes in the thermodynamic excess functions on variation of the composition of the mixture with changes in the microdynamic structure. The molecular reorientation and residence times may be obtained by measuring the nuclear magnetic relaxation times or the decay of the spin-echo amplitude (self-diffusion coefficient).

This method was applied to the study of the hydration of large, singly charged ions, *e.g.* Br^-, I^-, Rb^+ [1]. By combining results of measurements of relaxation times for protons with those for the large ions, it was shown that the range of the increased fluidity, as compared with pure water, extends right to the surface of the ion. In other words, the hydration sphere around the ions is not rigid. The activation energy for reorientation of the water molecules in the hydration sphere lies between 2 and 3 kcal/mole, *i.e.* below that for pure water. Measurements of relaxation times also show that the time for reorientation of the water molecules in the hydration sphere around non-polar groups (*e.g.* alkyl groups) is about twice as high as in pure water [2]. This effect has been described as "iceberg formation"[3] or "hydration of the second kind" [4]. The reorientation times of the dissolved particles and the activation energy for this process can be determined by isotopic substitution and extrapolation to infinite dilution. Smaller particles containing alkyl groups have a high mobility within their hydrate cages. These relationships were studied for the systems acetone/water and methanol/water over the entire composition range.

[GDCh-Ortsverband Göttingen (Germany), January 14th, 1965] [VB 905/211 IE]
German version: Angew. Chem. 77, 453 (1965)

[1] *H. G. Hertz*, Ber. Bunsenges. physik. Chem. *67*, 311 (1963); *H. G. Hertz* and *M. D. Zeidler*, ibid. *67*, 774 (1963).

[2] *H. G. Hertz* and *M. D. Zeidler*, Ber. Bunsenges. physik. Chem. *68*, 821 (1964).

[3] *H. S. Frank* and *M. W. Evans*, J. chem. Physics *13*, 507 (1945).

[4] *H. G. Hertz*, Ber. Bunsenges. physik. Chem. *68*, 907 (1964).

Control of Electrochemical Reactions by Means of Foreign Sorbates

Hellmuth Fischer, Karlsruhe (Germany)

The sorption of foreign substances and their orientation on a metallic surface largely depend on the surface charge of the metal, which may be varied by means of a potential. This constitutes the principal difference in the efficiency of such sorbates in electrochemical and in non-electrochemical heterogeneous reactions. The following examples were given for the effect, dependent on potential, of a sorbed foreign substance in electrode reactions:

1. During the dissolution of iron in acid, the anodic transfer of iron into the solution, which is accelerated by sorbed hydroxide ions, may be inhibited by more strongly surface-active sorbates, *e.g.* chloride, other anions or polar molecules such as phenylthiourea, as a function of the potential.

2. The drastic effect of a potential-controlled change from adsorption to desorption (or *vice versa*) is shown, *e.g.* in the evolution of H_2 or in the deposition of Ni on a nickel cathode (marked change in capacity, coverage of deposit, and overvoltage).

3. A galvanostatic formation of rhythmic-lamellar structures, coupled with periodic potential fluctuations, can be observed when copper is deposited in the presence of *o*-phenanthroline. The overvoltage alters with the abrupt changes in the sorptive coating, and in each period nucleation, specific crystal growth, and levelling of the deposit occur in turn.

4. In the case of electro-crystallization, the sorbates may be incorporated into the metal. Electron microscopy and spectrophotometry indicate occlusion densities of the same order, *e.g.* 10^{18}–10^{20} molecules/cm² for *o*-phenanthroline in Ni.

5. The inhibition by sorbed 5,6-benzoquinoline, which varies over a wide potential range (about 800 mV), was discussed using the redox system $V^{3+}/V^{2+}/Hg$ as an example. By comparing the current density *vs.* potential curves in 0.1 N HCl and in 0.1 N HCl + 0.9 N KCl, mechanical blocking of the surface may be distinguished from an electrokinetic effect (repulsion between V^{3+} and V^{2+}). Potential *vs.* capacity curves, taken in vanadium-free electrolytes under otherwise similar conditions, confirm the occurrence of inhibition and sorption of foreign substances within the same potential ranges.

[GDCh-Ortsverband Freiburg (Germany), January 15th, 1965] [VB 906/213 IE]
German version: Angew. Chem. 77, 459 (1965)

Recent Investigations of Covalent Inorganic Fluorides

O. Glemser, Göttingen (Germany)

Difluorodiazine N_2F_2 is obtained by direct fluorination of NaN_3 in a continuous process at room temperature. On adding chlorine to the fluorine, highly explosive chlorofluorodiazine N_2FCl is produced. On passing NO with fluorine at 650 °C through a CaF_2 tube, nitrogen trifluoride is formed:

$$2\,NO + 2\,F_2 \rightarrow NO_2F + NF_3$$

NF_3 is often considered to be only slightly reactive. On being passed into molten sulfur at 200 °C it yields a little $N_3S_3F_3$, but at 400 °C good yields of thiazyl fluoride NSF and thiothionyl fluoride SSF_2 are obtained. In this way NSF and SSF_2 can be obtained easily on a preparative scale.

Nitrogen-sulfur-fluorine compounds can be divided into the acyclic compounds NSF, $S_3N_2F_2$, NSF_3, and the cyclic compounds $N_4S_4F_4$, $N_3S_3F_3$, S_4N_3F. Of the former, NSF_3 can be reacted with diethylamine to give the stable compound $NSF_2N(C_2H_5)_2$ which contains an N≡S triple bond as does NSF_3.

For the preparation of fluorides from chlorides by exchange, fused salts can be used as reaction media, *e.g.* a melt of NaF/KF/LiF or a solution of fluorides in molten $KCl/ZnCl_2$. In this way, large quantities of CSF_2 were prepared from $CSCl_2$ for the first time. Plastic polymers can be produced from CSF_2.

Fluorides of transition metals have been obtained in two ways: by fluorination of the metals with elemental fluorine under pressure, or by fluorination of metal powder in a fluidized bed. By the former method, yellow and very unstable chromium hexafluoride as well as unstable and hygroscopic osmium heptafluoride have been prepared for the first time. By fluorination in a fluidized bed CrF_6, ReF_7, MnF_4, PbF_4, and BiF_5 can be prepared simply and quickly. Depending on the reaction conditions, chromium powder reacts with hydrogen fluoride to yield either pure CrF_2 or pure CrF_3.

[GDCh-Ortsverband Braunschweig (Germany),
January 25th, 1965] [VB 907/214 IE]
German version: Angew. Chem. 77, 463 (1965)

The Kinetics at Solid Phase Boundaries

H. Rickert, Karlsruhe (Germany)

Solid-state galvanic cells are often suited to kinetic studies on solids at elevated temperatures. We have studied the passage of silver through the phase boundary solid silver/solid silver sulfide [1]. This system is particularly favorable, because the conductivity of the silver in silver sulfide is already very high at 200 °C ($\sigma_{Ag^+} \approx 1\ \Omega^{-1}\ cm^{-1}$) and, as a result, stationary states and equilibria are rapidly established.

With silver iodide as auxiliary electrolyte, which shows virtually pure silver ion conduction, it is possible, despite the predominating electronic conduction of silver and silver sulfide at 200 to 300 °C, to measure the flow of silver – or the flow of silver ions or electrons alone – through the phase boundary solid silver/solid silver sulfide, as a function of the difference between the chemical potential of silver and the electrochemical potential of the silver ions and of the electrons.

Potentials were measured with given galvanostatic currents. Platinum electrodes exchange electrons; therefore, the electrochemical potential of the electrons in platinum, in the absence of current flow, is equal to that in the neighboring Ag_2S phase. Silver/silver iodide electrodes exchange Ag^+ ions; therefore, the electrochemical potential of the silver ions in silver, in the absence of current flow, is equal to that in the neighboring Ag_2S phase. Silver, freshly deposited as whisker, may transgress into silver sulfide, in which case the difference between the chemical potentials of silver in silver and silver sulfide is but a few percent of the difference found *e.g.* in the transition from cast silver. Some whiskers, surface-etched at right angles to the longitudinal axis, showed a helical structure [2], which points to screw dislocations in the axis of the whisker. The low polarization voltages for the transition of silver from whiskers into silver sulfide could be explained in this way.

[GDCh-Ortsverband Karlsruhe (Germany),
January 28th, 1965] [VB 908/224 IE]
German version: Angew. Chem. 77, 463 (1965)

[1] *H. Rickert* and *C. D. O'Briain*, Z. physik. Chem., N. F. *31*, 71 (1962).

Oxidation of Organic Compounds by Combustion in a Jet

G. Kainz, Vienna (Austria)

The direct oxidation of organic compounds in a tube is often not quantitative since the sample vapors are not always mixed with a sufficient quantity of oxygen. Quantitative oxidation is possible using the following arrangement: in a combustion tube there is an insert tube tapering to a jet which is surrounded by a platinum tube supported by spacers (analogous to a Bunsen burner). The sample is vaporized or decomposed in the insert tube, with exclusion of oxygen. The volume of the insert tube is such that it can contain the sample in the gaseous state. The volatile products are swept out by nitrogen through the heated jet, and burn with the formation of an intense flame (oxygen is fed into the outer tube). Non-volatile products remaining in the insert tube are subsequently burned with oxygen. Micro- and semimicro-quantities can be oxidized rapidly. The elements C, H, halogens including F, S, and P are then determined by the usual methods.

Combustion in a jet can also be used in the determination of traces of halogen and sulfur in the ppm region in volatile samples (natural gas, petrol). For these purposes an insert tube is used which has a ring of jets and is surrounded by a funnel-shaped tube. The sample vapors burn as in a Bunsen burner. The throughput is up to 2 ml of petrol per minute.

[Österreichische Gesellschaft für Mikrochemie und
Analytische Chemie, Leoben (Austria),
January 29th and 30th, 1965] [VB 913/221 IE]
German version: Angew. Chem. 77, 463 (1965)

[2] *V. Sattler*, *L. Albert*, and *H. Rickert*, unpublished.

SELECTED ABSTRACTS

1,4a,8,8a-Triazaboradecalin *(1)* is a new bicyclic ring system containing boron, nitrogen, and carbon that has been described by *K. Niedenzu*, *P. Fritz*, and *J. W. Dawson*. It is formed in 75 % yield by transamination from trisdimethylaminoborane and bis-3-aminopropylamine in a 1:1 ratio in dilute solution in benzene; *(1)* melts at 38–41 °C.

$$B[N(CH_3)_2]_3 + [H_2N(CH_2)_3]_2NH \rightarrow \text{(1)} + 3\ HN(CH_3)_2$$

1,3,2-Diazaboracyclohexanes or -heptanes are formed analogously in inert solvents, *e.g.* benzene, from bisdimethylaminoboranes and aliphatic α,ω-diamines. / Inorg. Chem. *3*, 1077 (1964) / –La. [Rd 187/396 IE]

Quantitative analysis of sulfur hexafluoride and its derivatives was studied by *G. C. Demitras* and *A. G. MacDiarmid*. SF_6 is unusually resistant to chemical attack but does react with sodium in liquid ammonia even at −64 °C. A solution of sodium in 1,1-diphenylethylene/glycol dimethyl ether also reacts quantitatively with SF_6 within a few minutes at room temperature.

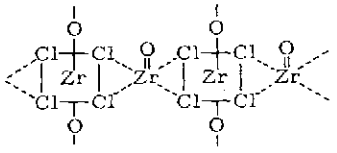
$$8\ Na + SF_6 \rightarrow Na_2S + 6\ NaF$$

The authors consider that the reaction proceeds as follows. The diphenylethylene first removes an electron from the sodium and the resultant "diphenylethyl radical ion" $[(C_6H_5)_2C-\dot{C}H_2]^{\ominus}$ passes the electron on to the SF_6 molecule. Here the electron is accomodated in to the relatively low-energy free 3d orbital of the sulfur to form a relatively unstable $SF_6^{\ominus}$ ion. This ion ejects a fluoride ion and the residual SF_5 radical reacts further with the "sodium solution". / Inorg. Chem. *3*, 1198 (1964) / –La. [Rd 188/397 IE]

The preparation of anhydrous zirconium(IV) oxide chloride has been achieved by *K. Dehnicke* and *K. U. Meyer* by the reaction of equivalent amounts of Cl_2O and $ZrCl_4$ in CCl_4 at −15 °C:

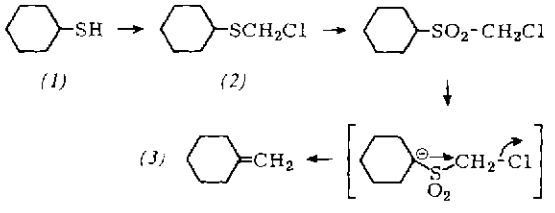
$$ZrCl_4 + Cl_2O \rightarrow ZrOCl_2 + 2\ Cl_2$$

Anhydrous $ZrOCl_2$ is a white, highly hygroscopic crystalline solid and is stable up to 250 °C. It forms adducts readily with $POCl_3$ and pyridine. With water, it forms hydrated ZrO_2 besides $ZrOCl_2 \cdot 8\,H_2O$. It decomposes slowly above 250 °C with release of $ZrCl_4$.



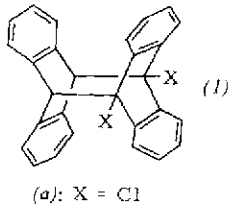
The structure proposed by the authors contains an arrangement of $ZrO^{2\oplus}$ ions and oxygen-bridged $ZrOCl_4^{2\ominus}$ ions. / Z. anorg. Chem. *331*, 121 (1964) / −La. [Rd 186/395 IE]

The conversion of thiols into homologous α-olefins is described by *L. A. Paquette*. Treatment of a thiol having at least one α-hydrogen atom, *e.g.* cyclohexane thiol *(1)* or 1-hexanethiol, with paraformaldehyde/HCl affords good yields of chloromethyl sulfides, *e.g.* chloromethyl cyclohexyl sulfide *(2)* (90% yield) or chloromethyl n-hexyl sulfide (71%). The sulfides can be oxidized with *m*-chloroperoxybenzoic acid in chloroform to the sulfones, which on refluxing with 25%

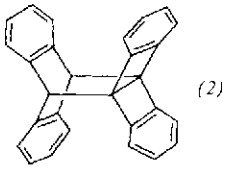


aqueous NaOH afford terminal olefins, *e.g.* methylenecyclohexane *(3)*, b.p. 88–92 °C (80% yield), or 1-heptene (77.6%). / J. Amer. Chem. Soc. *86*, 4383 (1964) / −Ma. [Rd 204/413 IE]

A derivative of „Dewar anthracene" has been made by *D. E. Applequist* and *R. Searle*. Anthracene and 9,10-dichloroanthracene were irradiated in benzene for 6 days under nitrogen to yield 9,10-dichlorodianthracene *(1a)*, m.p. 199 to 200 °C (decomp.), in 61% yield. The reaction of a suspension of *(1a)* in benzene/ether 69 °C at for 12 h with triphenylmethylsodium led to 9,10-dehydrodianthracene *(2)*, the desired derivative of "Dewar anthracene", in 26% yield.



(1)



(2)

(a): X = Cl
(b): X = Br

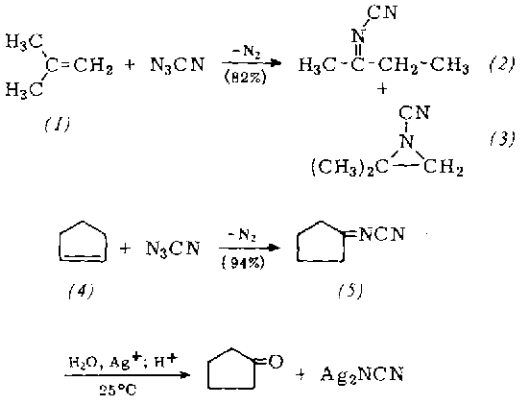
The ultraviolet spectrum of the product with λ_{max} = 269.3, 275.1, and 283.7 mμ and with ε = 4170, 4060, and 3020, respectively, is in accordance with structure *(2)*. The hydrocarbon *(2)*, m.p. 338–342 °C (decomp.), could be crystallized from xylene and sublimed at 180 °C/0.1 mm. Bromination of *(2)* afforded *(1b)*. Valence-bond isomerization of the electron system in the right-hand half of *(2)* to an anthracene-type distribution is prevented by the particular geometric configuration of the bridged structure. / J. Amer. chem. Soc. *86*, 1389 (1964) / −Eb. [Rd 193/402 IE]

Ethynylsulfur pentafluoride $F_5S{-}C{\equiv}CH$, b.p. 6 °C, was synthesized by *F. W. Hoover* and *D. D. Coffman* by thermal addition of sulfur chloride pentafluoride onto acetylene and subsequent bromination; *trans*-$F_5S{-}CH{=}CHCl$, $F_5S{-}CHBr{-}CHBrCl$, and *cis*- and *trans*-$F_5S{-}CBr{=}CHCl$ are formed. Besides $F_5S{-}C{\equiv}CH$, other derivatives can be prepared from these products: $F_5S{-}CHBr{-}CH_2Br$, $F_5S{-}CBr_2{-}CH_2Br$, $F_5S{-}CH_2{-}CH(OCH_3)_2$, $F_5S{-}CH_2{-}CH(OCOCH_3)_2$, and $F_5S{-}CBr{-}CH_2$. Diazomethane adds onto $F_5S{-}C{\equiv}CH$ in ether at 0 °C to form isomeric F_5S-substituted pyrazoles. Butadiene and dimethylbutadiene, for example, undergo Diels-Alder condensations with $F_5S{-}C{\equiv}CH$ to yield substituted 1,4-cyclohexadienes, which can be dehydrogenated to afford F_5S-substituted benzene derivatives. / J. org. Chemistry *29*, 3567 (1964) / −Jg. [Rd 241/449 IE]

The synthesis of cyanogen azide in almost quantitative yield has been achieved by *F. D. Marsh* and *M. E. Hermes* by the reaction of NaN_3 with cyanogen chloride in aprotic solvents, *e.g.* acetonitrile, at room temperature.

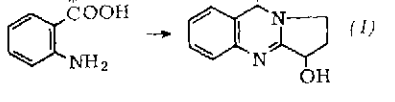
$$NaN_3 + ClCN \rightarrow N_3CN + NaCl$$

Cyanogen azide is a colorless oil which detonates on mechanical or thermal shock but is relatively safe to handle in solution. It behaves as an extremely reactive organic azide. It is reduced by H_2S to cyanamide in 80% yield; with triphenylphosphine it forms *N*-cyanotriphenylphosphinimine, m.p. 193–195 °C, in 88% yield. It reacts with olefins such as *(1)* or *(4)* at 0–35 °C to form *N*-alkylidenecyanamides such as *(2)* or *(5)* and/or *N*-cyanoaziridines *(3)*. The *N*-alkylidenecyanamides are rapidly hydrolysed to ketones with aqueous acids in the presence of $Ag^{\oplus}$ ions. This novel ketone synthesis is



generally applicable and proceeds without any rearrangement. / J. Amer. chem. Soc. *86*, 4506 (1964). [Rd 206/415 IE]

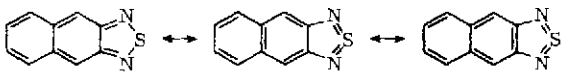
The incorporation of anthranilic acid into peganine (vasicine), a quinazoline alkaloid *(1)*, has been studied by *D. Gröger*, *S. Johne*, and *K. Mothes* by feeding [carboxy-^{14}C]-anthranilic acid to rooted leaves of *Adhatoda vasica* Nees. The labelled carbon atom recurred in the 4-position. The alkaloid can be degraded to (labelled) anthranilic acid by oxidation with permanganate, yielding 4-oxo-3,4-dihydroquinazolyl-3-acetic acid, esterification with diazomethane, and hydrolysis with 20% KOH. Pyrrolidinoquinazolines exhibit physiological



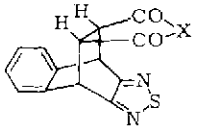
activity: *(1)* is a bronchioconstrictor, while its 4-oxo derivative is a bronchiodilator [1]. / Experientia *21*, 13 (1965) / −De. [Rd 229/437 IE]

[1] *D. R. Mehta*, *J. S. Naravane*, and *R. M. Desai*, J. org. Chemistry *28*, 445 (1963).

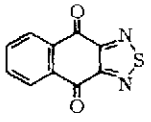
The synthesis of 1,2,5-naphtho[2,3-c]thiadiazole *(1)*, a very stable analogue of anthracene, has been reported by *M. P. Cava* and R. H. *Schlesinger*. Reaction of 2,3-diaminonaphthalene with thionylaniline in pyridine at 95 °C gave a 95% yield of the thiazole *(1)* as orange-red needles, m.p. 85–86 °C, which give Diels-Alder adducts *(2a)* and *(2b)* with *N*-phenylmaleimide and maleic anhydride. Oxidation of *(1)* with $Na_2Cr_2O_7$ in acetic acid produced the orange quinone *(3)*,



(1)



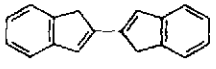
(2a): X = N-C_6H_5; *(2b)*: X = O



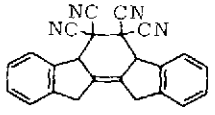
(3)

m.p. 246 °C (decomp.), in 46% yield. The heterocycle *(1)* exhibits aromatic properties. / Tetrahedron Letters *1964*, 3815 / –Ma. [Rd 197/406 IE]

The synthesis and properties of 2,2'-biindenyl *(1)* are described by *W. Lüttke* and *J. Grussdorf*. Although the dimerization of indene cannot be effected by debromination of 2-bromoindene with copper or silver powder or with alkali metals, the Grignard compound 2-indenylmagnesium bromide can be converted into *(1)*, m.p. 242–243 °C, by heating it in tetrahydrofuran with a solution of $CuCl_2$ in ether. Catalytic hydrogenation of *(1)* affords 2,2'-biindanyl, m.p. 165–166 °C. The conjugated diene system of *(1)* condenses with tetracyanoethylene



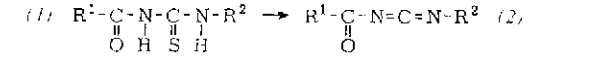
(1)



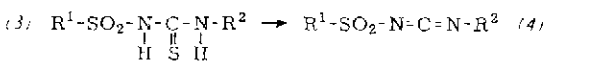
(2)

to give *(2)*, which decomposes above 180 °C. It is concluded from the ultraviolet spectrum of *(1)* that it probably occurs in the *s-trans*-form. / Chem. Ber. *98*, 140 (1965) / –Ma. [Rd 198/407 IE]

The synthesis of *N*-acyl- and *N*-sulfonylcarbodiimides has been described by *R. Neidlein* and *E. Heukelbach*. Phosgene plus triethylamine remove 1 mole of H_2S from acylthioureas *(1)* to form the *N*-acylcarbodiimides *(2)*, probably *via* *N*-acylformamidinium chlorides as intermediates. The derivatives of *(2)* with R^1 = H are highly reactive and polymerize within a few hours. Compounds obtained include *(2)*, R^1 = ethoxy, R^2 = cyclohexyl, b.p.80–82 °C/0.01 mm, in 37% yield, *(2)* R^1 = ethoxy, R^2 = isopropyl, b.p. 60–62 °C/0.01 mm, in 42% yield, and *(2)*, R^1 = ethoxy, R^2 = t-butyl, b.p. 63–65 °C/0.01 mm, in 45% yield. The products are colorless oils with a pungent odor. *N*-Sulfonylcarbodiimides *(4)* can be made from



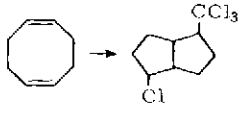
(1) R^1-C(=O)-N(H)-C(=S)-N(H)-R^2 → R^1-N=C=N-R^2 *(2)*



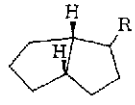
(3) R^1-SO_2-N(H)-C(=S)-N(H)-R^2 → R^1-SO_2-N=C=N-R^2 *(4)*

sulfonylthioureas by elimination of H_2S with HgO in dry benzene, and are very stable. Derivatives of this type include *(4)*, R^1 = *p*-tolyl, R^2 = phenyl, b.p. 140–145 °C/0.05 mm, obtained in 12% yield, and *(4)*, R^1 = methyl, R^2 = phenyl, b.p. 115–120 °C, obtained in 18% yield. / Tetrahedron Letters *1965*, 149 / –Ma. [Rd 200/409 IE]

Transannular free-radical cycloadditions of *cis,cis*-**1,5-cyclooctadiene** *(1)* have been investigated for the first time by *R. Dowbenko* (reactions in the cyclooctane series which lead to bicyclic products by an ionic mechanism [1] or *via* a carbene intermediate [2] are already known). When *(1)* is refluxed in CCl_4 and a small amount of dibenzoyl peroxide is added, the 1:1 adduct *(2)*, b.p. 84–87 °C/0.1 mm, is formed in 63% yield. The same adduct is formed in 33.5% yield on irradiation of a solution of *(1)* in CCl_4 with ultraviolet light, or in 73% yield by an ionic reaction, when a mixture of *(1)*, CCl_4, isopropanol, and a little $FeCl_3$ is refluxed for 2 days.



(1) *(2)*

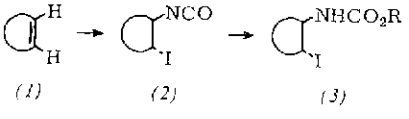


(3)

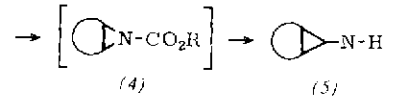
(a): R = CCl_3
(b): R = CO-NH-$C(CH_3)_3$
(c): R = CO-CH_3
(d): R = CHCl-$CO_2C_2H_5$

Analogous derivatives *(3)* of bicyclo[3,3,0]octane with the *exo-cis*-configuration are formed from *(1)*, *e.g.* with $CHCl_3$ [*(3a)*, b.p. 110–111 °C/9 mm, 37% yield], with t-butylformamide [*(3b)*, m.p. 134–135 °C, 51% yield], with acetaldehyde [*(3c)*, b.p. 89 °C/10 mm], and with ethyl chloroacetate [*(3d)*, b.p. 70 °C/0.08 mm]. / Tetrahedron *20*, 1843 (1964) / –Bi. [Rd 178/387 IE]

Aziridines were made from cyclic olefins using a new reaction by *A. Hassner* and *C. Heathcock*. Cyclic olefins *(1)* add on iodine isocyanate in a stereospecific manner when treated in ether cooled with ice with 1 mole of solid iodine and 1.3 moles of silver cyanate. The *trans*-2-iodo-1-isocyanates *(2)* formed can be converted without isolation into *trans*-2-carbamic esters *(3)* by reaction with methanol or ethanol. Treatment of *(3)* with approx. 1 N methanolic KOH at normal or somewhat elevated temperature causes hydrolysis of the iodo grouping and cyclization to the cycloalkene *N*-



(1) *(2)* *(3)*



(4) *(5)*

R = CH_3; C_2H_5

alkoxycarbonylimine *(4)*, which is not isolated but undergoes hydrolysis and decarboxylation to form the aziridine *(5)*. Products prepared include: cyclohexene → 1,2-iminocyclohexane (40% yield [3]); indene → 1,2-iminoindane (36% yield [1]); 1,2-dihydronaphthalene → 1,2-imino-1,2,3,4-tetrahydronaphthalene, m.p. 51–53 °C (54%); 2-cholestene → 23,33-iminocholestane (70%); and styrene → 2-phenylaziridine (38%). The overall yields in this sequence of reactions are higher than those in the cyclization of the analogous 2-iodo amine hydrochlorides, 2-amino alcohols, or 2-halogeno amines (which are also difficult to obtain). / Tetrahedron *20*, 1037 (1964) / –Bi. [Rd 179/388 IE]

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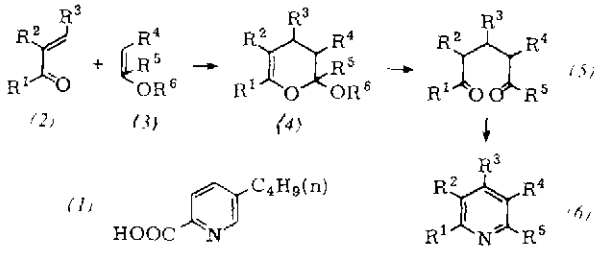
[1] *C. A. Cope* et al., J. Amer. chem. Soc. *82*, 4299 (1960).

[2] *L. Friedmann* and *H. Shechter*, J. Amer. chem. Soc. *83*, 3159 (1961).

[3] Isolated as the phenylurea derivative.

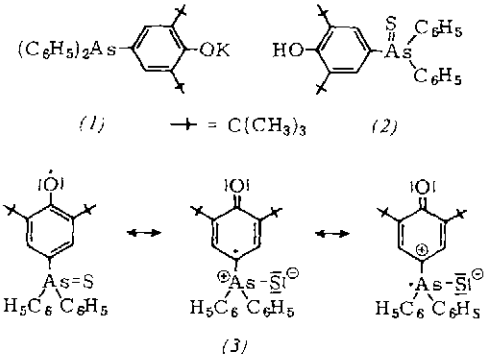
The synthesis of fusarinic acid *(1)* **and its isomers and homologues** has been achieved by *Yu. I. Chumakov* and *V. P. Sherstyuk*. The best means of preparing pyridines with two alkyl substituents is a diene condensation of α,β-unsubstituted aldehydes or ketones *(2)* with vinyl ethers *(3)*. The 2-alkoxy-3,4-dihydro-1,2-pyrans *(4)* formed in this way are hydrolysed to the 1,5-diketo compounds *(5)*, which condense with hydroxylamine to form substituted pyridines. For example, heating of equimolar amounts of 1-hexenyl ethyl ether and methyl vinyl ketone produces 2-ethoxy-3-n-butyl-6-methyl-3,4-dihydro-1,2-pyran, b.p. 106–107 °C/18 mm, in 47 % yield, which on hydrolysis with acetic acid and reaction with NH_2OH yields 37.5 % 2-methyl-5-n-butylpyridine, b.p. 220–221 °C. Oxidation of the latter compound with SeO_2 in pyridine affords 5-n-butylpyridine-2-carboxylic acid *(1)*, m.p. 100–101 °C. Isomeric and homologous pyridines and pyridinecarboxylic



(2) *(3)* *(4)* *(5)* *(1)* *(6)*

acids can be obtained analogously. / Tetrahedron Letters *1965*, 129 / –Ma. [Rd 201/410 IE]

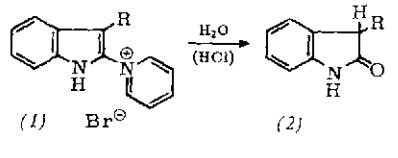
A mesomeric free arsenic radical has been synthesized by *E. Müller*, *H. Eggensperger*, *B. Teissier*, and *K. Scheffler*. The reaction of diphenylarsinylpotassium with 4-iodo-2,6-di-t-butylphenol produces *(1)*, which is then hydrolysed and treated with sulfur to yield the sulfide *(2)*. Dehydrogenation of *(2)* with PbO_2 or potassium hexacyanoferrate(III) in benzene produces the free radical *(3)* as a bright green solution, which rapidly turns light brown. The ESR spectrum of *(3)* contains four triplets, hence the unpaired electron is distributed over the *meta*-positions of the aroxyl



(1) *(2)* *(3)*

nucleus and the arsenic atom. Analogous free phosphorus radicals are already known. / Z. Naturforsch. *19b*, 1079 (1964) / –Ma. [Rd 202/411 IE]

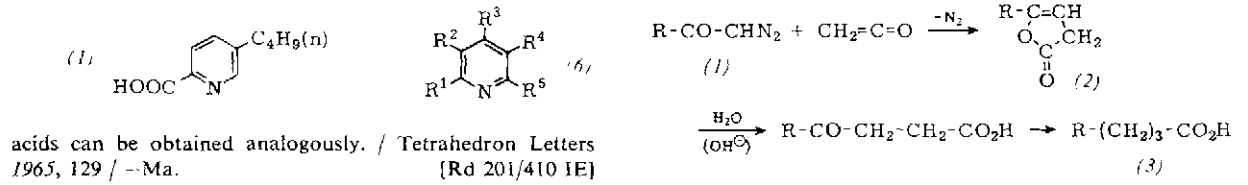
A new route from indoles to oxindoles has been discovered by *T. Kobayashi* and *N. Inokuchi*. The reaction of 3-substituted indoles with equimolar amounts of *N*-bromosuccinimide and pyridine in benzene at room temperature affords high yields of the yellow, crystalline pyridinium salts *(1)*. These salts are resinified by alkalies, but are readily hydrolysed by 3–6 N HCl to oxindoles *(2)*.



(1) *(2)*

Examples of the products obtained: R = CH_3, *(1a)*, 79.5 %, m.p. 231–233 °C, *(2a)*, 81.5 %, m.p. 123–124 °C; R = C_6H_5, *(1b)*, 100 %, m.p. 225 °C (decomp.), *(2b)*, 67 %, m.p. 181–184 °C; R = $-(CH_2)_2COOCH_3$, *(1c)*, 83 %, m.p. 225–226 °C, *(2c)*, 88 %, m.p. 168–170 °C; R = $-(CH_2)_2COOCH_3$, *(1d)*, 86 %, m.p. 169–170 °C (decomp.), *(2d)*, 89 %, m.p. 169–170 °C. Starting from methyl 3-indolylacetate (R = CH_2COOCH_3), hydrolysis of the oxindole ring and recyclization produces a 50 % yield of 2-oxo-1,2,3,4-tetrahydroquinoline-4-carboxylic acid, m.p. 214–215 °C. / Tetrahedron *20*, 2055 (1964) / –Bi. [Rd 176/385 IE]

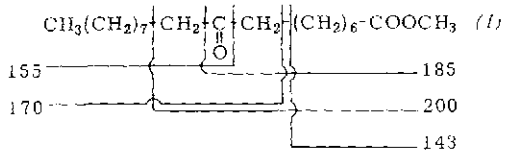
Extension of the chains of carboxylic acids by three carbon atoms can be achieved by a simple method developed by *W. Ried* and *H. Mengler*. Diazomethyl ketones *(1)* prepared from acid chlorides and diazomethane react with ketene in dry xylene on mild warming to yield β,γ-butenolides *(2)* by expulsion of nitrogen [1]; these enol lactones *(2)* are readily hydrolysed by 2 N NaOH to give γ-keto carboxylic acids. Wolff-Kischner reduction of each ketone produces the carboxylic acid *(3)* containing three carbons more than the original acid.



(1) *(2)* *(3)*

The whole sequence of reactions can also be applied to dicarboxylic acids. Acids extended in this way include: propionic acid → n-capronic acid (28 % yield); benzoic acid → γ-phenylbutyric acid (16 %); β-naphthoic acid → 4-(2-naphthyl)butyric acid (8.5 %); adipic acid → decane-1,10-dicarboxylic acid (22 %); suberic acid → dodecan-1,12-dicarboxylic acid (24.5 %). In exceptional cases the β,γ-butenolide can be converted into the corresponding carboxylic acid directly by catalytic hydrogenation, *e.g.* benzoic acid → γ-phenylbutyric acid (25.5). / Liebigs Ann. Chem. *678*, 113 (1964) / –Bi. [Rd 177/386 IE]

Location of a double bond in an olefinic chain by mass spectrometry was achieved by *G. W. Kenner* and *E. Stenhagen*. The olefin was converted into its epoxide with monoperoxyphthalic acid and isomerized with NaI to a mixture of two ketones: 5 mg of epoxide were heated in 2 ml of dimethylformamide plus 2 ml of methyl iodide with 40 mg of NaI. In the mass spectrometer, each ketone yielded the fragments from α-cleavage ($R-CH_2-C\equiv O^{\oplus}$ and $R'-CH_2-C\equiv O^{\oplus}$) and β-cleavage ($[R-CH_2-C(OH)=CH_2]^{\oplus}$ and $[R'-CH_2-C(OH)CH_2]^{\oplus}$), ocassionally together with a fragment of the type $RCH_2^{\oplus}$ also produced by β-cleavage. Treatment of methyl oleate with monoperoxyphthalic acid and NaI yielded methyl 9-oxooctadecanoate *(1)* and methyl 10-oxooctadecanoate *(2)*. The fragmentation of *(1)* can be represented schematically as follows:



(1)

Five analogous mass signals were obtained from *(2)*. Thus, a total of ten fragments were obtained from the mixture of *(1)* plus *(2)*, and these are therefore characteristic for methyl oleate. The same mass spectrum was obtained after analogous treatment of methyl elaidate. Here the mass numbers can be reconciled only with a double bond between C-9 and C-10. This technique has been applied to several long-chain esters with one double bond. / Acta chem. scand. *18*, 1551 (1964) / –Eb. [Rd 239/447 IE]

[1] Cf. *W. Ried* and *H. Mengler*, Angew. Chem. *73*, 218 (1961); Liebigs Ann. Chem. *651*, 54 (1962).

An alkoxide oxidation involving hydride transfer to dichlorocarbene and group migration during carbene reactions have been observed by *J. A. Landgrebe*. The strongly exothermal reaction of chloroform with sodium benzoxide in benzyl alcohol under argon and subsequent hydrolysis with aqueous NaOH produces 24.8–44.3% dibenzyl ether *(1)*, 15.4–44.3% benzyl orthoformate *(2)*, benzoic acid *(3)*, phenylacetic acid *(4)*, mandelic acid *(5)*, an unidentified acid, and methylene dichloride.

$$C_6H_5CH_2ONa + CHCl_3 \xrightarrow[2.\ H_3O^{\oplus}]{1.\ OH^{\ominus}} CH_2Cl_2 + (C_6H_5CH_2)_2O + (C_6H_5CH_2O)_3CH + C_6H_5COOH + C_6H_5CH_2COOH - C_6H_5CHOH{\cdot}COOH$$

(1) *(2)* *(3)* *(4)* *(5)*

Following the formation of dichlorocarbene, probably two reactions occur: abstraction of hydride from the alkoxide by the carbene dechlorination of the dichlorocarbene by alkoxide.

$$C_6H_5CH_2O^{\ominus} + :CCl_2 \rightarrow C_6H_5CHO + HCCl_2^{\ominus}$$

$$C_6H_5CH_2O^{\ominus} + :CCl_2 \rightarrow C_6H_5CH_2O\ddot{C}Cl + Cl^{\ominus}$$

(6)

Under the reaction conditions, the benzaldehyde undergoes a Tischenko reaction to give benzyl benzoate, which is recovered as benzoic acid. Sodium α-phenylethoxide reacts with $CHCl_3$ to form CH_2Cl_2, diphenyl ether, acetophenone, hydratropaic acid *(7)*, and atrolactic acid *(8)*. A chloroalkoxycarbene, *e.g. (6)*, is assumed to occur as an intermediate in these reactions. It is probably transformed *via* a short-lived isocarboxonium cation $ROC^{\oplus}$ into the carbonium ion $R^{\oplus}$, which then gives rise to the products isolated.

$C_6H_5CH(CH_3)-COOH$ *(7)* $\qquad$ $C_6H_5COH(CH_3)-COOH$ *(8)*

The formation of acids *(4)* and *(7)* can be explained by an O → C migration of a benzyl or α-phenylethyl group in the ion $ROC^{\oplus}$ or by rearrangement of the carbene $RO\ddot{C}Cl$ to the acyl chloride RCOCl. The formation of acids *(5)* and *(8)* can be explained by the action of a methylene dichloride anion, formed by hydride abstraction, on the carbonyl group of the

$$C_6H_5CHO - {}^{\ominus}CHCl_2 \rightarrow C_6H_5\underset{\underset{O^{\ominus}}{|}}{CH}CHCl_2 \quad (9)$$

benzaldehyde, giving rise to an anion of type *(9)*. / Tetrahedron Letters *1965*, 105 / – Ma. [Rd 199/408 IE]

BOOK REVIEWS

Mechanismen enzymatischer Reaktionen. 14. Kolloquium der Gesellschaft für physiologische Chemie vom 25.–27. April 1963 in Mosbach/Baden. [Mechanisms of Enzymatic Reactions. 14th Colloquium of the German Society for Physiological Chemistry, April 25–27th, 1963 in Mosbach/Baden (Germany)]. Springer-Verlag, Berlin-Göttingen-Heidelberg 1964. 1st Edit., IV + 366 pp., 104 illustrations, paperback DM 54.– (about $ 13.50).

The Gesellschaft für physiologische Chemie courageously ventured the subject "mechanisms of enzymatic reactions" as the main theme for its 14th "Mosbacher Kolloquium". The lectures have now appeared in print and make the results generally available. It is actually only the first group of five contributions which deals directly with this topic. In the other two groups, "Coenzymes" and "Hydrogen Transfer", with the exception of the lecture by *H. Sund* on "Die Struktur und Wirkungsweise NAD-abhängiger Dehydrogenasen" (the structure and mode of action of NAD-dependent dehydrogenases), problems are discussed which are only indirectly connected with enzymes. Not everything that was said at the conference and which has now been printed has the unblemished clarity of the contribution by *V. Prelog*, for example, "Über die Produkt- und Substratspezifizität der enzymatischen Reduktion von Carbonyl-Verbindungen" (on the product and substrate specificity of the enzymatic reduction of carbonyl compounds). Some reports read like verbatim copies of laboratory note-books: experimental data are given in abundance, but the relations among them or their consequences are not made directly apparent. This is admittedly due in part to the difficulties still encountered by any attempt to solve the problem of enzymatic catalysis, a situation which was perhaps best summarized by *Martius* in his remark: "Where the situation is so difficult and unsurveyable, there must be some doubt whether the center of the problem can be reached directly by purely chemical model experiments and considerations, as it were in a parachute jump".

Despite this scepticism, the volume gives a good – albeit incomplete – picture of the present status of this field of research.

H. Grünewald [NB 344/201 IE]

Advances in Heterocyclic Chemistry, Vol. 2. Edited by *A. R. Katritzky* in collaboration with *A. J. Boulton* and *J. M. Lagowsky*. Academic Press, New York - London 1963. 1st edit., XI + 458 pp., numerous tables, linen $ 14.00.

The essays in this second volume of the series can be classified into the following groups:

1. Equilibrium problems: Prototropic tautomerisms of five-membered rings containing one hetero-atom (25 pp.) or containing two or more hetero-atoms (55 pp.) [*A. R. Katritzky* and *J. M. Lagowski*].

2. Reactions of heterocyclic systems: Free-radical substitutions of heteroaromatic compounds (48 pp.) [*R. O. C. Norman* and *G. K. Radda*] and the reaction of diazomethane with heterocyclic compounds (42 pp.) [*R. Gompper*].

3. Reactions of specific heterocyclic systems: The action of metal catalysts on pyridine derivatives (25 pp.) [*G. M. Badger* and *W. H. F. Sasse*] and the acid-catalysed polymerization of pyrroles and indoles (24 pp.) [*G. F. Smith*].

4. New ring systems: Three-membered rings containing two hetero-atoms (48 pp.) [*E. Schmitz*].

5. Progress reports on specific systems: Advances in quinoxaline chemistry (41 pp.) [*G. W. H. Cheeseman*], 1,3-oxazine derivatives (33 pp.) [*Z. Eckstein* and *T. Urbanski*], the present state of selenazole chemistry (21 pp.) [*E. Bulka*], and recent developments in isoxazole chemistry (58 pp.) [*N. K. Kochetkov* and *S. D. Sokolov*].

The contributions all convey the impression of comprehensiveness and good knowledge of the subject matter on the part of the authors. The treatises of groups 1 and 2 are of particular importance since monograph series such as "Elderfield" and "Weissberger", by virtue of their fundamental aims, do not cover such topics. The efforts of *R. Gommper* demonstrate how difficult it is to attempt already an interpretation of the experimental results. The article on tautomerisms (in continuation of those in Vol. 1) lucidly reveals the supremacy of modern physical methods over classical methods and the precariousness of conclusions drawn from chemical findings. In the articles giving progress reports, the reader regrettably misses exact references to the research periods reviewed. Incidentally, it is probably unnecessary to

go too far back into the literature in most cases or to devote too detailed a treatment – as in the chapter on free-radical reactions – to analogies to processes with homocycles. However, references should be given to earlier review articles, *e.g.* 1,3-oxazines are dealt with in Vol. 6 of "Elderfield", even if only on 17 pages.

The organization of the book, the presentation of formulae and illustrations, and the numeration of compounds are clear and intelligible and help to find data rapidly. The volume is earnestly recommended to all working on the chemistry of heterocycles. *J. Goerdeler* [NB 301/160 IE]

Advances in Organometallic Chemistry. Vol. I. Edited by *F. G. A. Stone* and *R. West*. Academic Press, New York-London 1964. 1st Edit., XI + 334 pp., 10 Figs., 44 tables, linen £ 4.4.0 (about $ 11.75).

The exponential rise in the number of publications appearing in the field of organometallic chemistry makes it indispensible to have progress reports for both those with an active and those with only a casual interest in the subject. *F. G. A. Stone* and *R. West* are to be commended for having decided to initiate and edit a series on "Advances in Organometallic Chemistry"; the first volume has now appeared and further volumes will be issued annually.

The topics discussed in this first volume are highly variegated, in keeping with the nature of organometallic chemistry. The titles of the individual contributions are: "Diene Iron Carbonyl Complexes and Related Species" (43 pp., 134 references) [*R. Pettit* and *G. F. Emerson*]; "Reactions of Organotin Hydrides with Organic Compounds" (38 pp., 84 refs.) [*H. G. Kuivila*]; "Organic Substituted Cyclosilanes" (47 pp., 107 refs.) [*H. Gilman* and *G. L. Schwebke*]; "Fluorocarbon Derivatives of Metals" (73 pp., 156 refs.) [*P. M. Treichel* and *F. G. A. Stone*]; "Conjugate Addition of Grignard Reagents to Aromatic Systems" (16 pp., 59 refs.) [*R. C. Fuson*]; and "Infrared and Raman Spectral Studies of π-Complexes formed between Metals and C_nH_n Rings" (75pp., 156 refs.).

The reviews are fluently written and are almost generally critically descriptive. Frequently unpublished results from the authors' own work have been mentioned. The book is essentially free from printing and factual errors. Overlapping or repetitions in the text are rare, *e.g.* on pp. 27–28 and pp. 195–198, and are not disturbing. All in all, the editors have thus succeeded in creating a forum for the discussion of organometallic chemistry which will most certainly enjoy wide resonance. *G. N. Schrauzer* [NB 302/161 IE]

Analytische Anwendungen von Ionenaustauschern (Analytical Applications of Ion Exchangers). By *J. Inczédy*. Published by the Hungarian Academy of Sciences, Budapest 1964. 1st edit., 365 pp., 84 figs., 30 tables, linen DM 33.60 (about $ 8.50).

The title of this book indicates that discussion is restricted to the analytical applications of ion exchangers, but from its preface and table of contents the reader can see that the limits of the treatment are much more extensive. However, his expectations are then only partially fulfilled. The main emphasis in the book is placed upon the analysis of mixtures of inorganic ions (about 170 pp.), whereas "organic analysis" receives much less attention in about 40 pages. Thus, for example, the promising title "Separation of amino acids, peptides, and protein substances" heads merely a description of the separation of mixtures of amino acids; there is no reference to the many separations of peptides which have been carried out for some years, nor is there any mention of the analysis of protein mixtures. Correspondingly, there is also hardly any mention of ion exchangers constructed on a polysaccharide basis in other sections. On the other hand, there are chapters on the properties of synthetic resin-exchangers (16 pp.), the theory of ion exchange (27 pp.), and the use of ion-exchange columns in theory and practice (34 pp.) which go well into theoretical fundamentals but maintain due regard to practical aspects, *e.g.* procedures for testing synthetic resin exchangers (13 pp.). The text is frequently elaborated by lucid illustrations and well-packed tables; for example, one table is 21 pages long and summarizes information on the chromatographic separation of inorganic ions. The number of literature references is also correspondingly high (1200), and the layout of the book is excellent; for this reason and also because of its content of practical procedures which have frequently been checked by the author, the book can be earnestly recommended to analysts in inorganic laboratories. Apart from minor spelling errors – "y" causes the author particular difficulty – the German is quite good. *H. Determann* [NB 286/144 IE]

The Chemistry of Cationic Polymerization. Edited by *P. H. Plesch*. Pergamon Press, Oxford-London-New York-Paris 1963. 1st Edit., XV + 728 pp., numerous illustrs. and tables, linen £ 10.0.0 (about $ 27.75).

By adopting the reaction mechanism approach as a didactic principle, the editor of the present volume manages to correlate the cationically induced polymerizations of a number of rather different monomers. He is ably assisted in this extensive and difficult task by numerous colleagues from Anglo-American research teams, not only from universities and colleges, but also from the chemical industry. The specialized sections which are of recognizable individuality are aptly coordinated by introductory chapters on carbonium ions, on organic reactions related to cationic polymerization, and on comparisons between free-radical, cationic, and anionic polymerization mechanisms. These articles are extremely welcome, for they greatly facilitate comprehension of the frequently complex course of cationic polymerization reactions.

The specialized sections deal with all monomers which undergo cationic polymerization: aliphatic and aromatic mono-olefins (isobutylene and styrene in separate articles), conjugated and non-conjugated diolefins, vinyl ethers, cyclic ethers, aldehydes, ketones, and ketenes, vinyl thiocthers and cyclic thioethers, and cyclic imines. The book is well rounded off by concluding chapters on copolymerization, cationic reactions of polymers, cationic graft polymerization, cationic polymerizations induced by radiation, and experimental techniques.

The treatment given to the various topics is in correspondence with the title of the book, so that the chemistry and theoretical fundamentals of the subject are placed in the forefront. It is the editor's aim to produce a work that will be of interest primarily to pure scientists, and accordingly, the industrial importance, technology, and properties of the polymers are only touched upon. Also the literature reviewed (over 1500 references) is restricted to purely scientific publications. This volume will assuredly fill a gap in the literature on polymer chemistry, for it is full of topics for discussion.

H. Bestian [NB 307/166 IE]

Selected Values of Thermodynamic Properties of Metals and Alloys. By *R. Hultgren, R. L. Orr, P. D. Anderson*, and *K. K. Kelley*. John Wiley & Sons, New York-London 1963. 1st Edit., XI + 963 pp., numerous illustrs. and tables, linen £ 4.14.0 (about $ 13.00).

Knowledge of the thermodynamic properties of constructional materials is essential for numerous tasks encountered during the installation of nuclear reactors, and hence several books containing tables of data from this field have recently appeared, especially ones giving values of such properties at extreme temperatures. The tables in the present volume give the heat capacity C_p, the entropy, enthalpy, and free energy for 63 metallic elements both for low temperatures and for high temperatures up to the boiling points in the condensed phase (solid and liquid) and up to several thousand degrees Kelvin in the gaseous phase. In addition, very extensive data on the vapor pressures are frequently given. Introductory remarks about each element describe the experimental meth-

ods and give critical appraisals of the data. An especially valuable feature of the book is the inclusion of numerous equations for empirical representation of the thermodynamic functions of a given metal as a function of temperature.

The major portion of the book is devoted to binary alloys. Here the results for 168 systems are dealt with, and phase diagrams are included. The reader finds data on the integral and partial molar free energies, entropies, enthalpies, and activities or activity coefficients for individual temperatures; it is then easy to evaluate other thermodynamic quantities from these. Here the introductory comments frequently include data on the crystal structures of special alloy phases. In using this section, the experienced thermodynamist – who will normally skip the general introduction – must note that for liquid alloys, the standard states are generally the liquid elements and not the elements in the equilibrium state valid for the temperature in question; corresponding standards apply for solid alloys.

The literature index is long and rather complete; it covers publications up to about 1961. This and the critical evaluation of the data make the book an unusually helpful advisor for all scientists doing research in the field of thermodynamics at extreme temperatures. *K. Schäfer* [NB 304/163 IE]

Reagents and Reactions for Qualitative Inorganic Analysis. Fifth Report. Published by the International Union of Pure and Applied Chemistry, Analytical Chemistry Division, Commission on Analytical Reactions. Butterworths & Co. Publishers Ltd., London 1964. 1st edit., X + 88 pp., linen £1.12.6 (about $4.25).

This booklet contains a collection of qualitative reactions for the detection of 51 elements and radicals. These are mostly reliable color reactions, but sometimes also precipitation and crystal reactions. The performance of the tests requires only the most primitive facilities (they are mostly spot tests on filter paper and occasionally test-tube experiments). The limits of detection and interfering factors for each test are also given.

The value of the book lies principally in the fact that the reactions are described concisely, clearly, and uniformly, and that they have been checked in three different laboratories. However, some of the reactions included, *e.g.* a test for rhenium in which molybdenum interferes, or a test for vanadium which is also given by iron, will probably be of little use in practice. Nonetheless, since other reactions are also given in such cases, this is not a serious lapse, and the book can be thoroughly recommended.

R. Bock [NB 288/145 IE]

Progress in Inorganic Chemistry, Vol. 5. Edited by *F. A. Cotton.* Interscience Publishers, a Division of John Wiley & Sons, Inc., New York-London 1963. 1st edit., VIII + 564 pp., numerous illustrs. and tables, linen £ 5.5.0 (about $ 14.50).

Progress in inorganic chemistry – characterized both by development of new individual disciplines from solid state physics to organometallic chemistry, and by increasing numbers of research publications – has led to the innovation of the monograph series "Progress in Inorganic Chemistry" and "Advances in Inorganic Chemistry and Radiochemistry" alongside the classical abstract journals. In view of the current thirst for information, the general usefulness of both series is beyond question, but the present volume leaves some desires unfulfilled.

Its four articles deal with fields which lie very far apart: in his article "Dinitogen Trioxide", *I. R. Beattie* restricts his discussion mainly to the physical properties of this one compound; its interesting connections with other oxides of nitrogen is given only little consideration. *L. Mayer* has written a valuable review with 527 (!) references on the "Preparation of Primary, Secondary, and Tertiary Phosphines"; the readily surveyable systematic classification extends right up to the alphabetically arranged list of references.

In his treatise on the "Polarographic Behavior of Coordination Compounds", *A. A. Vlček* gives a well-planned introduction to the methods and scope of this section of electrochemistry. The book closes with a treatise by *A. D. Liehr*, "The Coupling of Vibrational and Electronic Motions in Degenerate and Nondegenerate Electronic States of Inorganic and Organic Molecules, Part III: Nondegenerate Electronic States"; Parts I and II are to be found in Volumes 3 and 4 of the series.

The last point mentioned induces the reviewer to direct a request at the editor: In consideration of the reasonable price of the volumes and above all of the excellent quality of most of the individual contributions, attempts should be made to avoid too great variances in the nature of the articles published together in one volume. Better coordination of the subject matter discussed can only be of benefit to the value of each individual volume.

H. Bock [NB 303/162 IE]

The Cyanine Dyes and Related Compounds. By *Frances M. Hamer.* Vol. 18 on The Chemistry of Heterocyclic Compounds, a Series of Monographs edited by *A. Weissberger.* Interscience Publishers, a Division of John Wiley & Sons, New York-London 1964. 1st edit., XXXVI + 790 pp., a few illustrs., numerous tables, linen £17.0.0 (about $47.00).

It is a long and laborious undertaking to describe over one hundred years of cyanine dyestuff chemistry, and hence the author of this volume deserves high recognition for working through the publications and patents on cyanine dyes since 1856 (the discovery of cyanine by G. Williams) until 1959 with such great care and for assorting the innumerable dyestuffs of this class as far as possible into an orderly system. The essential discoveries of the first 50 years of cyanine chemistry, during which the dyes were still produced mainly by empirical methods since their structures were unknown, have been lucidly reconstructed. The recapitulation of later developments has benefitted greatly from the fact that the author has herself participated in the research and applications of these dyes since the early nineteen-twenties. Thus she has succeeded in writing a book which is the only work of reference of this type available that the expert in this field can consult to find the numerous chemical syntheses and physical properties of even the most complicated dyestuffs.

Apart from describing the classical basic cyanines prepared from common and less usual heterocyclics, the book also includes other classes of polymethine dyes, *e.g.* hemicyanines, styryl dyestuffs, and the azacyanines, a class of dyes which has acquired new importance for coloring synthetics fibers. Long, detailed chapters are also devoted to dequaternized cyanines, the merocyanines, and hemioxonoles (neutrocyanines), and to acidic polymethines (oxonoles) and polynuclear cyanines. The book is also a treasure trove for dyestuff theorists, for example, thanks to its chapters on constitution and color and on spectral sensitization of silver halide emulsions. The fluently readable style of the text and the high quality of the print deserve a special mention. The only improvement to be desired in this volume is the inclusion of a patent index, and it is to be hoped that the author will be able to compile a sequel which is just as comprehensive and carefully edited to cover the developments in this subject since 1959. *O. Riester* [NB 295/153 IE]

Liquid Extraction. By *R. E. Treybal.* McGraw-Hill Series in Chemical Engineering, edited by *M. S. Peters.* McGraw-Hill Book Co. Inc., New York-San Francisco-Toronto-London 1963. 2nd Edit., 621 pp., numerous illustrs., linen, £ 6.8.0 (about $ 18.00).

The title of this book suffices to show the nomenclature difficulties encountered in the field of separations by distribution. The term "liquid extraction" here implies the technique normally called "liquid-liquid extraction" in America, "solvent extraction" in Britain, or "distribution between two

liquid phases" in Germany. Moreover, the content of the book is placed in the proper perspective only when it is considered that it is part of the "Series on Chemical Engineering", for it deals comprehensively and in detail with everything that seems to be of importance from the point of view of the U.S. chemical engineer, but contains little or nothing about the chemical fundamentals of distribution. For example, the chapters on "Prediction of Distribution" and "Choice of Solvent" do not discuss the question which solvents may be particularly suitable for separating a mixture of substances for chemical reasons, but contain graphic and mathematical aids for estimating the separatory effect to be expected for a given system of materials when the equilibrium data are only incompletely known.

The book is the accepted standard work on this topic in the U.S. American literature. The terminology coined therein – not always the best – has found acceptance in mineral oil technology even beyond the U.S.A., so that study of the book is the best introduction to literature on this theme. A few chapters (physico-chemical fundamentals, determination of the separatory effect – mostly *via* graphs or diagrams) are recommendable as an educational text on account of the clarity of the diction; others are hard to read, because for some chapters up to two pages are required solely for the key to the symbols used, because despite this other symbols occur the meaning of which is unclear, and because some definitions are insufficiently precise or even incorrect (*e.g.* the quantity A on p. 244). The book seems therefore rather inconvenient for the purpose of rapidly finding answers to isolated questions.

The new edition is some 50 % larger than the first edition of 1951; recent literature has been evaluated, and a short chapter on laboratory methods has been inserted. New examples from various fields – including inorganic chemistry – have been added, even though the book is presented from the viewpoint of the petroleum engineer (as shown, for example, by the frequently inapt use of the terms "raffinate" and "extract"). However, the problems discussed, including mass transfer and fundemental questions related to apparatus in particular, are presented in such great detail that anyone working on separations by distribution – even inorganic chemists – can read this book with profit.

Werner Fischer [NB 310/169 IE]

Progress in Reaction Kinetics, Vol. 2. Edited by *G. Porter*, in cooperation with *K. R. Jennings* and *B. Stevens*. Pergamon Press, Oxford-London-Edinburgh-New York-Paris-Frankfurt 1964. 1st Edit., VII + 391 pp., numerous illustrs. and tables, linen £ 4.4.0 (about $ 11.60).

Once again *G. Porter* has succeeded in securing prominent specialists to present excellent treatises on some important aspects of kinetics research.

G. C. Fettis and *J. H. Knox* give a review (36 pp., 64 references) on the rate constants of the reactions between halogen atoms on the one hand and molecules of hydrogen, hydrocarbons, and chlorocarbons on the other. The results are also discussed from the point of view of the methods involved. The fact that the reaction of hydrogen iodide is not a prototype of a bimolecular reaction deserves mention even in a book review.

R. J. Cvetanovic gives a comprehensive discourse (86 pp., 147 refs.) on energy transfer *via* excited mercury atoms. His formulation of the electron-deficient transition state involved (p. 127) is interesting.

H. M. Frey deals with the quantitative aspect of carbene chemistry (27 pp., 126 refs.). Insertion and addition reactions of carbene and substituted carbenes are described.

In the "Kinetics of *cis-trans*-isomerizations" of olefinic systems, *R. B. Cundall* deals with a field that has been studied with particular intensity within recent years (44 pp., 181 refs.). The same remark applies to the "Kinetics of Anionic Polymerization and Copolymerization" by *M. Swarc* and *J. Smid* (61 pp., 180 refs.). Both articles are characterized by their complete coverage of important publications on these subjects.

A review on the "Rate Constants of Protolytic Reactions in Aqueous Solution" by *M. Eigen, W. Kruse, G. Maars*, and *L. De Mayer* is necessarily a summary of *Eigen*'s publications. This is preceded by a discussion of the maximum reaction rate in solution. Regarding relaxation methods the reader is referred to specialized publications.

The chapter on "Reaction Rates of Some Haem Compounds" by *Q. H. Gibson* (12 pp., 67 refs.) gives an exemplary review of the status of kinetic investigations on biochemical systems. In conclusion, a non-review article by *R. M. Noyes* describes the formal kinetic treatment of secondary reactions in a general form. He defines and discusses the limits of validity of approximate solutions.

The final "Reaction Index" gives a list of more than 1000 reactions whose rate constants are discussed in the text. The book is an indispensible part of the libraries of chemical and physico-chemical laboratories. Its purchase for private use can be recommended even to individuals who are working in only one of the fields discussed. *H. Sinn* [NB 312/171 IE]

Volatile Silicon Compounds. By *E. A. V. Ebsworth*. Vol. 4 of the International Series of Monographs on Inorganic Chemistry, edited by *H. Taube* and *A. G. Maddock*. Pergamon Press, Oxford-London-New York-Paris 1963. 1st edit., vi + 179 pp., linen £2.2.0 (about $ 5.75).

The chemistry of the elements Si, Ga, and Sn has developed enormously during the last decade, and silicon compounds are in the forefront of this development. Here the author has disregarded silicates, silicones, silicon methylenes, and complicated carbon compounds containing silicon as a hetero atom in favor of simple compounds of silicon with other elements. This selection is particularly fortunate, since there is no comparable recent survey of this type, and since reliable statements about the nature of the bonding involved can best be made here. An introduction is followed by two chapters on the Si–H bond (simple compounds and their reactions). The third chapter deals with silicon halides. The fourth chapter deals with the Si–C and Si–Si group of compounds, the fifth chapter with those of Si and the elements N, P, and As, and the sixth chapter with the compounds of Si and elements of Group VI of the periodic table. Each chapter deals with the preparation of characteristic compounds and their physical and chemical properties, due regard being given to the results of spectroscopic investigations. The seventh chapter summarizes the data on compounds which do not fit well into the simple scheme selected. The literature has been covered up to 1961. A valuable feature of the book is the inclusion of much numerical data, *e.g.* energies of formation and bond lengths.

This book will prove a valuable companion to every chemist interested in this field. *G. Fritz* [NB 290/148 IE]

Zone Electrophoresis in Blocks and Columns. By *H. Bloemendal*. Elsevier Monographs. Elsevier Publishing Co., Amsterdam-London-New York 1963. 1st edit., viii + 219 pp., 75 figs., 13 tables, linen DM 22.50 (about $ 5.65).

Analytical and preparative zone electrophoresis is an inseparable part of protein chemistry nowadays. Separations of mixtures of similar proteins can be achieved on starch gels in an electrical field with an accuracy that is equalled by practically no other physical method. *Bloemendal* is therefore to be congratulated for this description of conventional apparatus for carrying out block, gel, and column electrophoresis (including continuous procedures), together with procedures for applying them in work with biological materials. The author has intentionally disregarded electrophoresis on paper or agar-agar and also electrophoresis without a solid support, since monographs on these topics have already been published, but he has included electrophoresis on columns with concen-

tration gradients, a technique which has recently been gaining more and more importance. The literature has been covered up to and including 1962, and numerous examples are given of separations of mixtures, with critical comparisons of the values of individual procedures. – A more readily surveyable arrangement of the examples according to the source of the materials or according to classes of compounds would have been of help to readers in finding suggestions for solving their own problems. A detailed discussion of methods for locating enzymes in the support after electrophoresis would also have been desirable, for this will undoubtedly become a large field of application in the future.

The whole of this small book is adapted to practical needs, and it is a helpful supplement to methodological manuals for biochemists, biologists, and physicians.

G. Pfleiderer [NB 292/150 IE]

Electrochemistry. Theoretical Principles and Practical Applications. By *G. Milazzo*. Translated from the Italian by *F. J. Mill*. Elsevier Publishing Co., Amsterdam-London-New York 1963. 1st edit., xv + 708 pp. numerous illustrs. and tables, linen DM 61.50 (about $15.50).

The present volume is an English version of a book which originally appeared in Italian in 1947. The new English edition is largely based on the German version which appeared in 1952 and which was thoroughly revised at that time.

A number of valuable additions have been included compared to the German edition, *e.g.* in the chapter on analytical applications and in the sections on electrochemistry in non-aqueous solutions and fused salts. However, by and large the text has been translated without much alteration. The apparent increase in the size of the book (708 pages in the English edition compared to 419 pages in the German edition) is mainly due to the smaller size of the pages in the English impression.

Therefore the book offers very little new material to the German reader. A radical revision including latest results has not been carried out. But the main disappointment here is that one of the major weaknesses of the earlier editions in the reviewer's opinion, namely the very unsystematic presentation of references to journal publications, has not been improved. In a book where many topics necessarily are summarized, it would be desirable that references to more detailed literature are included to a much larger extent.

A prominent feature of this book is its excellent survey of the technical applications of electrochemistry. The print and layout deserve special acknowledgement.

H. Gerischer [NB 287/146 IE]

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Color and Constitution of Azo Compounds

BY PRIV.-DOZ. DR. H. BOCK [1,2]

INSTITUT FÜR ANORGANISCHE CHEMIE DER UNIVERSITÄT MÜNCHEN (GERMANY)

BASED ON INVESTIGATIONS CARRIED OUT IN COLLABORATION WITH DR. G. RUDOLPH, DR. E. BALTIN, AND DIPL.-CHEM. J. KRONER

Attempts to explain the surprising violet color of the new azobisphosphonic acid derivatives $Y_2OP{-}N{=}N{-}POY_2$ have led to the preparation and spectroscopic characterization of more than 60 azo compounds. The long-wavelength $n \rightarrow \pi^*$ transitions on which the color depends exhibit regularities which justify the assumption of substituent-specific absorption increments. The complex relation between color and constitution of azo compounds can be qualitatively explained with the aid of orbital models. Infrared and ultraviolet spectral data show that conjugation is inhibited by tetra-coordinated phosphorus(V). The π-system of these compounds therefore comprises only four atoms, P–N–N–P. The unexpected violet color of the phosphorus azo compounds can be ascribed to a π^*/d orbital interaction. The substituent effects described have general significance, and $n \rightarrow \pi^*$ transitions of other chromophores are similarly affected.

A. Inorganic Azo Compounds
B. Preparation of Compounds
1. Azobisphosphonic Acid Derivatives
2. Substances for Spectroscopic Comparison
a) Phenylazophosphonic Acid Derivatives
b) Azodicarboxylic Acid Derivatives
c) Phenylazocarboxylic Acid Derivatives
d) Phenylazosulfonic Acid Derivatives
e) Other Phenylazo Derivatives
C. Spectroscopic Investigations
1. Absorption of Light by the Azo System
2. Electronic Spectra of the Azo Compounds
a) Azobisphosphonic Acid Derivatives
b) Phenylazophosphonic Acid Derivatives
c) Azodicarboxylic Acid Derivatives
d) Phenylazocarboxylic Acid Derivatives
e) Phenylazosulfonic Acid Derivatives
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g) Solvatochromic Effects
3. Discussion of the Electronic Spectra of the Azo Compounds
D. Model Considerations
1. Inductive Substituent Effects on the n Level
2. $n \rightarrow \pi^*$ and $\pi \rightarrow \pi^*$ Transitions in the LCAO-MO Scheme
a) Effects of Substituents on the π and π^* Levels
b) Calculation of the Electronic Transitions of Organic Azo Compounds
3. Participation of d-Orbitals in the $n \rightarrow \pi^*$ Transition in Phosphorus Azo Compounds
a) Arguments for the Hindrance of Conjugation by Tetracoordinated Phosphorus (V)
b) Discussion of a π^*/d Orbital Interaction
4. Summary: Color and Constitution of Azo Compounds
E. Outlook: $n \rightarrow \pi^*$ Transitions as Molecular Probes

A. Inorganic Azo Compounds

The first azo compound was prepared in 1834 by *Mitscherlich* [3], who obtained azobenzene by adding an alcoholic solution of nitrobenzene to one of potassium ethoxide. In 1858 *Griess* [4] discovered the diazonium salts, and this discovery initiated the rapid development of azo dyes, in which the N=N double bond is stabilized by aromatic nuclei. Less interest was subsequently

[1] *H. Bock*, Habilitation Thesis, Universität München, 1964, Extracts delivered as lectures in München (May 24th, 1961), Schloss Elmau (April 22nd, 1964), Freihurg (April 30th, 1964), Ludwigshafen (May 20th, 1964), Heidelberg (May 22nd, 1964), Göttingen (May 25th, 1964), and Zürich (November 16th, 1964).

[2] 14th Communication on Investigations on Nitrogen Compounds. – 13th Communication: H. Bock and K.-L. Kompa, Z. anorg. allg. Chem. *332*, 238 (1964).

[3] *E. Mitscherlich*, Annal. Pharm. (Liebigs Ann. Chem.) *12*, 311 (1834).

[4] *P. Griess*, Liebigs Ann. Chem. *106*, 123 (1858).

aroused by the less stable azoalkanes R–N=N–R, the azodicarboxylic acid derivatives YOC–N=N–COY, and the tetrazenes R_2N–N=N–NR_2. Finally, four azo compounds *(1)*, *(2)*, *(3)*, and *(4)* with inorganic substituents have been independently reported.

HO–N=N–OH KO_3S–N=N–SO_3K

(1) *(2)*

F–N=N–F H–N=N–H

(3) *(4)*

The colorless, explosive hyponitrous acid *(1)* is formed by the oxidation of hydroxylamine or by the reduction of nitrous acid [5]; its structure has been proved spectroscopically [6, 7]. The yellow dipotassium azobissulfonate *(2)*, unstable above 0 °C, is obtained by oxidation of hydrazine-1,2-bissulfonate [8] or amidosulfonic acid [9]. The colorless, stable difluorodiazine *(3)* is formed during thermal decomposition of fluoroazide [10, 11], electrolysis of ammonium fluoride [12, 13], or syntheses of N_2F_4 [14]. The yellow diimide *(4)*, which is stable at low temperatures only, has been detected after electrical discharges in atmospheres of hydrazine or hydrazoic acid [15].

The thermal stability of the azo compounds YX–N=N–XY is governed by the strength of the bond between the ligand XY and the azo nitrogen, since the bond energy of the molecular nitrogen formed on decomposition is 126 kcal/mole greater than that of the N=N double bond. The decomposition temperature is raised by conjugation involving an extensive π-electron system, or by a -I effect of electronegative substituents. For example, azobenzene boils at 297 °C without decomposition, and difluorodiazine survives the drastic conditions of N_2F_4 syntheses. Considerations of the similarity of the bond energies of P–N and C–N bonds [16], and a stabilizing π/d-conjugation between the N=N group and adjacent phosphorus atoms [17], led us to the synthesis of another class of inorganic azo compounds, namely the azobisphosphonic acid derivatives *(5)* [18, 19, 20].

Y_2OP–N=N–POY_2 (Y=OC_6H_5, OC_6H_5/OK, OK, C_6H_5, NR_2)

(5)

[5] Gmelins Handbuch der anorganischen Chemie, System Nr. 4 (Stickstoff). Verlag Chemie, Berlin 1936, pp. 877–883.

[6] *G. Kortüm* and *B. Finckh*, Z. physik. Chem. B *48*, 32 (1941).

[7] *L. Kuhn* and *E. R. Lippincott*, J. Amer. chem. Soc. *78*, 1820 (1956).

[8] *E. Konrad* and *L. Pellens*, Ber. dtsch. chem. Ges. *59*, 135 (1926).

[9] *A. Krettler* and *W. Teske*, Angew. Chem. *71*, 69 (1959).

[10] *J. F. Haller*, Ph. D. Thesis, Cornell University, Ithaca, N.Y. (U.S.A.), 1942; Gmelins Handbuch der anorganischen Chemie, System Nr. 5 (Fluor), Erg. Bd. Verlag Chemie Weinheim 1959, p. 246.

[11] *H. W. Roesky*, *O. Glemser*, and *D. Bormann*, Angew. Chem. *76*, 713 (1964), Angew. Chem. internat. Edit. *3*, 701 (1964).

[12] *M. Schmeisser* and *P. Sartori*, Angew. Chem. *71*, 523 (1959).

[13] *C. B. Colburn*, *F. A. Johnson*, *A. Kennedy*, *K. McCallum*, *L. C. Metzger*, and *C. O. Parker*, J. Amer. chem. Soc. *81*, 6397 (1959).

[14] *C. J. Hoffmann* and *R. G. Neville*, Chem. Reviews *62*, 5 (1962).

[15] *S. N. Foner* and *R. L. Hudson*, J. chem. Physics *28*, 719 (1958). Cf. also *E. J. Blau* and *B. F. Hochheimer*, J. chem. Physics *41*, 1174 (1964).

B. Preparation of Compounds

1. Azobisphosphonic Acid Derivatives

The hydrazine derivatives *(7)* required as starting materials were unknown, with the exception of the tetraphenyl ester (Y = OC_6H_5) [21]. It was first necessary to find a simple method of obtaining anhydrous hydrazine [22], in order to be able to carry out the hydrazinolysis of the readily hydrolysed phosphoric acid chlorides. The hydrazinolysis proceeds *via* intermediates *(6)* which can be isolated, and ultimately leads to the 1,2-bisphosphinylhydrazines *(7)*.

$$Y_2OPCl \xrightarrow[-HCl]{+N_2H_4} Y_2OP\text{-}NH\text{-}NH_2 \quad (6)$$

$$\xrightarrow[-HCl]{+Y_2OPCl} Y_2OP\text{-}NH\text{-}NH\text{-}POY_2 \quad (7)$$

Y = OC_6H_5, R

Finally, there was no known method for the oxidation of the readily solvolysed compounds *(7)*. *N*-Bromosuccinimide was found to be suitable for the selective oxidation of hydrazines in inert solvents [23], the formally (+1)-valent bromine being reduced to the element or, in the presence of pyridine, to hydrogen bromide.

The *N*-bromosuccinimide method permitted the preparation of the azobisphosphonic acid derivatives *(5)* with Y = OC_6H_5, C_6H_5, and $N(CH_3)_2$, the thio compound *(8)*, and the unsymmetrically substituted diphenylphosphinylbenzoyldiazene *(9)* [*]. The potassium azobisphosphonates *(14)* and *(13)* were obtained by hydro-

$(C_6H_5)_2SP$–N=N–$PS(C_6H_5)_2$ $(C_6H_5)_2OP$–N=N–CO–C_6H_5

(8) *(9)*

lysis of tetraphenyl hydrazine-1,2-bisphosphonate *(10)* *via* compounds *(11)* and *(12)* [18].

[16] *P. A. Fowell* and *C. T. Mortimer* [J. chem. Soc. (London) *1959*, 2913] obtained a value of 66.8 kcal/mole for the energy of the P–N single bond in $P(NR_2)_3$, compared with the value of 72.8 kcal/mole for the mean C–N bond energy.

[17] *D. P. Craig*, *A. Maccoll*, *R. S. Nyholm*, *L. E. Orgel* and *L. E. Sutton*, J. chem. Soc. (London) *1954*, 332.

[18] *H. Bock* and *G. Rudolph*, Chem. Ber. *94*, 1457 (1961).

[19] *G. Rudolph*, Doctorate Dissertation, Universität München, 1963; *H. Bock* and *G. Rudolph*, Chem. Ber., in the press.

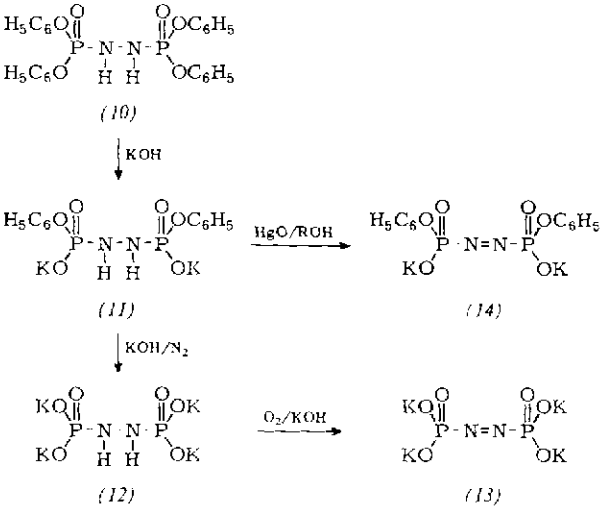
[20] For examples, see the Doctorate Dissertation of *E. Kinzel*, Universität München, 1964; *H. Bock* and *E. Kinzel*, Chem. Ber., in the press.

[21] *L. F. Audrieth*, *R. Gher*, Jr., and *W. C. Smith*, J. org. Chemistry *20*, 1288 (1955); *R. Klement* and *K. O. Knollmüller*, Chem. Ber. *93*, 834 (1960). The yield can be increased from 25% or 18% to 60% [*H. Bock* and *G. Rudolph*, Chem. Ber. *94*, 1461 (1961)].

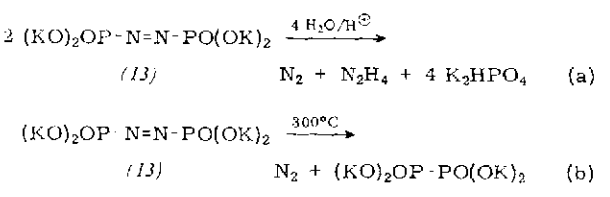
[22] *H. Bock* and *G. Rudolph*, Z. anorg. allg. Chem. *311*, 117 (1961). A critical survey of the methods of obtaining anhydrous hydrazine is given by *H. Bock*, Z. anorg. allg. Chem. *293*, 264 (1958).

[23] *H. Bock*, *E. Baltin*, and *G. Rudolph*, Chem. Ber., in the press.

[*] In accordance with *McBride* and *Bens* [J. Amer. chem. Soc. *81*, 5546 (1959)], it is suggested that the azo compounds be named "diazenes" [18], in agreement with the systematic nomenclature for nitrogen hydrides; this suggestion will be followed in the present paper where there is no simple trivial name.



The azobisphosphonic acid derivatives differ in their stabilities according to the substituents present, and show their "azo character" by intermolecular hydrolytic (a) and intramolecular thermal (b) decompositions [18, 20].



Tetrapotassium azobisphosphonate *(13)* loses nitrogen quantitatively only above 300 °C, whereas dipotassium azobissulfonate *(2)* does so already at 0 °C [8].

However, the preparative and spectroscopic investigations described in the present paper started from a much more fascinating phenomenon, namely the violet color of the azobisphosphonic acid derivatives.

2. Substances for Spectroscopic Comparison

The unexpectedly high wavelength of absorption of the small π-electron system of the azobisphosphonic acid derivatives is described in the LCAO–MO scheme by a considerable bathochromic shift of the weak $n \rightarrow \pi^*$ band in the visible region of the spectrum (cf. Section C.1). Whereas investigations into the cause of the violet color were baulked by the largely unknown effects of inorganic substituents with unoccupied d-orbitals, literature searches showed that the $n \rightarrow \pi^*$ band of the azo compounds YX–N=N–XY undergoes an increasing bathochromic shift with decreasing electronegativity of the substituents XY (Table 1). In order to find regularities, it was first necessary to obtain spectroscopic data for comparison.

Owing to the work involved in the synthesis of new azo compounds and because of their unknown thermal stability, attention was focussed on known classes of compounds. The empirical rule that, in azo compounds having a phenyl substituent on only one of the nitrogens,

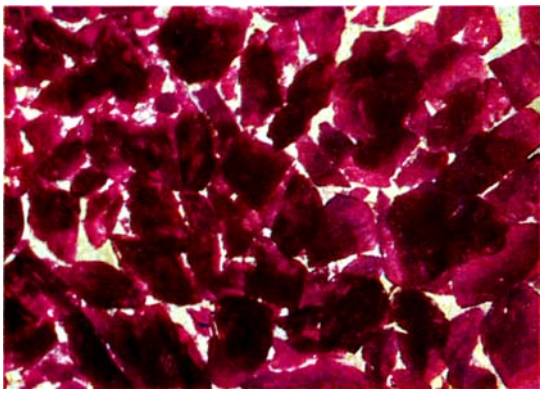
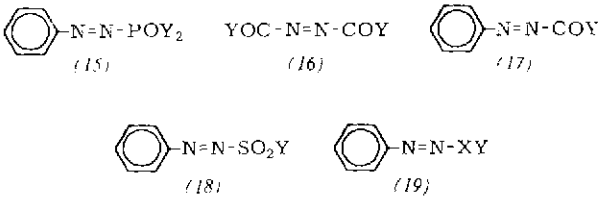


Fig. 1. Crystals of tetraphenyl azobisphosphonate in transmitted light (magnification ca. 4×).

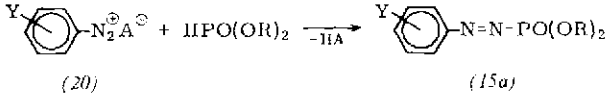
the substituent-nitrogen bond is stabilized by becoming part of the conjugated system, was found useful in this work. We prepared more than 60 known and unknown derivatives of phenylazophosphonic acid *(15)*, azodicarboxylic acid *(16)*, phenylazocarboxylic acid *(17)*, and phenylazosulfonic acid *(18)*, as well as other phenylazo compounds *(19)* [24–26].



The *N*-bromosuccinimide method developed for the oxidation of the 1,2-bisphosphinylhydrazines usually led to good yields of pure azo compounds.

a) Phenylazophosphonic Acid Derivatives

Phenylazophosphonic acid derivatives *(15)*, which were first prepared in 1958 by *Suckfüll* and *Haubrich* [27] from *p*-substituted phenyldiazonium salts *(20)* and dimethyl phosphonate, have a reasonable thermal stability.



The principle underlying this reaction, *i.e. Fischer*'s [28] synthesis of diazosulfonates, was adapted to non-aqueous solvents by using phenyldiazonium tetrafluoroborate [25]. Higher yields of phenylazophosphonic acid derivatives *(15b)* were always obtained, however, by synthesis *via* the hydrazines *(21)*, although some Lewis bases of the type $HPOY_2$ were not easily accessible.

[24] Cf. the summaries of unpublished work: *H. Bock*, *E. Baltin*, and *G. Rudolph*, Angew. Chem. *75*, 789 (1963); Angew. Chem. internat. Edit. *2*, 484 (1963); *H. Bock*, *E. Baltin*, *J. Kroner*, and *G. Rudolph*, Angew. Chem. *76*, 575 (1964), Angew. Chem. internat. Edit. *3*, 645 (1964); *H. Bock*, Lecture, Schloss Elmau, (April 22nd, 1964).

[25] *E. Baltin*, Doctorate Dissertation, Universität München, 1963; *H. Bock* and *E. Baltin*, Chem. Ber., Liebigs Ann. Chem., and Z. anorg. allg. Chem., in the press.

[26] *J. Kroner*, Diploma Thesis, Universität München, 1963. *H. Bock* and *J. Kroner*, Chem. Ber., in the press.

[27] *F. Suckfüll* and *H. Haubrich*, Angew. Chem. *70*, 238 (1958).

[28] *E. Fischer*, Liebigs Ann. Chem. *190*, 67 (1878).

$$H_5C_6\text{-}NH\text{-}NH_2 + ClPOY_2 \xrightarrow[-HCl]{} H_5C_6\text{-}NH\text{-}NH\text{-}POY_2 \quad (21)$$

$$\xrightarrow[-H_2]{} H_5C_6\text{-}N{=}N\text{-}POY_2 \quad (15b)$$

The 1-phenyl-2-phosphinylhydrazines *(21)* and phenylazophosphonic acid derivatives *(15b)*, with the exception of the dimethyl ester, were previously unknown, as were the thio and tosylimido compounds *(22)* and *(23)*.

$H_5C_6\text{–}N{=}N\text{–}PS(C_6H_5)_2$ *(22)* $\quad H_5C_6\text{–}N{=}N\text{–}P(C_6H_5)_2{=}N\text{–}Ts$ *(23)*

In the course of investigations on the relationship between *Hammett*'s σ-values and the $n \rightarrow \pi^*$ frequencies, other substituted dimethyl phenylazophosphonates *(15a)* were prepared with *p*-Y = NO_2, NNC_6H_5, CN, COOR, Cl, R, OR, NR_2, and *m*-Y = NO_2, CN, CF_3, COOR, Cl, OR, R [29].

b) Azodicarboxylic Acid Derivatives

The symmetrically substituted azodicarboxylic acid derivatives *(16)* desired for the spectroscopic investigations were all known, with the exception of the phenyl ester (Y = OC_6H_5) and the dimethylamide [Y = $N(CH_3)_2$] [30–33]. They were synthesized in the usual manner, *via* the hydrazines *(24)* and *(25)*.

$$YOCCl \xrightarrow[-HCl]{+N_2H_4} YOC\text{-}NH\text{-}NH_2 \quad (24) \xrightarrow[-HCl]{+YOCCl}$$

$$YOC\text{-}NH\text{-}NH\text{-}COY \quad (25) \xrightarrow[-H_2]{} YOC\text{-}N{=}N\text{-}COY \quad (16)$$

The following oxidizing agents were used: *N*-bromosuccinimide for dibenzoyldiazene (Y = C_6H_5), di-*p*-chlorobenzoyldiazene (Y = C_6H_4Cl), and diphenyl azodicarboxylate (Y = OC_6H_5) [26]; bromine for diacetyldiazene (Y = R) [30]; potassium dichromate for azodicarboxamide (Y = NH_2) [31]; and nitric acid for the dialkyl azodicarboxylates (Y = OR) [32]. Reaction of the esters with dialkylamines led to high yields of the azodicarboxylic dialkylamides (Y = NR_2) [26, 33].

The substitution of the carboxylic hydrazides *(24)* with other carbonyl chlorides, followed by oxidation of the hydrazine *(25)* with *N*-bromosuccinimide, led to unsymmetrically substituted azodicarboxylic acid derivatives ($Y^1 \neq Y^2$) [26].

$H_5C_6\text{–}CO\text{–}N{=}N\text{–}CO\text{–}C_6H_4Cl$ *(26)* $\quad H_5C_6\text{–}CO\text{–}N{=}N\text{–}CO\text{–}OR$ *(27)*

$RO\text{–}CO\text{–}N{=}N\text{–}CO\text{–}N(C_2H_5)_2$ *(28)*

Compound *(26)* is important for the calculation of the dipole moments of azo compounds [34], *(27)* for the proof of substituent-specific increments in the $n \rightarrow \pi^*$ absorption (Section C.3), and the phenyl-free derivative *(28)* for the assignment of the N=N vibration frequency in the infrared spectrum [26].

c) Phenylazocarboxylic Acid Derivatives

The first phenylazocarboxylic acid derivatives *(17)* (Y = C_6H_5, NH_2) were described by *E. Fischer* [28] in 1878; subsequently, the ethyl ester (Y = OC_2H_5) and the potassium salt (Y = OK) were found [35, 36]. A number of substituted phenylazocarboxamides (Y = NH_2) have recently been characterized by their electronic spectra [37]. This class of compounds also has not yet been systematically studied.

N-Bromosuccinimide was found to be an excellent oxidizing agent for the phenylhydrazine derivatives *(29)* also [25].

$$H_5C_6\text{-}NH\text{-}NH_2 + ClCOY \xrightarrow[-HCl]{} H_5C_6\text{-}NH\text{-}NH\text{-}COY \quad (29)$$

$$\xrightarrow[-H_2]{} H_5C_6\text{-}N{=}N\text{-}COY \quad (17)$$

(Y = C_6H_5, C_6H_4Cl, R, NR_2, OC_6H_5, OR)

The dimethylamide *(30)* (R = CH_3), however, is preferably prepared by aminolysis, and the potassium salt *(32)* (Y=OK) by hydrolysis of methyl phenylazocarboxylate [25].

$$H_5C_6\text{-}N{=}N\text{-}CO\text{-}NR_2 \quad (30) \xrightarrow{+H_2} H_5C_6\text{-}NH\text{-}NH\text{-}CO\text{-}NR_2 \quad (31)$$

$$+HNR_2 \uparrow \; -ROH$$

$$H_5C_6\text{-}N{=}N\text{-}CO\text{-}OR$$

$$-ROH \downarrow \; +KOH$$

$$H_5C_6\text{-}N{=}N\text{-}CO\text{-}OK \quad (32) \xrightarrow{+H_2} H_5C_6\text{-}NH\text{-}NH\text{-}CO\text{-}OK \quad (33)$$

Reduction of these compounds gives excellent yields of the hydrazines *(31)* and *(33)* [25].

d) Phenylazosulfonic Acid Derivatives

As expected, the thermal stability of the phenylazosulfonic acid derivatives *(18)* is considerably greater than that of similarly substituted azobissulfonic acid derivatives *(34)*.

$H_5C_6\text{–}N{=}N\text{–}SO_2Y$ *(18)* $\quad YO_2S\text{–}N{=}N\text{–}SO_2Y$ *(34)*

Thus dipotassium azohissulfonate *(2)*, or *(34)* with Y = OK, rapidly and quantitatively loses N_2 above 0 °C [25], whereas potassium phenylazosulfonate, *(18)* with Y = OK, loses nitrogen only above 215 °C. Phenylazophenyl sulfone, *(18)* with Y = C_6H_5, melts at 76 °C without decomposition [38], whilst 1,2-ditosylhydrazine lost nitrogen even at −50 °C during oxidation experiments [19].

We prepared known phenylazosulfonic acid derivatives *(18)* *via* diazosulfonates [28] or by oxidation of the hydrazines with *N*-bromosuccinimide (Y = C_6H_5, R) [38, 39]. The preparation of new phenylazosulfonic acid derivatives failed in most cases because suitable starting compounds were not obtainable; for example, phenylhydrazine reacts with dimethylaminosulfonyl chloride or methoxysulfonyl chloride

[29] *H. Bock* and *J. Kroner*, unpublished work.

[30] *H. H. Inhoffen*, *H. Pommer*, and *F. Bohlmann*, Chem. Ber. *81*, 507 (1948).

[31] *J. Thiele*, Liebigs Ann. Chem. *271*, 127 (1892).

[32] *T. Curtius* and *K. Heidenreich*, Ber. dtsch. chem. Ges. *27*, 773 (1894).

[33] *O. Diels* and *P. Fritzsche*, Ber. dtsch. chem. Ges. *44*, 3020 (1911).

[34] *H. Bock*, *H. tom Dieck*, *E. Kinzel*, and *J. Kroner*, unpublished work.

[35] *G. H. Heller*, Liebigs Ann. Chem. *263*, 278 (1891).

[36] *J. Thiele*, Ber. dtsch. chem. Ges. *28*, 2600 (1895).

[37] *R. Andrisano*, *A. Bellotti*, and *T. Vitali*, Ricerca sci. *30*, 2142 (1961); Chem. Abstr. *55*, 19474 (1961).

[38] *W. Königs*, Ber. dtsch. chem. Ges. *10*, 1531 (1877).

[39] *P. K. Dutt*, J. chem. Soc. (London) *125*, 1463 (1924).

YO_2SCl (Y = NR_2, OCH_3) in an inert solvent with liberation of sulfur dioxide. Methyl phenylazosulfonate *(36)* was finally obtained in almost 100 % yield as an unstable red oil *via* silver phenylazosulfonate *(35)* [25].

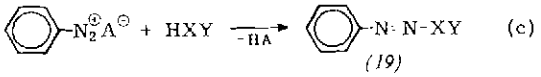
$$H_5C_6\text{-}N{=}N\text{-}SO_2\text{-}OK \xrightarrow[-KNO_3]{+AgNO_3} H_5C_6\text{-}N{=}N\text{-}SO_2\text{-}OAg \quad (35)$$

$$\xrightarrow[-AgI]{+CH_3I} H_5C_6\text{-}N{=}N\text{-}SO_2\text{-}OCH_3 \quad (36)$$

e) Other Phenylazo Compounds

The position of the $n \rightarrow \pi^*$ absorption maximum for azo compounds YX–N=N–XY is much more strongly influenced by the substituent X (adjacent to the azo group) than by Y (cf. Section C.1). Therefore phenylazo compounds *(19)* containing various substituents X (= B, C, N, O, Si, P, S, As, Se) were of great interest for spectrascopic investigations.

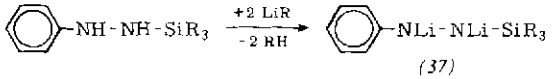
A number of phenylazo compounds *(19)*, XY = NR_2, S-C_6H_5, were obtained by diazo coupling [40,41]:



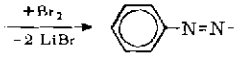
(c)

(19)

The interesting blue 1-phenyl-2-trialkylsilyldiazenes *(38)* are formed on oxidation of the dilithium hydrazide *(37)* with bromine [42]. The *p*-nitrophenylazo derivative *(39)* was obtained by methylation of silver *p*-nitrophenyldiazotate [43].

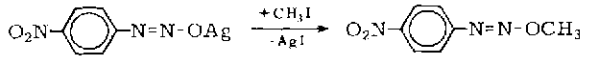


(37)



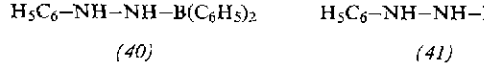
(38)

The unsubstituted 1-methoxy-2-phenyldiazene *(19)*, with XY = OCH_3, is explosive [44].



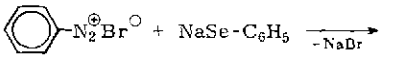
(39)

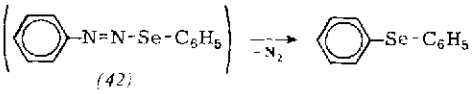
The phenylazo compounds mentioned above appear to exhaust the preparative possibilities: thus all attempts so far to oxidize new phenylhydrazine derivatives, such as *(40)* and *(41)*, containing boron or trivalent phosphorus led to brownish-black decomposition products [25,45].



(40) *(41)*

Similarly, 1-phenyl-2-selenophenyldiazene *(42)* could not be obtained by diazo coupling with sodium selenophenoxide, even at −5 °C; the reaction product was found to be diphenyl selenide [25].





(42)

C. Spectroscopic Investigations

1. Absorption of Light by the Azo System

The weak absorption of azo compounds YX–N=N–XY in the visible is described in the LCAO–MO scheme by the excitation of a non-bonding (n) electron of the azo nitrogen into the lowest antibonding (π^*) orbital of the molecule (Fig. 1) [46–50]. Contrary to the assumption of *Burawoy* [51], who distinguished between $\pi \rightarrow \pi^*$ transitions or K bands (K = conjugation) and $n \rightarrow \pi^*$ transitions or R bands (R = radical), the latter are in most cases singlet-singlet excitations with retention of the electron spin [52].

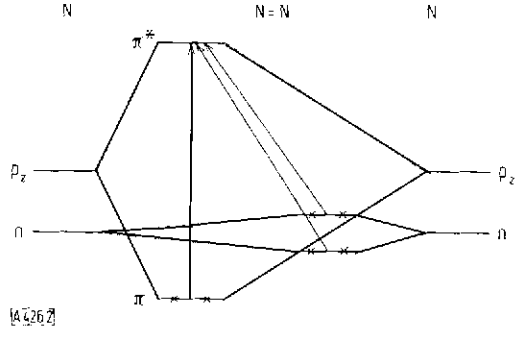


Fig. 2. Energy-level diagram for the azo group [49].

The low $n \rightarrow \pi^*$ intensity (molar extinction coefficients ε_m up to 10^3 l/mole/cm and oscillator strengths f up to 10^{-2}) follows from general selection rules: in planar *trans*-azo compounds with C_{2h} symmetry [46], the $n_s \rightarrow \pi^*$ ($^1B_g \leftarrow {}^1A_g$) transition is forbidden and the $\pi \rightarrow \pi^*$ ($^1B_u \leftarrow A_g$) transition is allowed. The assignment of the allowed $n_a \rightarrow \pi^*$ ($^1A_u \leftarrow {}^1A_g$) transition is uncertain [53]; the interaction of the *trans*-n orbitals probably remains small [49].

According to *Kasha* [52], $n \rightarrow \pi^*$ and $\pi \rightarrow \pi^*$ transitions can be differentiated with the aid of solvatochromic effects, which were first discovered by *Scheibe* [54] and

[40] *F. Heusler*, Liebigs Ann. Chem. *260*, 249 (1890).

[41] *A. Hantzsch* and *H. Freese*, Ber. dtsch. chem. Ges. *28*, 3241 (1895).

[42] *U. Wannagat* and *C. Krüger*, Z. anorg. allg. Chem. *326*, 288, 296, 304 (1964).

[43] *E. Bamberger*, Ber. dtsch. chem. Ges. *28*, 227 (1895).

[44] *H. v. Pechmann* and *L. Frobenius*, Ber. dtsch. chem. Ges. *27*, 672 (1894).

[45] The boron compounds were studied in collaboration with *H. Nöth* and *F. Regnet*, Universität München.

[46] *J. W. Sidman*, Chem. Reviews *58*, 689 (1958).

[47] *H. A. Staab*: Einführung in die Theoretische Organische Chemie, Verlag Chemie, Weinheim 1960.

[48] *S. F. Mason*, Quart. Rev. (chem. Soc., London) *15*, 287 (1961).

[49] *H. H. Jaffé* and *M. Orchin*: Theory and Applications of Ultraviolet Spectroscopy. Wiley, New York 1962; *cf.* however *G. Kortüm* and *H. Rau*, Ber. Bunsenges. physikal. Chem. *68*, 973 (1964).

[50] *J. N. Murrell*: The Theory of the Electronic Spectra of Organic Molecules. Methuen, London 1963.

[51] *A. Burawoy*, J. chem. Soc. (London) *1939*, 1177.

[52] *M. Kasha*, Discuss. Faraday Soc. *9*, 14 (1950).

[53] *M. B. Robin* and *W. T. Simpson*, J. chem. Physics *36*, 580 (1962).

[54] *G. Scheibe*, Ber. dtsch. chem. Ges. *59*, 2619 (1926).

later investigated by *Burawoy* [51]: as the polarity of the solvent is increased, n → π* bands in general undergo hypsochromic shifts (negative solvatochromism), and π → π* bands bathochromic shifts (positive solvatochromism). These phenomena may be due to hydrogen bonding and dipole-dipole interactions [46–50]. Measurements of solvatochromism of the azo compounds prepared are reported in Section C.2.g.

The configuration of the excited state in azo compounds is unknown, since the N=N group masks any vibrational fine structure, even in the vapor state [46]. The electronic spectra of N=N systems (except azobenzene and its derivatives) have so far attracted little interest, although *Hantzsch* and *Lifschitz* [55] discovered as early as 1911 that the spectra of azo compounds are greatly influenced by the subsituents present. In 1941, *Kortüm* verified the n → π* assignment of the long-wavelength azo band by protonating the azo nitrogens [56]. *Birnbaum*, *Linford*, and *Style* measured substituent effects in *p*-substituted *cis*- and *trans*-azobenzenes [57]. The LCAO–MO approximation has been applied not only to azobenzene [58,59], but also to diisopropyldiazene [53]. *Robin* and *Simpson* [53] also discussed possible assignments of the three absorption bands present in the spectrum. *Gerson* and *Heilbronner* investigated the electronic spectra of phenylazoazulenes, but the weak long-wavelength bands of these compounds are due to the azulene skeleton [60]. The direction of the n → π* transition moment in azobenzene was determined by *Hochstrasser* and *Lower* [61], who attribute the residual intensity of the symmetry-forbidden n → π* transition to antisymmetric molecular vibrations of the class a_u.

Comparison of the weak absorption maxima in the visible region of azo compounds YX–N=N–XY shows a decrease in the n → π* frequency with decreasing electronegativity of X. Note the appreciable variation in excitation energies ($\Delta E \approx 65$ kcal/mole) over the range of substituents listed in Table 1. Variations in the long-wavelength absorption as a result of changes in Y, on the other hand, lie within the limits shown.

Table 1. Color, long-wavelength absorption maxima, and absorption intensities for azo compounds YX–N=N–XY.

XY	F [10–14]	OY [6]	NY_2 [26,56]	CY_3 [53,56,62]
Color	colorless	colorless	colorless	yellowish
ν_m [cm^{-1}]	(45000) [a]	(40000) [a]	(36000) [a]	27600–29000
log ε_m	–	(3.6)	(3.9)	1.2–1.6

XY	SO_2Y [8,9]	COY [26,56]	C_6H_4Y [57]	POY_2 [18,19]
Color	deep yellow	orange	orange-red	violet
ν_m [cm^{-1}]	–	21300–25000	21100–23000	17600–18800
log ε_m	–	1.4–1.7	2.7–2.9	1.0–1.4

[a] Assignment uncertain.

2. Electronic Spectra of the Azo Compounds

a) Azobisphosphonic Acid Derivatives

The electronic spectra of the azobisphosphonic acid derivatives (Fig. 3 and Table 2) each contain one isolated band. The weak n → π* transitions, which determine the color, are of interest owing to their unusually low frequency. Changes in substituents Y cause displacements only within the narrow range of 17600 to 18800 cm^{-1}, and have little effect on the intensities (oscillator strengths $f = 1.8\times10^{-4}$ to 3.5×10^{-4}). The n → π* maximum of an unsymmetrically substituted azo compound in this series always lies between the maxima of the two symmetrically substituted compounds [for example, compare *(5d)* with *(5c)* and *(5e)*, or *(5g)* with *(5a)* and dibenzoyldiazene *(16a)* (Table 4)]. The n → π* bands of all phosphorus azo compounds are steeper on the long-wave length side; with the aid of the *Franck-Condon* principle it is possible to explain this asymmetry by conjugational effects (Section C.3).

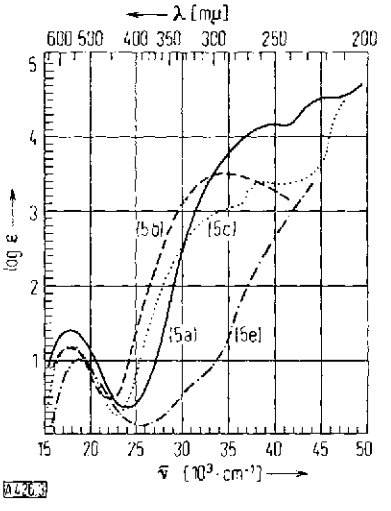


Fig. 3. Electronic spectra of some azobisphosphonic acid derivatives $Y_2OP–N=N–POY_2$ (cf. Table 2).

The absorption of the azobisphosphonic acid derivatives increases in the ultraviolet region, with no distinct maximum; care is therefore required in making assignments. The phenyl esters *(5c)* and *(5d)* clearly show ^1L_b bands due to the

[55] *A. Hantzsch* and *J. Lifschitz*, Ber. dtsch. chem. Ges. *45*, 3011 (1912).

[56] *G. Kortüm*, Z. physik. Chem. *B 50*, 361 (1941).

[57] *P. P. Birnbaum*, *J. H. Linford*, and *D. W. G. Style*, Trans. Faraday Soc. *49*, 735 (1953).

[58] *W. Maier*, *A. Saupe*, and *A. Englert*, Z. physik. Chem. N. F. *10*, 273 (1957).

[59] *H. H. Jaffé*, *Si-Jung Yeh*, and *R. W. Gardner*, J. molecular Spectroscopy *2*, 120 (1958).

[60] *F. Gerson* and *E. Heilbronner*, Helv. chim. Acta *42*, 1877 (1959).

[61] *R. M. Hochstrasser* and *S. K. Lower*, J. chem. Physics *36*, 3505 (1962).

[62] *O. Ruff* and *W. Willenberg*, Ber. dtsch. chem. Ges. *73*, 724 (1940).

[63] The electronic spectra referred to here and in the remainder of this paper were measured in dioxane, except where otherwise noted. The positions of the absorption maxima ν_m are expressed in cm^{-1} and molar extinctions ε_m in liter/mole/cm. The oscillator strengths were obtained from the band-widths $\Delta\nu_{1/2}$ at half the maximum intensity with the approximation $f = 4.315\times10^{-9}\cdot\varepsilon_m\cdot\Delta\nu_{1/2}$ [49]. For π → π* bands in which the short-wavelength side was partly masked by adjacent bands, $\Delta\nu_{1/2}$ was taken from the long-wavelength side assuming symmetrical bands. For partly masked n → π* branches, ν_m and ε_m were calculated using the equation of a symmetrical or unsymmetrical Gauss curve [65] selected to fit the unmasked part of the band. The agreement between experimental and calculated values confirms that the n → π* bands are unsymmetrical for phosphorus azo-compounds, and symmetrical for all other classes of azo compounds investigated (Section C.3).

[64] The maximum errors in the spectral data recorded are estimated to be, in general, ±100 cm^{-1} in the positions of the bands, and ±10% in the molar extinctions (cf. [67]). The azo compounds studied exhibit little solvatochromism (Section C.2.a). With few exceptions, their spectra were all recorded in dioxane. All the solutions obeyed the Beer-Lambert law.

benzene nucleus, confirmed by both the fine structure and the fact that the extinction of *(5c)* is twice that of *(5d)*. However, a molar extinction five times as great and the lack of fine structure in the tetraphenyl compound *(5a)* raises doubts regarding a similar ^1L_b assignment in this case. The first indication of the position of the $\pi \rightarrow \pi^*$ band of the P–N=N–P chromophore is provided by the maximum of the

Table 2. Absorption maxima and intensities for phosphorus azo compounds $Y_2OP-N=N-XY$ (in dioxane) [63, 64].

	XY	$n \rightarrow \pi^*$			$\pi \rightarrow \pi^*$		
		ν_m [cm^{-1}]	ε_m	f	ν_m [cm^{-1}]	ε_m	f
(5a)	$PO(C_6H_5)_2$	17600	23	0.00026	(39200)	(13000)	– [a]
(5b)	$PO[N(CH_3)_2]_2$	17800	13	0.00023	(34900)	(3000)	(0.12)
(5c)	$PO(OC_6H_5)_2$	18000	16	0.00026	(37300) (38500) (39200)	(2300)	– [a]
(5d)	$PO(OC_6H_5)(OK)$	18600	13	0.00022	(37300) (38500) (39200)	(1200)	– [a]
(5e)	$PO(OK)_2$ [b]	18800	11	0.00018	–	–	– [a]
(5f)	$PS(C_6H_5)_2$ [c, d]	18600	–	–	–	–	– [a]
(5g)	$PO(C_6H_5)_2$ $CO(C_6H_5)$	19650	38	0.00075	(39000)	(10000)	– [a]

[a] Indistinct maximum in the short-wave length ascent of the curve.
[b] In water. [c] In ethanol. [d] Decomposition point; −20 °C.

tetrakis(dimethylamino) derivative *(5b)*, which contains no phenyl groups. Of the many attempts to locate the $\pi \rightarrow \pi^*$ bands of other azobisphosphonic acid derivatives by analysis of the ascending part of the long-wave length curve, the method employing the subtraction of the hydrazine absorption led unexpectedly to smooth difference curves.

The symmetrical Gauss curves which may be used to approximate the difference curves have maxima at roughly the same frequencies irrespective of the substituent Y [$\nu_m^{(1)}$ ca. 31000 cm^{-1}; $\nu_m^{(2)}$ ca. 35000 cm^{-1}], but different heights. Further information regarding the $\pi \rightarrow \pi^*$ absorption of the phosphorus azo compounds will be provided by qualitative model considerations (Section D.3.a).

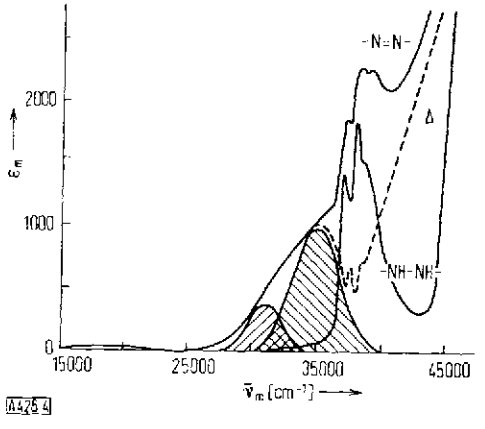


Fig. 4. Absorption difference (broken line) of tetraphenyl azobisphosphonate and tetraphenyl hydrazino-1,2-bisphosphonate.

b) Phenylazophosphonic Acid Derivatives

Three bands can be distinguished in the electronic spectra of the phenylazophosphonic acid derivatives (Fig. 5 and Table 3).

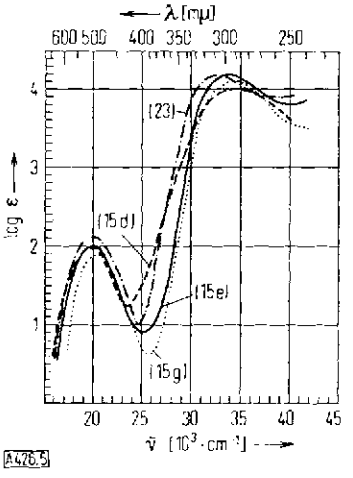


Fig. 5. Electronic spectra of representative phenylazophosphonic acid derivatives $H_5C_6-N=N-PZY_2$ (cf. Table 3).

The weak absorption in the visible region is identified as an $n \rightarrow \pi^*$ transition by a slight but distinct negative solvatochromism (cf. Section C.2.a). The maxima lying between 32000 and 35000 cm^{-1} (f ca. 0.3) are assigned to $\pi \rightarrow \pi^*$ transitions. Another band characteristic of the particular substance occurs above 40000 cm^{-1}; this band will not be discussed here, since the solvent (dioxane) absorbs in this region.

Attention should again be drawn to the steeper descent on the long-wavelength side of the $n \rightarrow \pi^*$ bands; this asymmetry cannot be attributed to interference by adjacent bands on the short-wavelength side, in view of the low extinctions at 25000 cm^{-1}.

c) Azodicarboxylic Acid Derivatives

The electronic spectra of some azodicarboxylic acid derivatives are presented in Fig. 6 and Table 4. The $n \rightarrow \pi^*$ transitions fit in well with the regularities observed in the azo-bisphosphonic acid derivatives (Section C.2.a). Thus the maxima and the extinctions of the unsymmetrical compounds *(16g)* or *(16h)* again lie between those of the symmetrically substituted compounds *(16a)* and *(16f)*, or *(16f)* and *(16c)*.

Table 3. Absorption maxima and intensities for phenylazophosphonic acid derivatives $H_5C_6-N=N-PZY_2$ (in dioxane) [63, 64].

	XY	$n \rightarrow \pi^*$			$\pi \rightarrow \pi^*$		
		ν_m [cm^{-1}]	ε_m	f	ν_m [cm^{-1}]	ε_m	f
(15c)	$PO(R)_2$ [a]	(19500)	(77)	–	(35000)	(11500)	–
(15d)	$PO[N(CH_3)_2]_2$	19800	93	0.0016	34700	9600	0.31
(15e)	$PO(C_6H_5)_2$	19950	100	0.0017	33800	13800	0.33
(15f)	$PO(OC_6H_5)_2$	20300	94	0.0016	33400	13400	0.31
(15g)	$PO(OR)_2$	20500	73	0.0012	34100	12000	0.27
(15h)	$PO(OK)_2$ [b]	20700	(65)	(0.0011)	35000	(11300)	(0.19)
(22)	$PS(C_6H_5)_2$	20300	145	0.0026	34000	13600	0.37
(23)	$PNTs(C_6H_5)_2$	19950	129	0.0022	32900	14400	0.36

[a] Unstable.
[b] Spectrum of the ethanolic hydrolysis solution at about 75 % conversion.

The n → π* oscillator strengths of the azodicarboxylic acid derivatives are about three times those of the phosphorus analogues, and the bands are symmetrical. The wavelength of the n → π* transition of dibenzoyldiazene *(16a)* is surprisingly high (21300 cm^{-1}), but the π → π* transition indicates an energetically favorable π-electron system involving the benzene nuclei. The same is true of ethyl benzoylazocarboxylate *(16g)*, the π→π* molar extinction of which is eight times that of diphenyl azodicarboxylate *(16e)* in the same region.

Azodicarboxylic acid derivatives in general exhibit peculiar ultraviolet spectra: the spectra in dioxane show only inflections, whereas those in methanol show maxima shifted to the blue. Investigations are in progress to determine whether this behavior is due to photo-induced *cis-trans* isomerization [66].

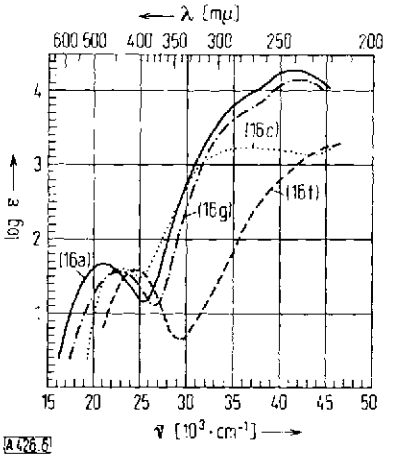


Fig. 6. Electronic spectra of representative azodicarboxylic acid derivatives YOC-N=N-COY (cf. Table 4).

Table 4. Absorption maxima and intensities for azodicarboxylic acid derivatives YOC-N=N-COY (in dioxane) [63, 64].

	XY	n → π*			π → π*		
		ν_{max} [cm^{-1}]	ε_{max}	f	ν_{max} [cm^{-1}]	ε_{max}	f
(16a)	$CO(C_6H_5)$	21300	42	0.00098	41500	19900	0.62 [a]
(16b)	$CO(CH_3)$ [b]	(22100)	(30)	(0.0005)	(> 42000)	—	—
(16c)	$CO[N(CH_3)_2]$	23050	39	0.00076	(38000)	(1600)	—
					34100	2400	0,08 [c]
(16d)	CO-Piperidino	23050	44	0.00084	(37000)	(1500	—
					33700	2400	0.08 [c]
(16e)	$CO(OC_6H_5)$	24500	40	0.00096	(40000)	(2000)	—
					36700	3650	0.05 [c]
(16f)	$CO(OC_2H_5)$	24700	39	0.00071	(47600)	(2200)	— [d]
(16g)	$CO(C_6H_5)$ $CO(OC_2H_5)$	23000	36	0.00083	41900	13700	0.43 [a]
(16h)	$CO(OC_2H_5)$ $CO[N(C_2H_5)_2]$	(23400)	(43)	(0.00082 [e]	(35000)	(1000)	—
					34500	1200	0.05 [c]
(16i)	CO(OK) [f]	25000	25	0.00047	—	—	— [g]

[a] Additional point of inflection at 35000 cm^{-1}. [b] Unstable. [c] In methanol. [d] Incipient absorption due to dioxane. [e] Inflection, maximum calculated in accordance with [63]. [f] In 1 N KOH. [g] No further maximum up to 41000 cm^{-1} [56].

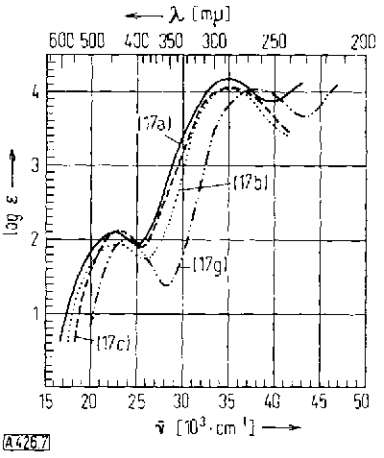


Fig. 7. Electronic spectra of selected phenylazocarboxylic acid derivatives $H_5C_6-N=N-COY$ (cf. Table 5).

Table 5. Absorption maxima and intensities for phenylazocarboxylic acid derivatives $H_5C_6-N=N-COY$ (in dioxane) [63, 64].

	XY	n → π*			π → π*		
		ν_{max} [cm^{-1}]	ε_{max}	f	ν_{max} [cm^{-1}]	ε_{max}	f
(17a)	$CO(C_6H_5)$	22550	121	0.0026	34700	13400	0.32
(17b)	$CO(CH_3)$	22800	88	0.0021	34850	10800	0.26
(17c)	$CO[N(CH_3)_2]$	23100	129	0.0025	35250	10700	0.31
(17d)	$CO(NH_2)$	23500	124	0.0027	35550	10200	0.28
(17e)	$CO(OC_6H_5)$	23700	133	0.0028	34350	12400	0.31
(17f)	$CO(OCH_3)$	23800	131	0.0025	34850	10000	0.25
(17g)	CO(OK) [a]	23900	98	0.0018	37700	10600	0.29

[a] In ethanol.

a π → π* band between 34000 and 38000 cm^{-1}, and a further band above 42000 cm^{-1}, which was not measured owing to the incipient dioxane absorption. The oscillator strengths are roughly the same as those of the phenylazophosphonic acid derivatives (Section C.2.b). The two groups of phenylazo compounds differ, however, in the shape of the n → π* band, which in the case of the phenylazocarboxylic acid derivatives is symmetrical. The symmetry of the long-wavelength bands, which are only discernible as shoulders, can be ascertained by comparison with calculated symmetrical and unsymmetrical Gauss curves [63].

d) Phenylazocarboxylic Acid Derivatives

The electronic spectra of the phenylazocarboxylic acid derivatives (Fig. 7 and Table 5) also contain three absorption maxima: an n → π* band falling within the narrow range of 22500 to 24000 cm^{-1} (depending on the substituent Y),

e) Phenylazosulfonic Acid Derivatives

As in the case of the phenylazocarboxylic acids, three maxima can be distinguished in the electronic spectra of the phenylazosulfonic acid derivatives (Fig. 8 and Table 6). The n → π*

[65] *C. Sandorfy*: Die Elektronenspektren in der Theoretischen Chemie, Verlag Chemie, Weinheim 1961, p. 32.

[66] *E. Koerner von Gustorf* and *B. Kim*, Lecture, Freiburg 1964; Angew. Chem. 76, 592 (1964).

bands are symmetrical. The spectrum of the oily, readily decomposed methyl ester *(18c)* is unreliable, since this compound could not be purified.

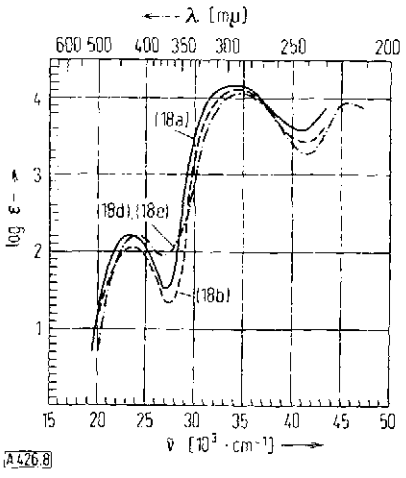


Fig. 8. Electronic spectra of representative phenylazosulfonic acid derivatives $H_5C_6-N=N-SO_2Y$ (cf. Table 6).

Table 6. Absorption maxima and intensities for phenylazosulfonic acid derivatives $H_5C_6-N=N-SO_2Y$ [63, 64].

	XY	$n \rightarrow \pi^*$			$\pi \rightarrow \pi^*$		
		ν_m [cm^{-1}]	ε_m	f	ν_m [cm^{-1}]	ε_m	f
(18a)	$SO_2(C_6H_5)$	23400	159	0.0035	33900	14000	0.36
(18b)	$SO_2(CH_3)$	23500	116	0.0021	34250	13200	0.35
(18c)	$SO_2(OCH_3)$ [a]	(24100)	(117)	—	—	—	—
(18d)	$SO_2(OK)$ [b]	24200	154	0.0028	34750	11200	0.26
(18e)	$SO_2(OAg)$ [b]	24250	169	0.0030	34750	10200	0.26

[a] Unstable above 0 °C. [b] In water.

The close agreement between the spectra of the stable potassium phenylazosulfonate *(18d)* and silver phenylazosulfonate indicates that the reproducibility of the measurements is satisfactory, assuming that the influence of the cation is the same in both cases [64].

f) Other Phenylazo Compounds

In the electronic spectra of phenylthiophenyldiazene *(19a)*, 1-phenyl-3,3-dimethyltriazene *(19b)*, and methoxy-*p*-nitrophenyldiazene *(39)* (Fig. 9 and Table 7), the $n \rightarrow \pi^*$ bands, which have been displaced towards shorter wavelengths, are

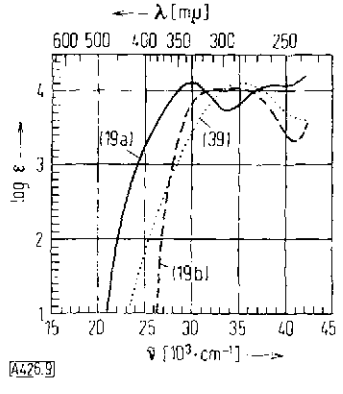


Fig. 9. Electronic spectra of 1-phenyl-2-thiophenyldiazene, 1-phenyl-3,3-dimethyltriazene, and methoxy-*p*-nitrophenyldiazene (cf. Table 7).

presumably masked by the intense $\pi \rightarrow \pi^*$ absorptions; thus the yellow color of these compounds is due to the $\pi \rightarrow \pi^*$ bands, which extend into the visible region of the spectrum.

Table 7. Absorption maxima and intensities for phenylazo compounds $H_5C_6-N=N-XY$ and $O_2N-C_6H_4-N=N-OR$ [63, 64].

	XY	$\pi \rightarrow \pi^*$		
		ν_m [cm^{-1}]	ε_m	f
(19a)	$S(C_6H_5)$	29950	12300	0.31
(19b)	$N(CH_3)_2$	(34300)	(10200)	—
(39)	$O(CH_3)$	25500	13200	0.37

The weak long-wavelength band is absent from the spectra of the colorless tetraalkyltetrazenes, too; the $n \rightarrow \pi^*$ maximum must therefore lie above 32000 cm^{-1} in the case of *trans*-dialkylamino groups (C_{2h}) (cf. Table 1).

g) Solvatochromic Effects

The effects of solvatochromism on the $n \rightarrow \pi^*$ and $\pi \rightarrow \pi^*$ bands of the azo compounds YX–N=N–XY are only slight [25]; appreciable shifts are observed only when the Z values of the solvents differ greatly [67, 68] and with unsymmetrical azo compounds. Thus the $n \rightarrow \pi^*$ band of phenylazophosphonic tetramethyldiamide exhibits the expected hypsochromic shift (cf. Section C.1); the $n \rightarrow \pi^*$ excitation energy in water is 2.1 kcal/mole higher than in cyclohexane. At the same time the $\pi \rightarrow \pi^*$ transition undergoes a 2000 cm^{-1} bathochromic shift corresponding to a 5.7 kcal/mole decrease in the $\pi \rightarrow \pi^*$ excitation energy. The constancy of the molar extinctions [69], which is required for conjugational effects, is satisfied within experimental error, except in the case of the $n \rightarrow \pi^*$ value in water (Table 8).

It may be concluded (with some caution) from the small solvatochromic effects that the differences in polarity between the ground states and the excited states of azo compounds YX–N=N–XY are also small (cf. Section D.2.a).

3. Discussion of the Electronic Spectra of the Azo Compounds

The starting point of our investigations was the unexpected violet color of the azobisphosphonic acid derivatives. The spectroscopic data obtained were used to construct a Platt diagram (Fig. 10), from which it should be possible to discern relationships between color and constitution

[67] *K. Dimroth, C. Reichardt, T. Siepmann,* and *F. Bohlmann,* Liebigs Ann. Chem. *661*, 1 (1963). Cf. also the extensive studies on solvatochromism in substituted azobenzenes [*K. Dimroth,* S.-B. Ges. Beförd. ges. Naturwiss. Marburg *76*, 3 (1963); Chem. Zbl. *1954*, 9481]. The latter exhibit considerably solvatochromism of the $\pi \rightarrow \pi^*$ bands, in contrast to azobenzene itself [25, 57, 59].

[68] *E. M. Kosower,* J. Amer. chem. Soc. *80*, 3253 (1958).

[69] *G. Scheibe, H. Dörfling,* and *J. Assmann,* Liebigs Ann. Chem. *544*, 240 (1940).

Table 8. Solvatochromism of selected azo compounds XY—N=N—XY. The solvents are arranged in order of increasing ($n \rightarrow \pi^*$) or decreasing ($\pi \rightarrow \pi^*$) Z values [64].

	Solvent	$(H_5C_6)_2PO$-N=N-$PO(C_6H_5)_2$		H_5C_6-N=N-$PO(NR_2)_2$		ROOC-N=N-COOR		H_5C_6-N=N-COOR		H_5C_6-N=N-SO_2R	
		ν_m [cm^{-1}]	ε_m	ν_m [cm^{-1}]	ε_m	ν_m [cm^{-1}]	ε_m	ν_m [cm^{-1}]	ε_m	ν_m [cm^{-1}]	ε_m
$n \rightarrow \pi^*$-Bands	Cyclohexane	–	– [a]	19700	78	24800	39	23900	156	23500	116
	Benzene	17700	24	19800	90	24800	45	23900	140	23500	126
	Dioxane	17700	21	19800	93	24700	47	23900	146	23500	116
	Chloroform	17950	24	19850	96	24650	38	23800	140	23700	135
	Ethanol	17900	24	19900	95	14900	36	23900	142	23750	133
	Water	–	– [a]	20500	120	–	– [c]	–	– [c]	–	– [a]
$\pi \rightarrow \pi^*$-Bands	Water	–	– [a]	33200	10000	–	– [c]	–	– [c]	–	– [a]
	Ethanol	39500	14400	34250	10600	–	– [d]	34700	10800	34100	12300
	Chloroform	39400	13000	34250	10400	–	– [d]	34250	10300	33700	13300
	Dioxane	39400	12300	34700	9400	–	– [d]	34850	8800	34250	13200
	Benzene	–	– [b]	34500	11300	–	– [d]	34800	10200	33900	11950
	Cyclohexane	–	– [a]	35200	12200	–	– [d]	35400	10200	34700	12100

[a] Insoluble. [b] Absorption due to solvent. [c] Decomposition by solvent. [d] No absorption up to 42500 cm^{-1}.

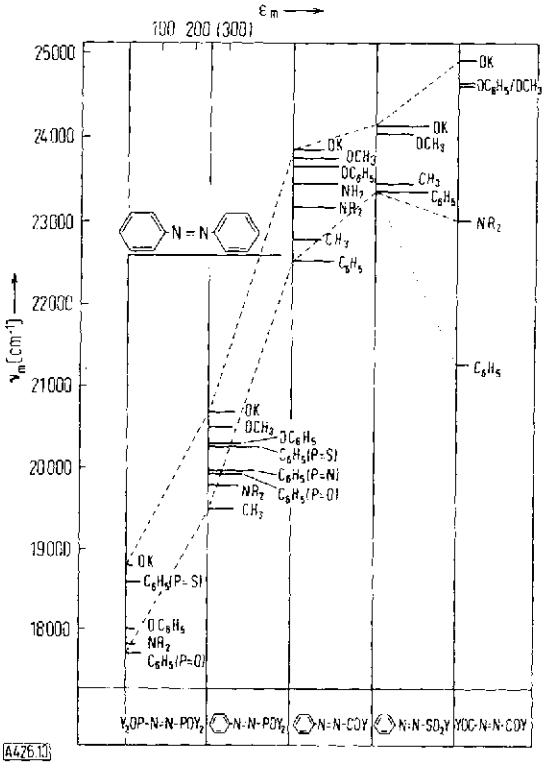


Fig. 10. Platt diagram of the $n \rightarrow \pi^*$ maxima of diacyldiazenes YX—N=N—XY and acylphenyldiazenes H_5C_6—N=N—XY.

of azo compounds. In the azo systems YX-N=N-XY examined, the substituents XY affect the positions, intensities, and shapes of the bands as follows:

The $n \rightarrow \pi^*$ maxima exhibit a bathochromic shift as the electronegativity (EN) of the substituent X adjacent to the azo group is reduced [$EN_C(2.5) \approx EN_S(2.5) > EN_P(2.1)$]. At the same time, the excitation energies of the $n \rightarrow \pi^*$ bands in the region of from 25000 to 17600 cm^{-1} (Fig. 10) decrease by 21 kcal/mole; the total difference $\Delta E_{n \rightarrow \pi^*}$ over the entire range of substituents XY is about 65 kcal/mole (Table 1). The more distant substituents Y, on the other hand, cause only minor bathochromic shifts ($\Delta E_{n \rightarrow \pi^*} \approx 3$ to 10 kcal/mole) in the order $C_6H_5 \approx R \approx NR_2 > OR > O^{\ominus}$ [70]. To a first approximation, therefore, each substituent group XY contributes a definite increment to the $n \rightarrow \pi^*$ absorption; consequently, the $n \rightarrow \pi^*$ maxima of unsymmetrically substituted azo compounds A–N=N–B lie between those of A–N=N–A and B–N=N–B (Table 9).

The $n \rightarrow \pi^*$ intensities follow the same rule (Table 9). The *trans*-azobenzenes have the highest oscillator strengths ($\bar{f} = 135 \times 10^{-4}$ [57]), followed by phenylazo compounds ($\bar{f} = 20 \times 10^{-4}$) and finally azodicarboxylic acid and azobisphosphonic acid derivatives ($\bar{f} = 5 \times 10^{-4}$). Of the substituents Y, the highest extinctions are often exhibited by C_6H_5, and the lowest frequently by $O^{\ominus}$.

The $n \rightarrow \pi^*$ bands of azocarboxylic acid and azosulfonic acid derivatives are symmetrical, whilst those of phosphorus azo compounds are unsymmetrical. According to the Franck-Condon principle [71,72], if the interatomic distances in the ground state and in the first excited state

Table 9. $n \rightarrow \pi^*$ absorption maxima and oscillator strengths of symmetrically and unsymmetrically substituted azo compounds YX—N=N—XY.

A	B	A—N=N—A		A—N=N—B		B—N=N—B	
		ν_m [cm^{-1}]	$f \cdot 10^4$	ν_m [cm^{-1}]	$f \cdot 10^4$	ν_m [cm^{-1}]	$f \cdot 10^4$
$PO(C_6H_5)_2$	C_6H_5	17700	3.5	19950	17	22600	100
$PO(C_6H_5)_2$	COC_6H_5	17700	3,5	19650	7.5	21350	9.4
$PO(OC_6H_5)_2$	$PO(OK)_2$	18000	2.6	18600	2.2	18800	1.8
$PS(C_6H_5)_2$	C_6H_5	(18600)	(7) [a]	20300	26	22600	100
$CO(C_6H_5)$	COOR	21350	9.4	23000	8.3	24700	7.1
C_6H_5	COOR	22600	100	23800	25	24700	7.1

[a] Decomposition at –20 °C.

[70] On consideration of negative solvatochromism (Section C.2.g) for the anions studied in water (Y = $O^{\ominus}$), the order would be $O^{\ominus} > OR$.

[71] The discussion of the shapes of the bands was suggested by Dr. *F. Dörr*, Technische Hochschule, München.

[72] Cf. *H. A. Staab*: Einführung in die Theoretische Organische Chemie. Verlag Chemie, Weinheim 1960; ref. [49], p. 134.

are not too different, transitions close to the O,O-transition should be energetically favored and therefore lead to a steeper descent on the long-wavelength side of the band (Fig. 11). Thus the spectra indicate that excitation into the π^* state of the P–N=N–P system does not cause appreciable lengthening of the N–N bond. The required compensation by conjugation in the ground state of phosphorus azo compounds could involve empty phosphorus d-orbitals of suitable symmetry (see Section D.3.b).

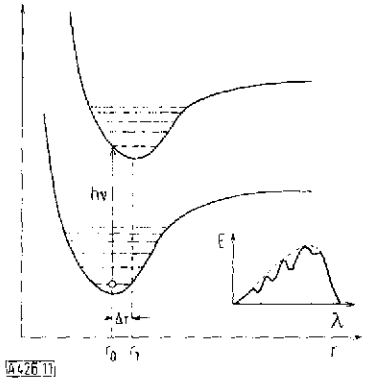


Fig. 11. Application of the Franck-Condon principle to the discussion of the shape of the $n \rightarrow \pi^*$ band.

In the $\pi \rightarrow \pi^*$ transitions of azo compounds, the excitation energies increase and the oscillator strengths decrease from azobenzene ($\nu_m = 31000\ cm^{-1}$, $f = 0.6$), through phenylazo compounds ($\nu_m = 33000$ to $35000\ cm^{-1}$, $\bar{f} = 0.3$) to azobisphosphonic acid and azodicarboxylic acid derivatives ($\nu_m > 35000\ cm^{-1}$, $\bar{f} = 0.05$). The narrow absorption region of phenylazo compounds with such different substituents XY as OR, NR_2, COY, SO_2Y, and POY_2 points to the determining influence of the phenylazo chromophore.

Further investigations, made to compare the above substituent effects on the $n \rightarrow \pi^*$ transitions with those on P=O and C=O stretching frequencies [19,25,26] or on ^{14}N- and ^{31}P-NMR signals [73] will be reported later.

D. Model Considerations

An important result arising from the discussion of the azo absorption in the visible and ultraviolet regions of the spectrum is that the positions and intensities of the $n \rightarrow \pi^*$ bands can be described by substituent-specific increments. However, the complex mechanism of the effect of the substituent XY on the excitation of the N=N group still remains to be elucidated. We shall therefore consider the following possible substituent effects in qualitative LCAO–MO models: inductive displacement of the n level in relation to the π^* orbital, modification of the π system with the n level constant, and interaction of the molecular orbitals of the azo group with empty d-orbitals of suitable symmetry.

[73] The ^{14}N and ^{31}P nuclear resonance spectra were kindly recorded by Dr. *G. Englert*, Freiburg.

1. Inductive Substituent Effects on the n Level

The n level (Fig. 2) of the lone electron pairs on the azo nitrogen atoms, which are orthogonal to the π system, is not taken into account numerically by the simple LCAO–MO theory, and is therefore usually regarded as constant [53,57–59], obviously an unsatisfactory approximation. Till now, n levels and inductive effects acting on them are considered only in small molecules [46] and are allowed for by empirical parameters. Thus *Nagakura* [74], *Jansen* [75], and *Sandström* [76] took as the n level of the lone electron pair the Coulomb integrals of the hetero-atoms in question, made self-consistent by ω-iterations (cf. Section D.2). We shall now attempt to estimate the result of the inductive substituent effect on the energy of the n level.

The energy of the lone electron pair on the uncharged nitrogen atom is taken to be

$$E_n^\circ = A_n\,(Z_{eff,n}^\circ)^2 \qquad (d)$$

where A_n is a constant and Z_{eff} the effective nuclear charge corresponding to the principal quantum number n [77]. On introduction of the inductive substituent effect, the energy of the lone electron pair is changed as a result of the partial charge now carried by the nitrogen. Let the new energy be

$$E_n' = A_n\,(Z_{eff,n}')^2 = A_n\,(Z_{eff,n}^\circ + \sigma\Delta Q)^2 \qquad (e)$$

The value of the screening constant σ for electronic interactions within the same shells is 0.35 [77]. ΔQ expresses the change in the electron density on the nitrogen atom as a result of induction. The quantities involved in Equation (e) can be estimated as follows: the constant A_n is given by the effective nuclear charge $Z_{eff,n}^\circ$ of the uncharged nitrogen atom [78] acting on an electron, and the ionization energy of the nitrogen [79]. According to *Pauling*, ΔQ can be obtained from the relationship between the ionic character of a bond and the difference in the electronegativities of the two bonded atoms [80]. On substitution in Equation (e), it is found that the energy E_n° of the n level in the azo group can vary by about ± 25 kcal as a result of the inductive effect of the substituent XY.

[74] *S. Nagakura*, Bull. chem. Soc. Japan *25*, 164 (1952).

[75] *M. J. Janssen*, Recueil Trav. chim. Pays-Bas *79*, 1066 (1960).

[76] *J. Sandström*, Acta chem. Scand. *16*, 1616 (1962); *17*, 678, 731, 937, 1380 (1963).

[77] *J. C. Slater*, Physic. Rev. *36*, 57 (1930).

[78] According to *Slater* [77], $Z_{eff,n}^\circ = (Z - \sigma)/n = 1.95$ electronic charges for nitrogen, where the nuclear charge $Z = 7$, and the principal quantum number $n_L = 2$. The screening constant σ is made up of the components 2×0.85 for the K-shell and 4×0.35 for the L-shell.

[79] The ionization energy E_N^I of nitrogen is 14.54 ev (cf. *R. W. Kiser*: Tables of Ionization Potentials. United States Atomic Energy Commission, TID-6142). Putting $E_n^\circ = E_N^I$, Equation (d) gives $A_n = 3.83$ ev.

[80] The ionic character IC of a bond can be estimated from the difference ΔEN in the electronegativities of the bonded atoms, using the equation $IC = 1 - \exp[-0.25\,(\Delta EN)^2]$ (*L. Pauling*: The Nature of the Chemical Bond. 3rd Edit., Cornell University Press, Ithaca 1960). Thus the difference in the electronegativities of nitrogen and possible substituents on the azo group ($EN_F = 4.0$; $EN_N = 3.0$; $EN_P = 2.1$) is about ± 1, causing a change in the electron density on the nitrogen of $\Delta Q \approx IC = \pm 0.22$. The equation of *N. B. Hannay* and *C. P. Smith* [J. Amer. chem. Soc. *68*, 171 (1946)] gives I. C. = 0.195

With these assumptions, the inductive effects on the n level of azo compounds range from 27000 cm^{-1} ($\Delta EN_{N-P} = +0.9$) to 45000 cm^{-1} ($\Delta EN_{N-F} = -1.0$), based on a tetrazene standard with the $n \rightarrow \pi^*$ maximum $\nu_m \equiv 36000$ cm^{-1} and the value $\Delta EN_{N-N} \equiv 0$. From the spectroscopic evidence (cf. Table 1), such a result appears to be reasonable.

2. $n \rightarrow \pi^*$ and $\pi \rightarrow \pi^*$ Transitions in the LCAO-MO Scheme

a) Substituent Effects on the π and π^* Levels

The overlapping of coplanar p_z atomic orbitals of azo nitrogen atoms and substituents XY gives rise to a conjugated system which is described in the LCAO–MO scheme by bonding (π) and antibonding (π^*) molecular orbitals, the former containing two electrons each, the latter being empty (Fig. 2). Differences in the electronegativities of the azo group and the substituent XY cause a displacement of the levels of these molecular orbitals similar to the displacement of the n level (Section D.1). Both π and π^* levels in the quasi-alternant systems present are lowered by -I effects [81] and raised by +I effects. Thus, the energy difference $\Delta E_{\pi\rightarrow\pi^*} = \Delta E_{\pi^*} - \Delta E_{\pi}$ should be kept small by small changes in the electron densities on the azo nitrogens during the $\pi \rightarrow \pi^*$ transition (cf. Section C.2.g), and in contrast to the $n \rightarrow \pi^*$ transition, the $\pi \rightarrow \pi^*$ band should be displaced only slightly (Fig. 12a).

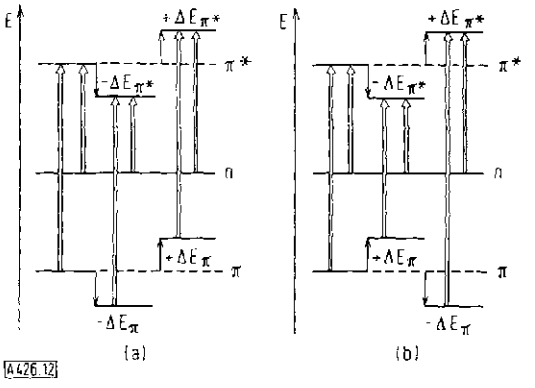


Fig. 12. Inductive (a) and conjugative (b) substituent effects on π and π^* levels of azo compounds.

Conjugative substituent effects, on the other hand, can alter the $\pi \rightarrow \pi^*$ energy difference considerably, since π and π^* levels are affected in an opposing manner in quasi-alternant systems (Fig. 12b). Thus increasing the number of centers of the π-system or decreasing the interaction between the atomic orbitals results in a bathochromic shift of the $\pi \rightarrow \pi^*$ bands.

Owing to the orthogonality of the n level with respect to the π-electron system, conjugative substituent effects act only as second-order perturbations on the former, by changing the effective nuclear charge of the azo nitrogen atoms (Section D.1).

[81] In accordance with *H. A. Staab* (ref. [72], p. 559), the -I effect is defined as the withdrawal of electrons by more strongly electronegative substituents.

b) Calculation of the Electronic Transitions of Organic Azo Compounds

The effects of substituents on π and π^* levels, which have been qualitatively discussed in Section D.2.a, can be verified with satisfactory results in the single-electron scheme of the simple *Hückel* theory [82, 83]. This is best illustrated in the case of the organic azo compounds, where the N=N group is not flanked by hetero-atoms which are difficult to deal with. Since the results were expected to be at best semi-quantitative, we have not carried out parameter variations using spectroscopic data, but simply used verified literature values [83–85]. In spite of this limitation, the calculation yields values for the $\pi \rightarrow \pi^*$ excitation energies in satisfactory agreement with the experimental values (Table 10).

Table 10. Comparison of calculated and spectroscopically determined values of the $\pi \rightarrow \pi^*$ excitation energies in organic azo compounds [86].

A–N=N–B		$\pi\rightarrow\pi^*$ (found)	$\pi \rightarrow \pi^*$ (calc.)			
A	B	ν_m [cm^{-1}]	E [β]	E_{π^*} [β]	ΔE [β]	ν_m [cm^{-1}]
C_6H_5	C_6H_5	31500	0.660	−0.277	0.937	31500 [a]
C_6H_5	COC_6H_5	34700	0.888	−0.158	1.046	35200
COC_6H_5	COC_6H_5	(35000) [b]	1.000	−0.017	1.017	34200
COC_6H_5	COOR	(35000) [b]	1.000	−0.038	1.038	34900
C_6H_5	COOR	34850	0.893	−0.188	1.081	36400
C_6H_5	R	38500 [87, 88]	0.865	−0.359	1.224	41100
COOR	COOR	(47600) [c]	1.402	−0.061	1.463	49200
COOR	R	(<45000) [d]	1.440	−0.258	1.698	57000
R	R	61400 [53]	1.500	−0.500	2.000	67000

[a] Wave-number standard 0.937 β ≡ 31500 cm^{-1}.

[b] Point of inflection around 35000 cm^{-1} (Section C.2.c).

[c] Displaced towards higher wavelengths owing to incipient solvent absorption.

[d] Not measured, but no absorption up to 45000 cm^{-1} [89].

The calculated wave numbers for benzoylphenyldiazene, phenylazocarboxylates, and azodicarboxylates, based on azobenzene as standard, agree to within ±1600 cm^{-1} (±0.2 ev) with the experimental values. The values for dibenzoyldiazene, benzoylazocarboxylates, and alkylazocarboxylates confirm the as yet uncertain spectroscopic assignment. The only notable discrepancies are shown by compounds containing alkyl substituents R; these

[82] *J. D. Roberts*: Notes on Molecular Orbital Calculations. Benjamin, New York 1961.

[83] *A. Streitwieser* Jr.: Molecular Orbital Theory. Wiley, New York 1961. This also includes a detailed list of the common hetero-atom parameters.

[84] The set of parameters used for the azodicarboxylate anion was adjusted by *A. Zweig* and *A. K. Hoffmann* [J. Amer. chem. Soc. *85*, 2736 (1963)] with the aid of polarography and electron spin resonance data.

[85] The calculations were carried out according to $\alpha_x = \alpha_0 + h_x\beta_0$ and $\beta_{xx} = k_{xx}\beta_0$ with the following hetero-atom parameters (in β units): $h_N = 0.5$ and $k_{N=N} = k_{C=N} = k_{C=C} = 1$ [58, 60, 83, 84] $h_O = 1.2$ and $k_{C=O} = 1.6$ [83, 84], and $h_O = 2.0$ and $k_{C-O} = 0.8$ [83, 84]. Each carboxyl group supplies four electrons to occupy the levels.

[86] The calculation was carried out on an IBM 7090 computer at the Rechenzentrum München-Garching; the complete HMO program was set up by Dipl.-Phys. *P. Straub* and Dr. *E. Weltin*, Zürich. For the spectroscopic data, see Section C.2.d and the literature cited there.

[87] *R. O'Connor*, J. org. Chemistry *26*, 4375 (1961).

[88] *A. Burawoy*, J. chem. Soc. (London) *1937*, 1865.

[89] *M. C. Chaco* and *N. Rabjohn*, J. org. Chemistry *27*, 2765 (1962), and personal communication.

substituents are insufficiently accounted for in simple HMO calculations. The $\pi \rightarrow \pi^*$ transition moments Q and the oscillator strengths f were not determined, since the calculated values for these quantities disagree with the experimental values even in the case of azobenzene, which is well conjugated and contains only two hetero-atoms ($f_{exp} = 0.56$; $f_{calc.} = 1.70$ [58]). On the other hand, satisfactory values of the Coulomb integrals α_N (as an approximate measure of the n level of the azo nitrogen atoms) were obtained by the ω-technique [74–76, 83] [Equation (f), $\omega = 1.4$], after a single iteration step (Table 11).

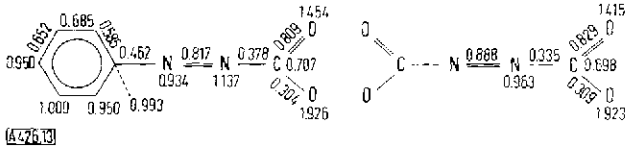
$$\alpha_N = \alpha_0 + (1 - q_N)\omega\beta_0 \qquad (f)$$

Table 11. Comparison of calculated and spectroscopically determined $n \rightarrow \pi^*$ excitation energies in organic azo compounds [85].

A–N = N–B		n→π* (found)	n → π* (calc.)			
A	B	ν_m [cm^{-1}]	q_N [β]	α_N [β]	ΔE [β] [a]	ν_m [cm^{-1}] [b]
COC_6H_5	COC_6H_5	21300	0.963	0.551	0.568	19100
COC_6H_5	C_6H_5	22550	1.129 0.938 [c]	0.453	0.611	20500
C_6H_5	C_6H_5	22600	1.072	0.399	0.676	22700
COC_6H_5	COOR	23000	0.952 0.970 [c]	0.551	0.589	19800
C_6H_5	COOR	23800	0.934 1.113 [c]	0.467	0.655	22000
COOR	COOR	24700	0.963	0.551	0.612	20600
C_6H_5	R	24800	1.000 1.095 [c]	0.434	0.792	26500
COOR	R	26500	1.037 0.915 [c]	0.534	0.793	26600
R	R	28000	1.000	0.500	1.000	33600

[a] E_{π^*} eigenvalues from Table 10.
[b] Based on the wavelength standard 0.937 β ≡ 31500 cm^{-1} (Table 10).
[c] The second q_N value applies to the substituent B; the α_N values are arithmetic means.

The $n \rightarrow \pi^*$ wave numbers, again taking the azobenzene $\pi \rightarrow \pi^*$ transition as standard, place most of the organic azo compounds in the correct order, *i.e.* dibenzoyldiazene > benzoylphenyldiazene > azobenzene > phenylazoalkanes > alkylazocarboxylates > dialkyldiazenes. The close agreement of the value for azobenzene is probably fortuitous. On the other hand, the low $n \rightarrow \pi^*$ excitation energies of all the compounds containing $-CO_2-$ groups require further iteration steps or a parameter variation, using values which follow from the MO molecular diagrams of phenylazocarboxylates and azodicarboxylates (Fig. 13).



A 426.13

Fig. 13. MO diagrams for phenylazocarboxylates and azodicarboxylates showing charge densities and bond orders.

At a hetero-atom/carbon ratio of 3:1, the greatest error is due to ester carbon atom, which is far from self-consistency. The azo nitrogen should also be assigned a higher value of the Coulomb integral α, owing to the high negative charge on the $-CO_2-$ group. Moreover, the C–N bond order appears to be too low. A new set of parameters [90] found by perturbation methods gives, *e.g.* for azodicarboxylates, the correct $n \rightarrow \pi^*$ excitation energy $\nu_m = 24900$ cm^{-1} together with an almost unchanged $\pi \rightarrow \pi^*$ value ($\nu_m = 50100$ cm^{-1}).

3. Participation of d-Orbitals in the $n \rightarrow \pi^*$ Transition in Phosphorus Azo Compounds

a) Arguments for the Hindrance of Conjugation by Tetracoordinated Phosphorus (V)

The violet color of the phorphorus azo compounds cannot be explained by the above orbital models. Before discussing the possibility of a π^*/d orbital interaction (Section D.3.b), we shall show that the π-electron system of the azobisphosphonic acid derivatives comprises only the four atoms P–N–N–P. New arguments will be presented in support of the still controversial [91–96] hindrance of conjugation by tetracoordinated phosphorus (V) [97–99], which passes on electronic effects as second-order perturbations [99].

The frequencies of the P=O valence vibrations of all phosphorus azo compounds obey the empirical electronegativity relationship proposed by *Bell, Heisler, Tannenbaum*, and *Goldenson* [100], indicating that substituent effects on phosphorus atoms are predominantly inductive [18, 19, 25]. Correspondingly no similar relationship could be established for the C=O valence vibrations in conjugated azocarboxylic acid derivatives [25, 26].

[90] First- and second-order perturbation calculations from eigenvectors and polarizabilities [83] gave the following adjusted parameters [85]: $\alpha_C = \alpha_C + 0.3\beta$; $\alpha_N = \alpha_C + 0.75\beta$; $\beta_{C-N} = 0.8\beta$.

[91] *D. P. Craig*, J. chem. Soc. (London) *1959*, 997.

[92] *D. P. Craig, M. L. Heffernan, R. Mason*, and *N. L. Paddock*, J. chem. Soc. (London) *1961*, 1376.

[93] *N. L. Paddock*, Quart. Rev. (chem. Soc., London) *18*, 185 (1964).

[94] *N. L. Paddock* in: Developments in Inorganic Polymer Chemistry. Elsevier, London 1962, p. 92.

[95] *M. I. Kabachnik*, Tetrahedron *20*, 655 (1964).

[96] *C. T. Mortimer* in: Reaction Heats and Bond Strength. Pergamon Press, Oxford 1962, p. 191.

[97] *M. J. S. Dewar, E. A. C. Lucken*, and *M. A. Whitehead*, J. chem. Soc. (London) *1960*, 2423.

[98] Cf. ref. [49], p. 466.

[99] *H. Bock*, Lectures, Freiburg and Heidelberg 1964.

[100] *J. V. Bell, J. Heisler, H. Tannenbaum*, and *J. Goldenson*, J. Amer. chem. Soc. *76*, 5185 (1954).

The $n \rightarrow \pi^*$ and $\pi \rightarrow \pi^*$ bands of the phenylazodiphenylphosphinic acid derivatives $H_5C_6-N=N-PZ(C_6H_5)_2$, where Z = NR, O, S, (Table 3) confirm that within the accuracy of the measurements [64], no modification of the conjugated system occurs through the tetracoordinated phosphorus(V).

Phosphorus-nitrogen chains synthesized by us [18,25, 101] confirm by their color the inhibition of conjugation by tetracoordinated phosphorus [*].

$$=\overset{|}{\underset{|}{P}}-N=N-\overset{|}{\underset{|}{P}}= \quad \text{violet} \qquad -N=\overset{|}{\underset{|}{P}}-N=N- \quad \text{deep red}$$

$$-\overset{|}{\underset{|}{P}}=N-N=N- \quad \text{golden yellow}$$

$$-\overset{|}{\underset{|}{P}}=N-\overset{|}{\underset{|}{P}}=N- \quad \text{colorless}$$

In particular, phosphinimido chains [93,94] are always colorless, no matter how many chain units are present, and the longest-wavelength absorption of the phenyl-substituted compounds is the ^1L_b band of the benzene nucleus [102]. Comparison of these compounds with the corresponding diphenylpolyenes [103], which absorb in the visible region when the number of C=C units is greater than 3, shows that linear combination of p_z and

$$(H_5C_6)_3P=N-\overset{|}{\underset{|}{P}}=N-\overset{|}{\underset{|}{P}}=N-\overset{|}{\underset{|}{P}}=N-PO(C_6H_5)_2 \quad (43)$$

$$\nu_m > 36700\ cm^{-1} \quad (^1L_b)$$

$$(H_5C_6)_2C=\underset{|}{\underset{|}{C}}-\underset{|}{\underset{|}{C}}=\underset{|}{\underset{|}{C}}-\underset{|}{\underset{|}{C}}=\underset{|}{\underset{|}{C}}-\underset{|}{\underset{|}{C}}=C(C_6H_5)_2 \quad (44)$$

$$\nu_m = 25100\ cm^{-1}$$

d-orbitals does not give a π-electron system similar to that given by p_z-p_z orbitals.

Consequently, the only picture which remains plausible for the azobisphosphonic acid derivatives *(5)* is that proposed by *Dewar*, *Lucken*, and *Whitehead* [97]. This model involves overlap of two unoccupied orthogonal d-orbitals of suitable symmetry (*e.g.* d_{xz} and d_{yz}) with the p_z-orbitals of the azo nitrogen and the P=O oxygen, which are localized at two corners of the sp^3-phosphorus tetrahedron, with slight increase of the bond angle. Each of the resulting π-electron systems, which are practically perpendicular to each other, ends on the phosphorus atom, and their conjugative interaction is negligible.

b) Discussion of a π^*/d Orbital Interaction

In the above model, electronegative substituents place a positive partial charge on the phosphorus, thus contracting the empty d-orbitals by which the azophosphorus system is defined. The possible combinations of a d-orbital of phosphorus with the π, n, or π^* orbitals of the N=N group (Fig. 24) can be discussed only qualitatively, owing to the lack of data. π/d and n/d interactions are in contradiction with the spectroscopic findings, and can therefore be immediately ruled out: the π/d model would require a hypsochromic shift of the resulting $n \rightarrow \pi d^*$ transition with increasing interaction, whilst the n/d model requires an allowed $nd \rightarrow nd^*$ transition of high intensity owing to the fact that the ground state (nd) and the first excited state (nd*) have the same symmetry. The π^*/d model [104], in which the combination of the π^* level and the d-orbital are favored by energy considerations, is the only one which reproduces a bathochromic shift of the forbidden $n \rightarrow \pi\ d_1^*$ band with increasing interaction (Fig. 14).

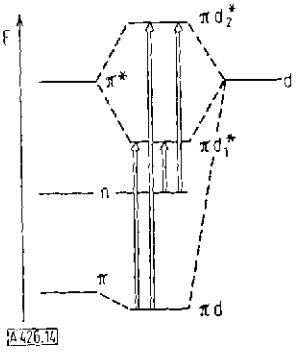


Fig. 14. Energy level diagram for π^*/d interactions.

The spectroscopic arguments in favor of the postulated π^*/d interaction in the azobisphosphonic acid derivatives are as follows:

Comparison with azodicarboxylic acid derivatives (Section C.2.e) shows that the azobisphosphonic acid derivatives have twice as many bands in the $\pi \rightarrow \pi^*$ region, as required (Fig. 3), those at the longest wavelengths having a low intensity ($n \rightarrow \pi d_x^*$ transitions?). Although the exact position of the $\pi d \rightarrow \pi d_2^*$ transition for phosphorus azo compounds is unknown ($\nu_m \geqslant 46000\ cm^{-1}$), the farther-reaching requirement of the model, namely that the energy difference between the πd_1^* and πd_2^* levels should be constant for transitions from the same ground state, appears to be satisfied: the difference in the wave numbers of the two (x = 1,2) $n \rightarrow \pi d_x^*$ bands is about 15000 cm^{-1}, whilst that in the case of the two $\pi d \rightarrow \pi d_x^*$ bands seems to be at least 13000 cm^{-1} (Section C.2.a).

E. Summary: Color and Constitution of Azo Compounds

The complex relationship between color and constitution in azo compounds can be qualitatively explained by orbital models. If the other variables are arbitrarily kept constant, the effects of substituents on the $n \rightarrow \pi^*$ transition, on which the color depends, are as follows:

1. Substituents XY can cause a considerable change in the position of the n level by an inductive effect, the change depending on the electronegativity of the substituent in relation to the azo nitrogen. An increase in the effective nuclear charge of the azo nitrogen lowers the n

[101] *H. Bock* and *W. Wiegräbe*, Angew. Chem. *75*, 789 (1963), Angew. Chem. internat. Edit. *2*, 484 (1963).

[*] Cf. also the granate-red triphenylphosphinazine $(C_6H_5)_3P=N-N=P(C_6H_5)_3$ synthesized by *R. Appel* and *R. Schöllhorn*, Angew. Chem. *76*, 991 (1964); Angew. Chem. internat. Edit. *3*, 805 (1964).

[102] *K. L. Paciorek*, Inorg. Chem. *3*, 97 (1964).

[103] *K. W. Hausser*, *R. Kuhn*, and *A. Smakula*, Z. physik. Chem. B *29*, 384 (1935).

[104] *D. F. Harnish* and *R. West*, Inorg. Chem. *2*, 1083 (1963).

level, and causes a hypsochromic shift of the $n \rightarrow \pi^*$ transition, and *vice versa*.

2. The π^* level is affected by inductive and conjugative effects of the substituent XY. In the quasi-alternant systems in question, the π^* level is lowered (raised), with a consequent bathochromic (hypsochromic) shift of the $n \rightarrow \pi^*$ transition, by $-I$ ($+I$) effects, and by expansion (contraction) of the π-electron system or decrease (increase) in the interaction of the orbitals, respectively.

3. Inductive and conjugative effects of the substituent XY on the occupied π level also affect the n level in accordance with (1), by changing the effective nuclear charge of the azo nitrogen.

4. Additional interaction with unoccupied d-orbitals of suitable symmetry should lead to a splitting of the π^* level, and hence once more to a bathochromic displacement of the resulting $n \rightarrow \pi d^*$ transition.

The model outlined in the present paper, which has been simplified by considering the various substituent effects separately and by disregarding the intensity ratios, is only crude, although probably correct in principle. Further spectroscopic studies and further calculations should lead to a gradual refinement of our knowledge of the fascinating relationships between color and constitution in azo compounds.

F. Outlook: $n \rightarrow \pi^*$ Transitions as Molecular Probes

The substituent effects which were first described in detail for azo compounds have general significance: $n \rightarrow \pi^*$ bands occur in all π-electron systems which contain hetero-atoms with lone electron pairs, and in which the weak long-wavelength absorptions are not totally masked by an intense $\pi \rightarrow \pi^*$ band. In addition to numerous hetero-aromatic compounds, such systems are also found in the important unsaturated groups C=O, C=S, and N=O. In all these cases, literature values and our own results confirm that the $n \rightarrow \pi^*$ excitation depends on the substituents in the same manner as in the azo compounds. Thus the $n \rightarrow \pi^*$ transition always undergoes a bathochromic shift (F < O < N < C) with decreasing electronegativity of the substituents XY; participation in conjugation (*e.g.* XY = C_6H_5) and, above all, interaction with a d-orbital (*e.g.* XY = SiR_3) act in the same direction (Table 12).

Table 12. Substituent effects on the $n \rightarrow \pi^*$ transition (ν_m in cm^{-1}) in azo, carbonyl, thiocarbonyl, and nitroso compounds.

XY	F	OR	NR_2	CR_3	C_6H_5	SiR_3/C_6H_5
YX=N-N=XY	(45000)	(40000)	(36000)	28000	22600	17000 [42]
$(YX)_2C=O$	–	49000	45000	36400	30100	24200 [105]
$(YX)_2C=S$	–	33000 [106]	30300 [106]	19800 [106]	16500 [106]	–
YX=N-O	32180 [107]	28100	27700	15050	13250	–

Substituent-specific absorption increments (Section C.3) are also found, for example, in thiocarbonyl compounds; the $n \rightarrow \pi^*$ absorptions of unsymmetrically substituted compounds ABC=S always lie between those of the symmetrically substituted compounds $A_2C=S$ and $B_2C=S$ (see Table 13).

Table 13. $n \rightarrow \pi^*$ maxima and molar extinctions of some symmetrically and unsymmetrically substituted thiocarbonyl compounds $(YX)_2C=S$ [106,108].

A	B	$A_2C=S$		ABC=S		$B_2C=S$	
		ν_m [cm^{-1}]	ε_m	ν_m [cm^{-1}]	ε_m	ν_m [cm^{-1}]	ε_m
C_6H_5	R	16000	185	17600	48	20000	3.5
R	SR	20000	3.5	21700	18	23300	35
R	OR	20000	3.5	26500	19	33000	– [a]
R	NH_2	20000	3.5	27300	36	34500	100
SR	OR	23300	35	28000	52	33000	– [a]
$NH(OCH_3)$	OR	26200	42	30000	95	33000	– [a]

[a] Shoulder in the absorption curve.

Table 14 confirms that the magnitudes of the substituent increments in various π-electron systems are comparable. The differences in $n \rightarrow \pi^*$ excitation energies of compounds with alkoxy and phenyl substituents agree within $\pm 10\%$.

Table 14. Energy differences for the $n \rightarrow \pi^*$ transitions of various π-electron systems with the substituents YX=OR and C_6H_5.

π-System	YX=N-N=XY	$(YX)_2C=O$	$(YX)_2C=S$	YX=N-O
ν_m (OR)	(40000) [a]	49000	33000 [106]	28100
ν_m (C_6H_5)	22600	30100	16500 [106]	13200
$\Delta\nu_m$ [cm^{-1}]	17400	18900	16500	14900
ΔE [kcal]	49	54	47	43

[a] Assignment uncertain.

Current spectroscopic investigations present the possibility of using the $n \rightarrow \pi^*$ transitions as "molecular probes" to obtain information regarding the mechanism of the contraction of empty d-orbitals with increasing nuclear charge, and of obtaining in this way a general theory of substituent effects on π-electron systems.

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[105] *A. G. Brook*, J. Amer. chem. Soc. *79*, 4373 (1957); *A. G. Brook, M. A. Quigley, G. J. D. Peddle, N. V. Schwartz*, and *C. M. Warner*, ibid. *82*, 5102 (1960).

[106] *M. J. Janssen*, Recueil Trav. chim. Pays-Bas *79*, 454, 464 (1960).

[107] *H. S. Johnston* and *H. J. Bertin* jr., J. molecular Spectroscopy *3*, 683 (1959).

[108] *J. Fabian* and *R. Mayer*, Spectrochim. Acta *20*, 299 (1964).

New Methods in Preparative Organic Chemistry IV

Isonitrile Syntheses

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In spite of the large number of reactions which involve the formation of isonitriles, the only preparative routes to these compounds, until recently, were the classical isonitrile syntheses discovered about one hundred years ago by Gautier and Hofmann. These methods are not generally applicable, and give satisfactory yields only in exceptional cases. Isonitriles have recently become readily available by the elimination of water from N-substituted formamides, using acyl halides of Group IV–VI elements in the presence of bases as dehydrating agents. A dehydrating system with a particularly wide range of application consists of phosgene with tertiary amines. This system generally provides the easiest and most productive route to isonitriles, particularly where large quantities (> 1 mole) are to be prepared.

1. Introduction
2. The Alkylation of Cyanides
3. The Reaction of Primary Amines with Dichlorocarbene
4. α-Eliminations from Formic Acid Derivatives of Primary Amines
5. Redox Reactions
6. Abnormal Beckmann Rearrangements
7. Ring-Cleavage Reactions of Heterocyclic Compounds
8. Ring-Closure of α-Halogenoacylamines followed by α-Cycloelimination

1. Introduction

Almost one hundred years have passed since the discovery of isonitriles by *Gautier* [1–1d] and *Hofmann* [2–2b].

Although fundamental problems in organic chemistry, such as the problem of isomerism [1–4] and the question of whether carbon can exist in the divalent state [5–9], have at times stimulated investigations of the isonitriles, little experimental effort has been devoted to the chemistry of these compounds, in spite of their wide reactivity.

The principal reason for the relatively small volume of publications on the subject [3] is that convenient and generally applicable methods for the preparation of isonitriles have only become available in the last few years (cf. Section 4).

The development of the chemistry of isonitriles has probably suffered only little delay through the characteristic odor of volatile isonitriles, which has been described by *Hofmann* and *Gautier* as "highly specific, almost overpowering", "horrible", and "extremely distressing". It is true that many potential workers in this field have been turned away by the odor, but this is heavily outweighed by the fact that isonitriles can be detected even in traces, and that most of the routes leading to the formation of isonitriles were discovered through the odor of these compounds.

In the early days of isonitrile chemistry, the isonitriles were formulated as compounds of divalent carbon [1–1d, 5–5d]

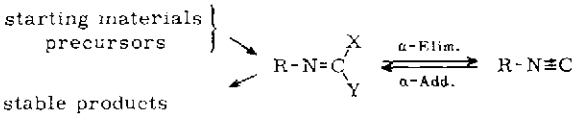
$$R-N{=}C^{II}$$

As the picture of the chemical bond became more refined, this was replaced by a semipolar formula and by two resonance structures [6].

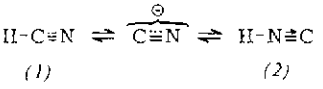
$$R-N{\equiv}C \qquad \left\{R-\underline{N}=\underline{C} \longleftrightarrow R-\overset{\oplus}{N}{=}\overset{\ominus}{C}\right\}$$

[1] *A. Gautier*, Liebigs Ann. Chem. *142*, 289 (1867).
[1a] *A. Gautier*, Liebigs Ann. Chem. *146*, 119 (1868).
[1b] *A. Gautier*, Liebigs Ann. Chem. *149*, 29, 155 (1869).
[1c] *A. Gautier*, Liebigs Ann. Chem. *151*, 239 (1869).
[1d] *A. Gautier*, Ann. Chimie (4), *17*, 103, 203 (1869).
[2] *A. W. Hofmann*, C. R. hebd. Séances Acad. Sci. *65*, 484 (1867).
[2a] *A. W. Hofmann*, Liebigs Ann. Chem. *144*, 114 (1867).
[2b] *A. W. Hofmann*, Liebigs Ann. Chem. *146*, 107 (1868).
[3] Reviews: *V. Migrdichian*: The Chemistry of Organic Cyanogen Compounds, Reinhold Publ. Corp., New York 1947; p. 393; *P. Kurtz* in *Houben-Weyl*: Methoden der Organischen Chemie. Thieme, Stuttgart 1952, Vol. 8, p. 351; *I. Ugi*, Angew. Chem. *74*, 9 (1962); Angew. Chem. internat. Edit. *1*, 8 (1962); *K. Sjöberg*, Svensk kem. Tidskr. *75*, 493 (1963); *R. Oda* and *T. Shono*, J. Soc. org. synth. Chem., Japan *22*, 695 (1964); *I. Ugi*, Jb. Akad. Wiss. Göttingen, in the press; see also: *I. Ugi*, *K. Offermann*, and *H. Herlinger*, Chimia *18*, 278 (1964).
[4] *M. H. Guillemard*, Ann. Chimie (8), *14*, 311 (1908).
[5] *I. U. Nef*, Liebigs Ann. Chem. *270*, 267 (1892).
[5a] *I. U. Nef*, Liebigs Ann. Chem. *280*, 291 (1894).
[5b] *I. U. Nef*, Liebigs Ann. Chem. *287*, 265 (1895).
[5c] *I. U. Nef*, Liebigs Ann. Chem. *298*, 202, 368 (1897).
[5d] *I. U. Nef*, Liebigs Ann. Chem. *309*, 126 (1899).
[6] *H. Lindemann* and *L. Wiegrebe*, Ber. dtsch. chem. Ges. *63*, 1650 (1930).
[7] *D. L. Hammick*, *R. G. A. New*, *N. V. Sidgwick*, and *L. E. Sutton*, J. chem. Soc. (London) *1930*, 1876.
[8] *N. V. Sidgwick*, Chem. Reviews 9, 77 (1931).
[9] *R. G. A. New* and *L. E. Sutton*, J. chem. Soc. (London) *1932*, 1415.

Nevertheless, even modern quantum chemistry does not oppose the continued use of the classical concept of the formal divalence of the isonitrile carbon. This picture is quite convenient, since it comprises the entire chemistry of the isonitriles, which is ultimately reducible to α-eliminations and α-additions [3].



Apart from the alkylation of the cyanide ion or of hydrogen cyanide *(1)*, the tautomer *(2)* of which [10] already contains formally divalent carbon, reactions in which



isonitriles are formed always involve the loss of two monovalent groups or one divalent group from a compound containing formally tetravalent carbon, either by α-elimination or by redox reactions.

2. The Alkylation of Cyanides

Hydrogen cyanide is tautomeric with the parent compound of the isonitriles, *i.e.* hydrogen isocyanide [10]. It reacts with diazomethane to form a mixture of acetonitrile and methyl isonitrile [11].

$$CH_2N_2 + HCN \rightarrow CH_3{-}CN + CH_3{-}NC$$

Hydrogen cyanide adds onto ethylene, under the action of a silent electrical discharge, to yield ethyl isonitrile [12].

$$C_2H_4 + HCN \xrightarrow{\Delta E_{el}} C_2H_5{-}NC$$

The principal products of nucleophilic attack of the free ambident cyanide ion [13] on alkylating agents, such as alkyl halides, alkali monoalkyl sulfates, and dialkyl sulfates, are nitriles. Isonitriles are formed only in small quantities (≪ 25%) [4, 5b, 14–15]:

$$R{-}X + CN^{\ominus} \rightarrow R{-}CN + R{-}NC$$

The alkylation of complexed or internally complexed cyanides, on the other hand, occurs preferentially on the nitrogen.

Isonitriles were first prepared by *Gautier* [1–1d], by the reaction of silver cyanide with alkyl iodides; isonitrile complexes are formed [15–18], from which the isonitriles are liberated by potassium cyanide. This method gives yields of up to 55%, based on the silver cyanide [17].

$$R{-}I + [AgCN] \rightarrow [R{-}NC{\cdot}AgI] \xrightarrow{KCN} R{-}NC$$

Considerable quantities of alkyl isonitriles are also formed on decomposing the products of the reaction of alkyl iodides and copper(I) cyanide [4, 16a], whereas very little isonitrile (about 3%) is obtained when zinc, cadmium, and nickel cyanides are treated in a similar manner [4].

Alkyl isonitriles can be eliminated by heat [20] or by the action of alkali metal hydroxides [19] or cyanides [4, 16a, 21] on the alkylation products of alkali metal or silver hexacyanoferrates(II) [19] or hexacyanocobaltates(III).

When ethanolic solutions of hydrogen hexacyanoferrate(II) containing hydrogen cyanide are heated to 120 °C, they yield up to 40% of ethyl isonitrile [22]. The partial "esterification" of the hydrogen hexacyanoferrate(II) is followed by the replacement of isonitrile ligands by hydrogen cyanide. Similar behavior is observed with hydrogen hexacyanocobaltate(III) [22–24].

$$H_4[Fe(CN)_6] \xrightarrow{n\,C_2H_5OH} H_{4-n}[(C_2H_5{-}NC)_nFe(CN)_{6-n}] \xrightarrow{n\,HCN} n\,C_2H_5{-}NC$$

3. The Reaction of Primary Amines with Dichlorocarbene

The carbylamine reaction, *i.e.* the reaction of primary amines with chloroform [25] and strong bases, such as ethanolic potassium hydroxide solution [2–2b, 27–29], solid alkali metal hydroxide [6, 30–34], or potassium

[10] *K. H. Meyer* and *H. Hopf*, Ber. dtsch. chem. Ges. *54*, 1709 (1921); *A. Dadieu*, ibid. *64*, 358 (1931); *L. Reichel* and *O. Strasser*, ibid. *64*, 1997 (1931); *G. Herzberg*, J. chem. Physics *8*, 847 (1940); *C. R. McCrosky*, *F. W. Bergstrom*, and *G. Waitkins*, J. Amer. chem. Soc. *64*, 722 (1942); *F. Klages* and *K. Mönkemeyer*, Chem. Ber. *83*, 501 (1950); *W. Brügel*, *G. Danmiller*, and *O. Rommel*, Angew. Chem. *68*, 440 (1956).

[11] *A. Peratoner* and *F. C. Palazzo*, Gazz. chim. ital. *38*, 102 (1908).

[12] *L. Francesconi* and *A. Ciurlo*, Gazz. chim. ital. *53*, 327 (1923); *P. M. Aronović*, *N. K. Bel'skij*, and *B. M. Michailov*, Izvest. Akad. Nauk SSSR, Otdel. khim. Nauk *1956*, 696.

[13] Review: *R. Gompper*, Angew. Chem. *76*, 412 (1964); Angew. Chem. intern. Edit. *3*, 560 (1964); *W. P. Griffith*, Quart. Rev. *16*, 188 (1962).

[14] *F. Kaufler* and *C. Pomeranz*, Mh. Chem. *22*, 492 (1901).

[14a] *R. Merckx*, *J. Verhulst*, and *P. Bruylants*, Bull. Soc. chim. Belgique *42*, 177 (1933).

[15] *J. Wade*, J. chem. Soc. (London) *81*, 1596 (1902).

[16] *E. G. J. Hartley*, J. chem. Soc. (London) *109*, 1296 (1916).

[16a] *E. G. J. Hartley*, J. chem. Soc. (London) *1928*, 780.

[17] *H. L. Jackson* and *B. C. McKusick*, Org. Synth., Coll. Vol. IV Wiley, New York 1963, p. 438.

[18] Analogous reactions with halogenosilanes and halogenogermanes: *T. A. Bittner*, *W. H. Knoth*, *R. V. Lindsey*, and *W. H. Sharkey*, J. Amer. chem. Soc. *80*, 4151 (1958); *J. J. McBride*, J. org. Chemistry *24*, 2029 (1959); *D. Seyferth* and *N. Kahlen*, J. org. Chemistry *25*, 809 (1960); *A. D. Craig*, *J. V. Urenovitch*, and *A. G. McDiarmid*, J. chem. Soc. (London) *1962*, 548.

[19] *F. Hölzl*, *W. Hauser*, and *M. Eckmann*, Mh. Chem. *48*, 71 (1927).

[20] *I. Ugi* and *C. Steinbrückner*, Angew. Chem. *71*, 386 (1959).

[21] *L. Malatesta*, Progr. inorg. Chem. *1*, 283 (1959).

[22] *W. Z. Heldt*, J. org. Chemistry *26*, 3226 (1961).

[23] *F. Hölzl*, *T. Meier-Mohar*, and *F. Viditz*, Mh. Chem. *53/54*, 237 (1929); *F. Hölzl* and *J. Krakora*, ibid. *64*, 97 (1934).

[24] *F. Hölzl*, Z. Elektrochem. angew. physik. Chem. *43*, 319 (1937).

[25] Bromoform [26] and iodoform [27] are less suitable.

[26] *T. L. Davis* and *W. F. Yelland*, J. Amer. chem. Soc. *59*, 1998 (1937).

[27] *S. Bose*, J. Indian chem. Soc. *35*, 376 (1958).

[28] *M. Passerini*, Gazz. chim. ital. *50 II*, 340 (1920).

[29] *M. Passerini* and *G. Banti*, Gazz. chim. ital. *58*, 636 (1928).

[30] *F. A. Cotton* and *F. Zingales*, J. Amer. chem. Soc. *83*, 351 (1961).

[31] *H. C. Biddle*, Liebigs Ann. Chem. *310*, 1 (1900).

[32] *L. Malatesta*, Gazz. chim. ital. *77*, 238 (1947).

[33] *P. A. S. Smith* and *N. W. Kalenda*, J. org. Chemistry *23*, 1599 (1958).

[34] *D. Ross*, Doctorate Dissertation, Universität München, 1957; *A. Dellmayer*, Diploma Thesis, Universität München, 1959.

t-butoxide [34–36], has been recommended [84] for the qualitative detection of primary amines, and was considered for a long time to be the most useful method for the preparation of isonitriles [36–36f].

In 1897, *Nef* [5c, 37] interpreted the Hoffmann carbylamine reaction as the addition of dichlorocarbene [38] to primary amines [39–41], followed by β-elimination of one molecule of hydrogen chloride and α-elimination of another.

$$R{-}NH_2 \xrightarrow{CCl_2} R{-}\overset{\oplus}{N}H_2{-}\overset{\ominus}{C}Cl_2 \longrightarrow R{-}NH{-}CHCl_2$$
$$\xrightarrow{\beta\text{-Elim.}} R{-}N{=}CHCl \xrightarrow{\alpha\text{-Elim.}} R{-}NC$$

A similar mechanism is followed in the formation of isonitriles (15–43% yield) by the thermal decomposition of sodium trichloroacetate in the presence of arylamines, such as aniline, *p*-toluidine, or *p*-anisidine [42],

$$3\,Ar{-}NH_2 + CCl_3{-}CO_2Na \rightarrow Ar{-}NC + 2\,Ar{-}NH_2{\cdot}HCl + NaCl + CO_2$$

and possibly also in the reaction of primary amines (n-butylamine, aniline) and carbon tetrachloride with copper [43].

4. α-Eliminations from Formic Acid Derivatives of Primary Amines

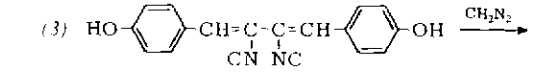
4.1 The Elimination of Water from N-Monosubstituted Formamides

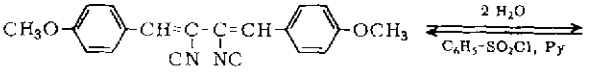
Considering their hydrolysis products, *Gautier* [1b–1d] suggested that isonitriles might be regarded as formic acid derivatives of primary amines, and that it should therefore be possible to prepare them by elimination of water from *N*-monosubstituted formamides. However, *Gautier*'s attempts [1d] to achieve such dehydrations did not have the desired result.

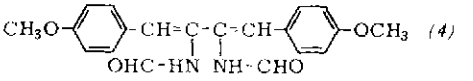
$$R{-}NH_2 + HCOOH \underset{+H_2O}{\overset{-H_2O}{\rightleftharpoons}} R{-}NH{-}CHO \underset{+H_2O}{\overset{-H_2O}{\rightleftharpoons}} R{-}NC$$

Wegler [44] re-examined this idea in 1938. On treating *N*-monosubstituted formamides with thionyl chloride, he found traces of isonitriles among the products. The low yields were probably due to the sensitivity of the isonitriles to acids.

The reaction of a formamide with a dehydrating halide in the presence of a base was first carried out by *Hagedorn* and *Tönjes* during an attempt to elucidate the constitution of xanthocillin *(3)* [45–47]. The starting material was "*O,O'*-dimethylxanthocillin dihydrate" *(4)* and the dehydrating agent used was benzenesulfonyl chloride in pyridine.



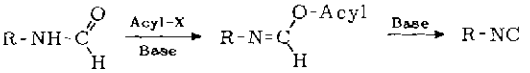




The antibiotic xanthocillin *(3)*, which was discovered [47] by *Rothe* in 1948 in cultures of *Penicillium notatum* Westling and *Penicillium chrysogenum*, is the only known naturally occurring isonitrile. It presumably arises by oxidative dimerization of tyrosine, the isonitrile group being formed from a formylamino group under the dehydrating action of an energy-rich phosphate [*] (see Section 4.14).

It has also been shown that many acylating agents (phosgene (Section 4.11), cyanuric chloride (Section 4.12), benzenesulfonyl chloride and toluenesulfonyl chloride (Section 4.13), phosphorus tribromide [48], phosphorus trichloride [48], phosphorus oxychloride (Section 4.14), phosphorus pentachloride [48], phosphorus pentoxide [48], and thionyl chloride [48]) eliminate water from *N*-monosubstituted formamides in the presence of bases [trialkylamines and dialkylarylamines (Section 4.11), pyridine (Sections 4.13 and 4.14), quinoline (Sections 4.11 and 4.13), potassium carbonate (Section 4.12), and potassium t-butoxide (Section 4.14)]. Particularly suitable combinations for the preparation of isonitriles are phosgene/triethylamine (Section 4.11), benzenesulfonyl chloride or toluenesulfonyl chloride/pyridine or quinoline (Section 4.13), and phosphorus oxychloride/pyridine or potassium t-butoxide (Section 4.14).

The reaction of *N*-monosubstituted formamides with acylating agents and bases proceeds in two steps: the base-catalyzed *O*-acylation is followed by the nucleophilic α-elimination of a proton and an acid anion.



[35] *T. Shingaki* and *M. Takebayashi*, Bull. chem. Soc. (Japan) *63*, 617 (1963).

[36] The yields of the carbylamine reaction are: up to 20% with ethanolic potassium hydroxide solution as the base, up to 45% with solid alkali, and up to 55% with potassium t-butoxide. Higher yields claimed in the literature ([32, 35, 36a] *inter alia*), probably relate to mixtures of isonitriles and primary amines.

[36a] *W. Schneidewind*, Ber. dtsch. chem. Ges. *21*, 1323 (1888).

[36b] *H. Rupe* and *K. Glenz*, Liebigs Ann. Chem. *436*, 184 (1924).

[36c] U.S. Pat. 2342794 (Febr. 29th, 1944); U.S. Pat. 2347772 (May 2nd, 1944), Celanese Corp., inventor *H. Dreyfus*.

[36d] *D. Samuel, B. Weinraub*, and *D. Ginsburg*, J. org. Chemistry *21*, 376 (1956).

[36e] *H. Feuer, H. Rubinstein*, and *A. T. Nielsen*, J. org. Chemistry *23*, 1107 (1958).

[36f] *E. Jungermann* and *F. W. Smith*, J. Amer. Oil Chemists' Soc. *36*, 388 (1959).

[37] *V. Meyer* and *P. Jacobson*: Lehrbuch der Organischen Chemie. De Gruyter, Leipzig 1922, Vol. I/1, p. 419.

[38] *J. Hine*, J. Amer. chem. Soc. *72*, 2438 (1950); *W. v. E. Doering* and *A. K. Hofmann*, ibid. *76*, 6162 (1954).

[39] Secondary and tertiary amines add onto dichlorocarbene in a similar manner, but no dehydrochlorination leading to isonitriles occurs in these cases [40, 41].

[40] *M. Saunders* and *R. W. Murray*, Tetrahedron *6*, 88 (1959) *11*, 1 (1960); *M. B. Frankel* and *H. Feuer*, Tetrahedron Letters *1959*, No. 7, p. 5; see also [41] and Section 7.

[41] *J. Ploquin*, Bull. Soc. chim. France (5), *14*, 901 (1947).

[42] *A. P. Krapcho*, J. org. Chemistry *27*, 1089 (1962).

[43] *G. J. Beicht, I. E. Colwell*, and *J. G. Miller*, Chem. and Ind. *1960*, 203.

[44] *R. Wegler*, personal communication.

[45] *I. Hagedorn* and *H. Tönjes*, Pharmazie *11*, 409 (1956).

[45a] *I. Hagedorn* and *H. Tönjes*, Pharmazie *12*, 567 (1957).

[46] *I. Hagedorn et. al.*, Chem. Ber. *93*, 1584 (1960).

[47] *W. Rothe*, Pharmazie *5*, 190 (1950).

[*] Note added in proof: Recent investigations demonstrate a more complex sequence of reactions: *H. Grisebach* and *H. Achenbach*, Z. Naturforsch. *20 B*, 137 (1965).

[48] *I. Ugi* and *R. Meyr*, Chem. Ber. *93*, 239 (1960); cf. [49].

The elimination of hydrogen sulfide from *N*-monosubstituted thioformamides with cyanogen bromide or picryl chloride in the presence of bases [50] proceeds in a similar manner.

4.11 The Phosgene Method

4.111. General

The elimination of water from *N*-monosubstituted formamides using phosgene in the presence of tertiary amines (trimethylamine, triethylamine, tri-n-butylamine, *N,N*-dimethylcyclohexylamine, *N,N*-diethylaniline, pyridine, quinoline) [51] has been found to be convenient, economical [52], and very versatile with regard to the constitution of the starting materials. Most of the isonitriles recorded in the present paper were obtained by the phosgene method (cf. Table 1).

$$R{-}NH{-}CHO + COCl_2 + 2R_3^1N \rightarrow R{-}NC + CO_2 + 2R_3^1N{\cdot}HCl$$

In a recently developed, preferred variant of the phosgene method, a fast current of phosgene is, without external cooling, led into a vigorously stirred solution or suspension [53] of an *N*-alkylformamide or *N*-arylformamide in triethylamine/methylene chloride, until the refluxing caused by the heat of the reaction [51a] ceases (cf. Section 4.112). The isonitrile is isolated by introducing ammonia into the reaction mixture, filtering to remove the precipitated ammonium chloride, and concentrating the filtrate *in vacuo* [51b, 54]. The residual crude isonitrile is purified by distillation, recrystallization, reprecipitation, or chromatography. A particularly suitable method for the purification of crystalline isonitriles which are thermally unstable is by treating them (in a homogenizer [55]) with solvents which dissolve the impurities from the suspended isonitrile, followed by suction filtration.

For the preparation of low-boiling (b.p. $<100\,^{\circ}C/760$ mm Hg) isonitriles or of isonitriles which are unstable or sensitive towards ammonia, cf. the examples given in Section 4.112.

A variant of the phosgene method is the "one-step synthesis" of ester isonitriles. Hydroxyalkylformamides or hydroxyarylformamides react with phosgene (for conditions, see Section 4.112e) to form isocyanodialkyl carbonates or isocyanodiaryl carbonates.

$$2CHO{-}NH{-}A{-}OH + 3COCl_2 + 6R_3N \rightarrow CN{-}A{-}O{-}CO{-}O{-}A{-}NC + 2CO_2 + 6R_3N{\cdot}HCl$$

If hydroxyalkylformamides or hydroxyarylformamides are reacted with acylating halides (acyl chlorides, chlorophosphates) before treatment with phosgene, the reaction finally yields the isonitriles of the corresponding esters (see Section 4.112k).

$$Acyl{-}C + HO{-}A{-}NH{\cdot}CHO + COCl_2 \rightarrow Acyl{-}O{-}A{-}NC + CO_2 + 3R_3N{\cdot}HCl$$

As can be seen from Table 1, it is possible with the aid of the phosgene method to synthesize mono- and polyisonitriles [51–51b, 53, 56] of almost any constitution, provided that structural elements which destabilize the isonitrile [58] or which react with phosgene under the reaction conditions used [59] are avoided.

4.112. Procedures [67]

(a) *Ethyl Isonitrile*

730 g (10.0 moles) of *N*-ethylformamide, 5.0 l of tri-n-butylamine, and 3.0 l of 1,2,4-trichlorobenzene are placed in a 10 l three-necked flask, fitted with a stirrer, a wide gas inlet tube

[49] *I. Ugi* and *R. Meyr*, Angew. Chem. *70*, 702 (1958).

[50] German Published Patent Application 1158499 (Mar.2nd, 1962/Dec. 5th, 1963), Farbenfabriken Bayer AG., inventors: *W. Betz* and *I. Ugi*.

[51] *I. Ugi, W. Betz, U. Fetzer*, and *K. Offermann*, Chem. Ber. *94*, 2814 (1961); German Published Patent Application 1177146 (Aug. 3nd, 1960/Sept. 3rd, 1964), inventors: *I. Ugi* and *W. Betz*.

[51a] German Patent Application, Farbenfabriken Bayer AG., inventors: *H. Knupfer, I. Ugi, U. Fetzer*, and *U. Eholzer*.

[51b] German Patent Application, Farbenfabriken Bayer AG., inventor: *I. Ugi*.

[52] Even for large preparations (10–100 moles), the maximum time required, including working up, is only 8–15 hours; yields are up to 97%; auxiliary materials are cheap.

[53] German Published Patent Application 1158500 (Apr. 6th, (1962/Dec. 5th, 1963), Farbenfabriken BayerAG., inventor: *I. Ugi*.

[54] The triethylamine/methylene chloride distilled off can be used again for similar preparations without prior purification.

[55] For example, "Ultra-Turrax" from Messrs. Janke & Kunkel KG., Staufen i. Br. (Germany).

[56] Even the *N*-isocyanodialkylamines, which cannot bee obtained by the Hofmann method (see Section 3) [33], have been prepared by the phosgene method [57].

[57] *H. Bredereck et. al.*, Angew. Chem. *74*, 388 (1962); *76*, 580 (1964); Angew. Chem. internat. Edit. *1*, 334 (1962); *3*, 647 (1964).

[58] For example, 2,4-dinitrophenyl isonitrile and 1,4-dichloro-2,5-diisocyanobenzene cannot be obtained.

[59] *p*-Amino-, *p*-carboxy-, and p-aminosulfonylphenyl isonitriles, which can be prepared by the carbylamine reaction [9, 36d], cannot be obtained by the phosgene method. Isonitriles are very reactive towards phosgene [5–5b, 61] in the absence of bases [60].

[60] See also *A. A. R. Sayigh* and *H. Ulrich*, J. chem. Soc. (London) *1963*, 3146.

[61] *I. Ugi* and *U. Fetzer*, Chem. Ber. *94*, 1116 (1961).

[62] We are grateful to Frau Dr. *D. Lauerer* and Prof. *M. Pestemer* for carrying out infrared measurements. Dr. *E. Degener*, Dr. *H. Eck*, Dr. *H. Herlinger*, Dr. *K. W. Schellhammer*, Dr. *R. Schröter*, Dr. *H. Tarnow*, Dr. *H. Wilms*, and Dr. *W. Zecher* kindly supplied some of the starting materials. We should also like to thank *K. Holstein, H. Howey, U. Kretschmann, B. Luckas, H. Preikschat, H. Wolf*, and Frl. *U. Schlüter* for experimental assistance.

[63] The substances are arranged according to the number of C-, H-, Br-, Cl-, F-, N-, O-, P-, and S-Atoms present. "n.d." stands for "non-distillable oil".

[64] The yields marked "a"–"p" were obtained under reaction conditions corresponding to procedures 4.112 a-p.

[65a] *R. Neidlein*, Angew. Chem. *76*, 440 (1964); Angew. Chem. internat. Edit. *3*, 382 (1964).

[65b] *R. Neidlein*, Angew. Chem. *76*, 500 (1964); Angew. Chem. internat. Edit. *3*, 446 (1964).

[65c] *R. Neidlein*, Arch. Pharm. *297*, 589 (1964).

[66] According to a personal communication from *H. Herlinger*, $[\alpha]_D^{20} = -49.5\,^{\circ}$ for *(S)*-α-phenylethyl isonitrile (from *(S)*-(−)-α-phenylethylamine), cf. [36b].

[67] (a) The tertiary amines used must be free from water and from amines which can undergo acylation. The hydrogen chloride content of the phosgene should be low. *N*-Alkylformamides are generally readily available from primary aliphatic amines and the calculated quantity of commercial grade 70 to 95 per cent formic acid, by refluxing in chlorobenzene, toluene, or xylene and removing the water formed with the aid of a water separator. *N*-Arylformamides are obtained by heating primary arylamines for 2–15 hours at 70 to 105 °C with 2–10 times their weight of 85 to 100 per cent formic acid. The formamides used as starting materials must contain neither formic acid nor dimethylformamide. Sparingly soluble formamides are suspended and thoroughly stirred in a homogenizer before the reaction. Suitable drying agents for isonitrile solutions include anhydrous potassium carbonate or magnesium sulfate. Bath temperatures higher than 50 °C should be avoided for the concentration of isonitrile solutions.

(b) With a few exceptions, isonitriles exhibit no appreciable toxicity for mammals (cf. [1a]). As has been found in the toxicological laboratories at Farbenfabriken Bayer AG., Elberfeld, oral and subcutaneous doses of 500–5000 mg/kg can be tolerated by mice.

Table 1. Isonitriles prepared by the phosgene method [62, 63].

Compound [63]	Yield [%] [64]	M.p. [°C]	B.p. [°C/mm] [63]	Compound [63]	Yield [%] [64]	M.p. [°C]	B.p. [°C/mm]
C_1—C_6:				5-Chloro-2-methoxy-4-nitrophenyl isonitrile	65 (n)	117–118	–
Methyl isonitrile [1a, 71]	37 (a)	–	25–30/150	2,6-Dichlorobenzyl isonitrile	49 (n)	34–35	
Methylene diisonitrile [65a, c]	–	–	n. d.	3,4-Dichlorobenzyl isonitrile	46 (j)	–	129–130/0.01
Ethyl isonitrile [1a, 17, 71]	65 (a)	–	32–35/120	4,5-Dichloro-2-methoxyphenyl isonitrile	50 (n)	95–96	–
Ethylene diisonitrile [36c, 53]	64 (f) 51 (j) 52 [65c]	–	65–68/0.005	4-Chlorobenzyl isonitrile	54 (j)	–	105/110/0.2
Allyl isonitrile [4]	62 (d_2)	–	–	3-Chloro-2-methylphenyl isonitrile	79 (j)	–	67–68/0.15
Isopropyl isonitrile [1b, 36e]	75 (c)	–	82–83/750	4-Chloro-3-methylphenyl isonitrile	48 (j)	46–47	58–60/0.005
Ethyl isocyanoacetate	77 (b)	–	76–78/4	4-Chloro-2-methoxyphenyl isonitrile	73 (n)	95–97	–
N-Methyl-*O*-(β-isocyanoethyl)urethane	73 (h)	38–39	–	5-Chloro-2-methoxyphenyl isonitrile	23 (n)	75–76	–
n-Butyl isonitrile [26, 36e]	75 (f)	–	40–42/11	4-Nitrobenzyl isonitrile	84 (h)	103–104	–
t-Butyl isonitrile [5d, 32]	82 (c) 78 (d) 70 (d_2) 50 (d_1) 24 (d_3)	–	92–93/750	2-Methyl-5-nitrophenyl isonitrile	54 (n)	78–80	–
				2-Methyl-6-nitrophenyl isonitrile	16 (n)	81–86	–
2-Furylmethyl isonitrile	77 (j)	–	35–37/0.02	4-Methyl-3-nitrophenyl isonitrile	59 (n)	75–77	–
1,4-Diisocyanobutane [36c, 53]	58 (j) 32 [65c]	–	70–75/0.001	2-Methoxy-4-nitrophenyl isonitrile	65 (n)	158–160	–
Ethyl β-isocyanopropionate	64 (j)	–	39–40/0.001	4-Methoxy-2-nitrophenyl isonitrile	60 (n)	97–98	–
3-Dimethylaminopropyl isonitrile [33]	66 [51]	–	32–36/0.003	2-Methoxy-5-nitrophenyl isonitrile	87 (n)	103–105	–
C_7:							
Pentachlorophenyl isonitrile	64 (n)	188–191	–	Benzyl isonitrile [32, 36a]	82 [51] 77 (j)	–	92–93/11
2,4,6-Tribromophenyl isonitrile	86 (n)	113–115	–	2-Methylphenyl isonitrile [5, 73]	83 (j) 54 [51] 47 [60]	–	36–38/0.6
2,6-Dibromophenyl isonitrile	93 (i)	208–209	–	4-Methylphenyl isonitrile [2a, 5]	72 [51]	–	70–72/8
2,6-Dichlorophenyl isonitrile [74]	97 (i)	98–100	–	4-Methylsulfonylphenyl isonitrile	85 (i)	90–93	–
3,4-Dichlorophenyl isonitrile	42 (n)	32–33	–	Tricyclo[2.2.1.$0^{2,6}$]-2-heptyl isonitrile	84 (b)	–	56–58/1
3-Nitrophenyl isonitrile [27]	93 (n)	97–99	–	1,3-Diisocyanocyclohexane	97 [65c]	106–107	115–116/1.5
4-Nitrophenyl isonitrile [27]	68 (n)	119–120	–	1,4-Diisocyanocyclohexane [53]	96 [65b, c] 43 (n)	108–109	110–115/0.1
Phenyl isonitrile [2a, 51]	76 (j)	–	50–51/11	1-Cyanocyclohexyl isonitrile	73 (n)	36–38	–
Di-(2-isocyano-1-ethyl)-carbonate	86 (e)	56–59	–	1,2,3,6-Tetrahydrobenzyl isonitrile	87 (f)	–	48–50/0.01
Cyclohexyl isonitrile [34, 51, 73]	88 (f) 70 (j)	–	67–72/13	1,6-Diisocyanohexane [36c, 53]	79 (f) 29 (j) 38 [65c]	–	92–94/0.003
Methyl α-isocyanoisovalerate [51]	76 (j)	–	37–38/15	3-Diethylaminopropyl isonitrile [33]	65 (f)	–	40–42/0.004
t-Butyl isocyanoacetate [51]	77 (j) 75 (g)	–	38–40/0.1	C_9:			
2-Pyrrolidinoethyl isonitrile	64 (j)	–	46–48/0.02	2,4-Diisocyano-2,5,6-trichlorotoluene [53]	67 (o) 65 (n)	112–116	–
N-Methyl-*O*-(2-methyl-2-isocyano-1-propyl)urethane	73 (h)	63–65	–	2-(Pentachlorophenylthio)ethyl isonitrile	97 (h)	113–114	–
C_8:							
1,3-Diisocyanotetrachlorobenzene [53]	61 (i) 53 (n)	63–65	–	2,4-Diisocyanotoluene [53]	34 (n)	88–89	–
1,4-Diisocyanotetrachlorobenzene [53]	84 (i) 83 (n)	188–189 decomp.	–	2,6-Diisocyanotoluene [53]	32 (n)	84–86	–
2-Trifluoromethyl-4-chlorophenyl isonitrile	80 (n)		n. d.	2,5-Diisocyanotoluene [53]	72 (n)	154–155	–
2,4,6-Trichlorobenzyl isonitrile	49 (n)	134–136		2-Methoxycarbonyl-5-nitrophenyl isonitrile	20 (n)	68–70	–
2-Methoxy-3,5,6-trichlorophenyl isonitrile	65 (n)	92–93	–	3-Acetylphenyl isonitrile	97 (i)	45–49	–
1,2-Diisocyanobenzene [53]	32 (n)		n. d.	4-Chloro-2-methoxy-5-methylphenyl isonitrile	59 (n)	93–94	–
1,3-Diisocyanobenzene [53]	83 [65c] 74 (b) 55 (n)	106–107	–	5-Chloro-2,4-dimethoxyphenyl isonitrile	40 (n)	109–110	
				4-Chloro-2,5-dimethoxyphenyl isonitrile	84 (i)	150–151	–
1,4-Diisocyanobenzene [9, 53]	90 (i) 75 [65b, c] 47 (n)	100 decomp.	–	1-(4-Fluorophenyl)ethyl isonitrile	73 (f)	–	59–60/0.02
4-Cyanophenyl isonitrile	82 (i)	130 decomp.	–	2,4-Dimethyl-5-nitrophenyl isonitrile	46 (n)	77–78	–

Table 1 (continued)

Compound [63]	Yield [%] [64]	M.p. [°C]	B.p. [°C/mm] [63]	Compound [63]	Yield [%] [64]	M.p. [°C]	B.p. [°C/mm] [63]
2,4-Dimethyl-6-nitrophenyl isonitrile	29 (n)	50–52	–	6-Isocyano-3-methylquinoline	93 (i)	114–115	–
2-Methoxy-5-methyl-4-nitrophenyl isonitrile	83 (n)	135–136	–	5,6,7,8-Tetrahydro-1-naphthyl isonitrile	93 (j)	–	119–123/0.02
2,5-Dimethoxy-4-nitrophenyl isonitrile	86 (n)	134–137	–	2,5-Diethoxy-4-nitrophenyl isonitrile	57 (n)	140 decomp.	–
2-Chloro-4-(dimethylaminosulfonyl)phenyl isonitrile	44 (i)	98–101	–	2-Methyl-2-phenylpropyl isonitrile	58 (j)	–	68–75/0.05
α-Phenylethyl isonitrile [66]	87 (j)	–	50–54/0.001	1-(4-Tolyl)propyl isonitrile	53 (f)	–	70–73/0.001
2,3-Dimethylphenyl isonitrile	82 (f)	–	62–63/0.01	2,6-Diethylphenyl isonitrile	93 (f)	–	70–72/0.40
	52 (j)			2,4-Dimethyl-6-ethylphenyl isonitrile	78 (f)	–	72–74/0.002
2,4-Dimethylphenyl isonitrile	97 (f)	–	55–58/0.03		58 (j)		
2,5-Dimethylphenyl isonitrile [70]	85 (j)	–	56–58/0.01	Di-(2-methyl-2-isocyanopropyl) carbonate [53]	19 (j)	114–115	120–125/0.001
2,6-Dimethylphenyl isonitrile	84 (f)	72–73	70–75/0.3	1-(β-Isocyanoethyl)-3,6-ethano-hexahydroazepine	74 (j)	–	104–106/0.1
4-Methoxybenzyl isonitrile	25 (j)	–	90–95/0.05	C_{12}:			
4-Methoxy-2-methylphenyl isonitrile	27 (j)	–	68–69/0.0001	1,4-Diisocyanonaphthalene [53]	51 (o)	110–112	–
2,4-Dimethoxyphenyl isonitrile	41 (n)	67–68	–	1,5-Diisocyanonaphthalene [53]	61 (m)	150 decomp.	–
2,5-Dimethoxyphenyl isonitrile	65 (n)	64–65	–	2,7-Diisocyanonaphthalene	93 (m)	142–144	–
2-Phenylthioethyl isonitrile	80 (h)	–	85–90/0.001	5-Cyano-1-naphthyl isonitrile	69 (i)	150 decomp.	–
1,2,3,6-Tetrahydro-3,6-methanobenzyl isonitrile	63 (j)	–	36–40/0.008	*N*-(3,4-Dichlorophenyl)-*O*-(2-isocyano-2-methylpropyl)urethane-	87 (h)	122–125	–
1,2,3,6-Tetrahydro-5-methylbenzyl isonitrile	38 (j)	–	56–58/0.04	4,6-dimethylbenzene			
				1,3-Di(isocyanomethyl)-4,6-dimethylbenzene	15 (n)	68–69	–
2-Isocyano-2-methylpropyl methacrylate	37 (k)	–	88–92/0.02	1,3-Diisocyano-5-isopropyl-2-methylbenzene	24 (n)	70–75	–
N,N-Bis-(3-isocyanopropyl)-*N*-methylamine	54 (l)	–	131–134/0.2	1,4-Diisocyanodurene	82 (o)	127–128	–
				2,6-Diethyl-4-isocyanotoluene	58 (j)	–	72–74/0.002
2,4,4-Trimethylpentyl isonitrile [51]	56 (j)	–	45–50/3	Tris-(3-isocyanopropyl)amine	70 (p)	–	n. d.
Diethyl 2-isocyano-2-methylpropyl thionophosphate	22 (k)	–	70–75/0.004	C_{13}:			
				2-Isocyano-2',4,4',5,5'-pentachlorodiphenyl ether	84 (n)	63–64	–
C_{10}:							
1,4-Bis(isocyanomethyl)-tetrachlorobenzene	70 (m)	170 decomp.	–	2-Phenoxy-3,5-dichlorophenyl isonitrile	68 (i)	120 decomp.	–
8-Isocyanoquinoline	61 (i)	69–70	–	3-Isocyanodibenzofuran	29 (i)	113–114	–
1,3-Diisocyano-4,6-dimethylbenzene	73 (n)	105–107	–	4-Isocyanodibenzofuran	50 (i)	114–116	–
p-Ethoxycarbonylphenyl isonitrile	68 (n)	95–103	–	5-Isocyano-2-phenylbenzotriazole	77 (n)	157–159	–
6-Nitro-2,4,5-trimethylphenyl isonitrile	57 (n)	120–126	–	2-Isocyanobiphenyl	70 (n)	116–118	–
				5-Isocyanoacenaphthene	97 (i)	70–72	–
2-Phenyl-2-propyl isonitrile	45 (j)	–	62–64/0.003	4-Isocyanoazobenzene [28]	73 (n)	102–104	–
2,3,5-Trimethylphenyl isonitrile	79 (j)	–	77–79/0.04	2-Isocyanodiphenyl sulfide	70 (i)	70 decomp.	–
2,4,5-Trimethylphenyl isonitrile	61 (j)	29–31	77–80/0.05	2-Isocyanodiphenyl sulfone	68 (i)	78–80	–
5-Ethylsulfonyl-2-methoxyphenyl isonitrile	74 (n)	108–109	–	2-Ethoxy-1-naphthyl isonitrile	89 (i)	60–62	–
				5-Chloro-2,4-diethyl-1,3-diisocyano-6-methylbenzene	54 (n)	–	110–115/0.1
4-Dimethylaminobenzyl isonitrile	81 (i)	40–41	–				
Ethyl α-isocyanoisovaleroylglycinate	79 (h)	–	n. d.	2,4-Diethyl-1,3-diisocyano-6-methylbenzene [53]	51 (j)	–	108–110/0.5
1,6-Diisocyano-3-dimethylaminohexane	76 (f)	–	110–115/0.003	4-Cyclohexylphenyl isonitrile	91 (j)	–	93–95/0.005
1-Diethylamino-4-pentyl isonitrile	50 (j)	–	58–60/0.1	2,4-Diisopropyl-5-nitrophenyl isonitrile	72 (n)	70–71	–
C_{11}:							
2,4-Dichloro-1-naphthyl isonitrile	79 (n)	95–98	–	3-Methyl-1-(4-tolyl)-butyl isonitrile	68 (j)	–	98–100/0.02
4-Bromo-1-naphthyl isonitrile	61 (n)	88–118 decomp.	–	2,4-Diisopropylphenyl isonitrile	82 (j)	–	71–72/0.02
1-Naphthyl isonitrile [27]	82 (f)	–	90–95/0.005	2,6-Diisopropylphenyl isonitrile	80 (j)	–	94–96/0.7
2-Naphthyl isonitrile [27]	90 (f)	59–60	100–102/1				

Table 1 (continued).

Compound [63]	Yield [%] [64]	M.p. [°C]	B.p. [°C/mm] [63]	Compound [63]	Yield [%] [64]	M.p. [°C]	B.p. [°C/mm] [63]
n-Dodecyl isonitrile [36f, 68, 72]	59 (f) 43 (j)	—	115—118/0.1	1-Phenyl-2-(3,4-dichlorophenylthio)-ethyl isonitrile	98 (i)	—	n. d.
C_{14}:							
1,3-Diisocyano-4-(pentachlorophenylthio)-benzene	95 (m)	160 decomp.	--	1-(4-Chlorophenyl)-2-phenylethyl isonitrile	35 (i)	68—69	—
4,4'-Diisocyano-2,2',5,5'-tetrachloroazoxybenzene	65 (m)	116 decomp.	—	2-(4-Chlorophenylthio)-1-phenylethyl isonitrile	93 (i)	—	n. d.
4,4'-Diisocyano-2,2',6,6'-tetrachloroazoxybenzene	7 (m)	154 decomp.	--	1-Isocyano-1,2-diphenylethane	62 (n)	29—30	n. d.
3,3'-Dichloro-4,4'-diisocyanobiphenyl	88 (m) 39 (n)	300 decomp.	—	1-(4-Biphenylyl)ethyl isonitrile	47 (n)	45—46	—
6,6'-Dichloro-3,3'-diisocyanoazobenzene	51 (o)	152 decomp.	—	2',3-Dimethyl-4-isocyanoazobenzene	80 (i)	115—118	—
2',4'-Dichloro-2,4-diisocyanodiphenyl ether	79 (o)	102 decomp.	--	1-Phenyl-2-phenylthioethyl isonitrile	83 (i)	--	n. d.
3,3'-Dichloro-4,4'-diisocyanoazoxybenzene	67 (o)	132 decomp.	—	5-Benzylsulfonyl-2-methoxyphenyl isonitrile	71 (i)	156—157	—
2-*endo*-(*p*-Isocyanophenyl)-1,4,5,6,7,7-hexachlorobicyclo-[2.2.1]hept-5-ene	75 (i)	167—168	—	C_{16}:			
				1,4,5,6,7,7-Hexachlorobicyclo-[2.2.1]hept-5-ene-*endo*-dicarboxylic *N*-(*p*-isocyanophenyl)-*imide*	76 (h)	>260 decomp.	—
4'-Chloro-2,4-diisocyanodiphenyl ether	67 (o)	110 decomp.	—				
2,4',5-Trichlorobenzhydryl isonitrile	23 (n)	63—64	—	2,2',4,4'-Tetraisocyanobiphenyl	68 (m)	>120	—
2,2'-Diisocyanobiphenyl	70 (n)	101—104	--	1,5-Diisocyanoanthraquinone [53]	42 (m)	90—92	--
2,4'-Diisocyanobiphenyl	60 (o)	97—98	—				
4,4'-Diisocyanobiphenyl	94 (m) 79 [65c]	183—186	—	7-Isocyano-3-phenylcoumarine	41 (n)	100 decomp.	—
4,4'-Diisocyanoazobenzene	35 (o)	195 decomp.	—	3,3'-Dimethyl-4,4'-diisocyanobiphenyl	55 (o)	147—149	—
4,4'-Diisocyanodiphenylether	64 (o) 54 (n)	136—137	—	4,4'-Diisocyano-3,3'-dimethoxybiphenyl	93 (o)	240—243	--
3,3'-Diisocyanoazoxybenzene	71 (o)	96—100	—	3,3'-Diisocyano-4,4'-dimethylazoxybenzene	51 (o)	>130 decomp.	--
4,4'-Diisocyanodiphenylsulfone	93 (o)	>300 decomp.	—	*N*-Ethyl-*N*-(*p*-isocyanobenzoyl)-aniline	58 (i)	72—74	—
4,4'-Dichlorobenzhydryl isonitrile	72 (i) 61 (n)	73—74	—	4,4'-Dimethoxybenzhydryl isonitrile	88 (n)	127—128	—
2-Isocyanofluorene	97 (i)	58—59	—	1-Phenyl-2-(2-tolylthio)-ethyl isonitrile	88 (i)	—	n. d.
4-Isocyanobenzophenone	86 (n)	79—84	—				
4-Isocyano-3-methoxydibenzofuran	68 (n)	172—173	—	1-Phenyl-2-(3-tolylthio)-ethyl isonitrile	96 (i)	--	n. d.
Benzhydryl isonitrile	78 (n)	35—36	—	1-Phenyl-2-(4-tolylthio)-ethyl isonitrile	91 (i)	—	n. d.
2-Isocyano-2'-methyldiphenyl ether	55 (f)	37—40	113—115/0.05	C_{17}:			
1-Isocyano-4'-methyldiphenyl sulfide	83 (i)	68—71	—	4-(β-Naphthoxy)phenyl isonitrile	89 (i)	78—80	—
3-Isocyano-4-methoxydiphenyl sulfone	45 (n)	115—116	—	4-(β-Naphthylthio)-phenyl isonitrile	77 (i)	113—114	—
1,6,11-Triisocyanoundecane	87 (o)	—	n. d.	3,3'-Dichloro-4,4'-diisocyano-5,5'-dimethyldiphenylmethane	37 (n)	208 decomp.	—
C_{15}:							
2,4,4'-Triisocyanobiphenyl	83 (m)	100 decomp.	—	3,3'-Diisocyano-4,4'-dimethoxydiphenyl carbonate [53]	87 (e)	128—130	—
2,4,4'-Triisocyanodiphenyl ether	84 (m)	110 decomp.	—	4,4'-Diisocyano-3,3'-dimethyldiphenylmethane	42 (n)	87—89	--
1-Isocyanoanthraquinone	31 (n)	170 decomp.					
3,3'-Dichloro-4,4'-diisocyanodiphenylmethane	20 (m)	116—118	—	5,7-Dimethyl-2-(4-isocyano-3-tolyl)-benzothiazole	64 (n)	129—130	—
4,4'-Diisocyanobenzophenone	72 (m) 5 (n)	120 decomp.	—	2,6-Diethyl-4-isocyano-4'-nitroazobenzene	86 (i)	133—136	—
4,4'-Diisocyanodiphenylcarbonate	76 (e)	107—128	—	1,3-Diisocyano-2,4,6-triisopropylbenzene [53]	69 (n)	59—61	130—135/0.2
2-(4-Isocyanophenyl)-3,4-benzothiophene 1,1-dioxide	60 (n)	162—163	—	2,6-Di-t-butyl-4-(β-isocyanoethyl)-phenol	70 (n)	114 decomp.	--
				C_{18}—C_{20}:			
4,4'-Diisocyanodiphenylmethane [53]	83 (o) 72 (n)	131—133	—	3,3'-Diethoxy-4,4'-diisocyanobiphenyl [53]	65 (n)	140—142	—
2-(4-Isocyanophenyl)-6-methylbenzothiophene	59 (i)	175—176	—	4,4'-Diisocyano-3,3',5,5'-tetramethyldiphenyl sulfide	68 (o)	185—186	—
1-Phenyl-2-(2,5-dichlorophenylthio)-ethyl isonitrile	84 (i)	—	n. d.	3,3'-Diethyl-4,4'-diisocyanodiphenylmethane	80 (n)	83—84	—

Table 1 (continued)

Compound [63]	Yield [%] [64]	M.p. [°C]	B.p. [°C/mm] [63]
4,4'-Diisocyano-3,3',5,5'-tetramethyldiphenylmethane [53]	72 (o)	190 decomp.	—
4-Lauroylphenyl isonitrile	85 (i)	37–43	—
N-Benzyl-*N*-n-butyl-*N*,*N*-di-(3-isocyanopropyl)ammonium chloride	84 (o)	—	n. d.
4-n-Dodecylphenyl isonitrile	55 (i)	39–55	
4-n-Dodecyloxyphenyl isonitrile	72 (i)	29–34	—
n-Octadecyl isonitrile [36a, 36c, 36c, 68]	95 (h)	—	n. d.
5,5'-Diethyl-4,4'-diisocyano-3,3'-dimethyldiphenyl sulfide	66 (o)	81–82	—
N-n-Dodecyl-3-isocyanobenzamide	54 (i)	62–76 decomp.	—
N,*N*-Di-(3-isocyanopropyl)-*N*-n-dodecylamine	71 (p)	—	n. d.
C_{21}–C_{33}:			
Tri-(4-isocyanophenyl) thionophosphate	13 (n)	120–122	—
1-(4'-Chloro-4-biphenylyl)-2-(4-chlorophenyl)-ethyl isonitrile	89 (i)	116–118	—
2-(3,4-Dichlorophenylthio)-1-(4-biphenylyl)-ethyl isonitrile	92 (i)	74–75	—
1-(4-Biphenylyl)-2-phenylethyl isonitrile	31 (i)	102–103	—
4,4'-Diisocyano-3,3'-diisopropyldiphenylmethane	45 (n)	102–106	—
5,5'-Diethyl-4,4'-diisocyano-3,3'-dimethyldiphenylmethane [53]	90 (o) 68 (n)	128–130	—
2-(n-Dodecylthio)-1-phenylethyl isonitrile	84 (i)	—	n. d.
1,1-Bis-(4-isocyano-3-methylphenyl)cyclohexane	80 (o)	142 decomp.	—
4,4'-Diisocyano-3,3',5,5'-tetraethyldiphenyl sulfide	72 (o)	69–71	—
4,4'-Diisocyano-3,3',5,5'-tetraethyldiphenylmethane [53]	71 (o) 47 (n)	98–99	—
N,*N'*-Bis-(3-isocyano-4-methylphenoxycarbonyl)-1,6-diaminohexane	42 (h)	115–119	—
4,4'-Diisocyano-2,2',5,5'-tetramethyltriphenylmethane	55 (o)	102 decomp.	—
2-Methoxy-5-(*N*-methyl-*N*-n-octadecylaminosulfonyl)phenyl isonitrile	44 (i)	112–120 decomp.	—
N-Benzyl-*N*,*N*-di-(3-isocyanopropyl)-*N*-n-octadecylammonium chloride	86 (m)	—	n. d.

Data regarding the fungicidal, acaricidal, and insecticidal properties of isonitriles are reported in Belg. Pat. 641379 (June 12th, 1964; German priority: Dec. 17th, 1962), Farbenfabriken Bayer AG., inventors: *I. Ugi, U. Fetzer, F. Grewe, W. Behrenz, P. E. Frohberger, B. Homeyer, H. Scheinpflug,* and *G. Unterstenhöfer*; Spanish Pats. 294587 and 294588 (Febr. 7th, 1964; German priority: Dec. 17th, 1962) and Belg. Pats. 641309 and 641311 (June 12th, 1964; German priority: Dec. 17th, 1962), Farbenfabriken Bayer AG., inventors: *U. Fetzer, I. Ugi, G. Unterstenhöfer, W. Behrenz, P. E. Frohberger,* and *H. Scheinpflug*; cf. also [68, 74].

[68] U.S. Pat. 3012932 (Dec. 12th, 1961), Standard Oil of Indiana, inventor: *F. Bussert.*

dipping deeply into the liquid, and a wide gas outlet. The flask is cooled and stirred, and 1.00 kg (10.1 moles) of phosgene is led in at 20–30 °C over a period of 3–4 h, followed 1 hour later by 100 g of ammonia. The reaction product is distilled *in vacuo* (about 150 mm Hg) at 30–50 °C and collected in traps cooled by dry ice. The crude product (430 g) is distilled through a helix-packed column with reflux control; b.p. 32–35 °C/120 mm Hg, yield: 358 g (65 %).

(b) *Ethyl Isocyanoacetate*

105 g (1.06 mole) of phosgene dissolved in 900 ml of methylene chloride is added dropwise to a refluxing solution of 131 g (1.00 mole) of the ethyl ester of formylglycine in 320 ml of triethylamine and 500 ml of methylene chloride. The reaction mixture is concentrated *in vacuo* and 200 ml of benzene is added. The mixture is then filtered, concentrated once more, and distilled *in vacuo*; b.p. 76–78 °C/4 mm Hg, yield: 87 g (77 %).

(c, d) *t-Butyl Isonitrile*

(c) 1.00 kg (10.1 moles) of phosgene is led into a stirred solution of 1.01 kg (10.0 moles) of *N*-t-butylformamide in 1.30 kg of trimethylamine and 7.0 l of *o*-dichlorobenzene. The heat of the reaction is dissipated with the aid of a reflux condenser carrying cooling brine (−20 °C). Water is added, the layers are separated, and the non-aqueous layer is dried over anhydrous potassium carbonate or magnesium sulfate and fractionated; b.p. 90–92 °C/750 mm Hg, yield: 681 g (82 %).

(d) 1.00 kg (10.1 moles) of phosgene is added to 1.01 kg (10.0 moles) of t-butylformamide in 5.4 l of tri-n-butylamine and 2.5 l of 1,2,4-trichlorobenzene at 10–20 °C (cf. Section 4.112a). After the introduction of 50 g of ammonia, the reaction product is distilled at 120–150 mm Hg (bath temperature 80–85 °C) and purified by fractionation, yield: 648 g (78 %).

(d_1) If the product of a preparation according to 4.112d is isolated by steam distillation, the yield is 413 g (50 %).

(d_2) If the tri-n-butylamine of 4.112 d is replaced by 3.50 kg of *N*,*N*-diethylaniline, the yield of t-butylisonitrile is 582 g (70 %)

(d_3) If the tri-n-butylamine of 4.112d is replaced by 3.00 kg of quinoline, the yield is 222 g (24 %).

(e) *Di-(2-isocyanoethyl) Carbonate*

300 g (3.03 moles) of phosgene is led into a boiling solution of 178 g (2.00 moles) of 2-formylaminoethanol (prepared from 2-aminoethanol and methyl formate) in 1.00 l of triethylamine and 1.50 l of methylene chloride. The solution is then cooled to 20 °C, 110 g of ammonia is introduced, and the mixture is filtered and concentrated. The residue solidifies on standing; m.p. 58–60 °C, yield: 145 g (86 %).

To prepare diisocyanodiaryl carbonates by a similar method, it is recommended that the reaction mixture is worked up in analogy to the procedure given in Section 4.112 n.

(f) *Cyclohexyl Isonitrile*

1.27 kg (10.0 moles) of *N*-cyclohexylformamide, 3.20 l of triethylamine, and 4.50 l of methylene chloride are placed in the reaction vessel. The solution is stirred, and phosgene is led in sufficiently rapidly (300–400 g/h) to cause vigorous refluxing. When the solution ceases to boil (after about 1.04 kg of phosgene has been introduced), the introduction of phosgene is immediately stopped and the solution is cooled to about 20 °C. About 400 g of ammonia is led into the solution over a period of 1–2 hours, and the mixture is filtered and then concentrated *in vacuo*. The residue is distilled; b.p. 67–72 °C/14 mm Hg, yield: 955 g (88 %).

(g) *t-Butyl Isocyanoacetate*

100 g (1.01 mole) of phosgene is led into a boiling, stirred solution of 159 g (1.00 mole) of the t-butyl ester of formylglycine [51] in 400 ml of triethylamine and 400 ml of methylene chloride over a period of one hour. The solution is cooled in ice, saturated with ammonia (55 g in 50 min), and filtered. The residue is washed with methylene chloride, the solution is concentrated *in vacuo*, and the crude product is purified by distillation *in vacuo*; b.p. 52–58 °C/0.3 mm Hg, yield: 106 g (75 %).

(h) *p-Nitrobenzyl Isonitrile*

36 g (0.364 mole) of phosgene dissolved in 300 ml of methylene chloride is added to a boiling solution of 60.0 g (0.333 moles) of *N*-formyl-*p*-nitrobenzylamine in 110 ml of triethylamine and 400 ml of methylene chloride. The solvent is distilled off *in vacuo*, and the residue is taken up in 100 ml of benzene. The resulting solution is concentrated, filtered, and washed with cyclohexane; m.p. 103–104 °C, yield: 45.3 g (84 %).

(i) *p-Methylsulfonylphenyl Isonitrile*

796 g (4.00 moles) of *p*-methylsulfonylformanilide, 1.30 l of triethylamine, and 3.0 of methylene chloride are placed in the reaction vessel. 415 g (4.20 moles) of phosgene are led in without external cooling. The solution is saturated with ammonia at about 20 °C, filtered, and concentrated. The residue is mixed with ether/isopropanol (1:3), stirred in a homogenizer, and filtered; m.p. 88–89 °C, yield: 613 g (85 %).

(j) *α-Phenylethyl Isonitrile*

99 g (1.00 mole) of phosgene is led into an ice-cooled, stirred solution of 147 g (1.00 mole) of *N*-formyl-α-phenylethylamine in 350 ml of triethylamine and 1.0 l of methylene chloride. Water is added, the layers are separated, and the non-aqueous layer is dried and distilled *in vacuo*; b.p. 41–45 °C/0.001 mm Hg, yield: 112 g (87 %).

(k) *2-Methyl-2-isocyanopropyl Methacrylate*

314 g (3.00 moles) of methacryloyl chloride is added to a boiling solution of 351 g (3.00 moles) of 2-methyl-2-formylaminopropanol and a spot of phenothiazine in 1.50 l of triethylamine and 2.50 l of methylene chloride. 300 g of phosgene is then passed into the solution. Ice water is added; the non-aqueous layer is separated, washed with sodium bicarbonate solution, dried, and concentrated *in vacuo*. The crude product (498 g) can be purified in portions by distillation *in vacuo*; b.p. 65–70 °C/0.008 mm Hg, yield: 187 g (37 %).

(l) *N,N-Di-(3-isocyanopropyl)-methylamine*

1.02 kg (1.03 mole) of phosgene is led into a stirred, boiling solution of 1.015 kg (5.00 moles) of *N,N*-di-(3-formylaminopropyl)methylamine in 3.20 l of triethylamine and 5.00 l of methylene chloride. The solution is saturated with ammonia at 20 °C, filtered, and concentrated. The residue (730 g) is purified by molecular distillation; b.p. 131–134 °C/0.25 mm Hg, yield: 445 g (54 %).

(m) *2,7-Diisocyanonaphthalene*

107 g (0.50 mole) of 2,7-diformylaminonaphthalene is suspended in 320 ml of triethylamine and 1.20 l of methylene chloride, and thoroughly mixed in a homogenizer. 100 g (1.01 mole) of phosgene is led into the boiling suspension, followed by 35 g of ammonia. The suspension is filtered and the filtrate concentrated. The residue is stirred in isopropanol, filtered, and washed with ether; m.p. 142–144 °C, yield: 82 g (93 %).

(n) *4-Isocyanoazobenzene*

225 g (1.0 mole) of 4-formylaminoazobenzene, 320 ml of triethylamine, and 2.50 l of methylene chloride are placed in the reaction vessel. The mixture is cooled in ice and stirred, and 100 g (1.01 mole) of phosgene is led in. After one hour, water is added, the layers is separated, and the non-aqueous layer is dried and distilled *in vacuo*. The residue is washed with light petroleum; m.p. 102–104 °C, yield: 151 g (73 %).

(o) *4,4'-Diisocyanodiphenylmethane*

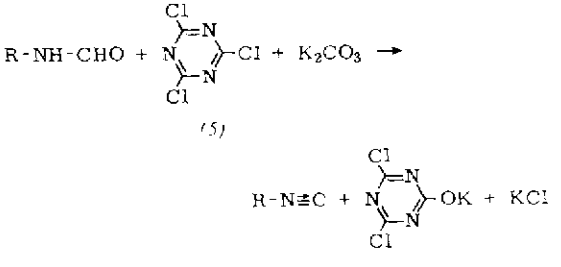
254 g (1.00 mole) of 4,4'-diformylaminodiphenylmethane is suspended in 650 ml of triethylamine and 1.0 l of methylene chloride, and thoroughly mixed in a homogenizer. The suspension is stirred and 200 g (2.02 moles) of phosgene is led in, whereupon the reaction mixture refluxes owing to the heat of the reaction. The mixture is saturated with ammonia at 20 °C, and the precipitated ammonium chloride is filtered off and washed with methylene chloride. The filtrate is concentrated *in vacuo* and the residue (219 g) is mixed with 150 ml of ether and 8 ml of isopropanol, stirred at 0 °C in a homogenizer, and separated by suction filtration; m.p. 131–133 °C, yield: 181 g (83 %).

(p) *N,N-Di-(3-isocyanopropyl)-n-dodecylamine*

200 g (2.02 moles) of phosgene is led into a stirred, boiling solution of 355 g (1.00 mole) of *N,N*-di-(3-formylaminopropyl)-n-dodecylamine, 650 ml of triethylamine, and 1.50 l of methylene chloride. The solution is saturated with ammonia at 20 °C, filtered, and concentrated. Steam is passed through the residue for a short time (about 5 min) to remove volatile impurities (mainly 3-chloropropyl isonitrile). Dark resins are removed by making use of their insolubility in ether. Concentration of the dried ether solution yields 218 g (71 %) of a light brown oil which cannot be distilled without decomposition.

4.12 Cyanuric Chloride as the Dehydrating Agent

The reaction of *N*-monosubstituted formamides with cyanuric chloride *(5)* and potassium carbonate in acetone has only been used for the preparation of a few simple isonitriles (n-butyl isonitrile, cyclohexyl isonitrile,



(5)

benzyl isonitrile) [69]. It may be a particularly mild method in special cases.

4.13. The Sulfochloride Method

Benzenesulfonyl chloride and toluenesulfonyl chloride in pyridine [45a, 70] are relatively mild dehydrating

[69] *R. Wittmann*, Angew. Chem. *73*, 219 (1961).

[70] *W. R. Hertler* and *E. J. Corey*, J. org. Chemistry *23*, 1221 (1958).

agents, and are particularly suitable for the preparation of small quantities of isonitriles.

$$R\text{-}NHCHO + Ar\text{-}SO_2Cl + 2\,Py \rightarrow R\text{-}NC + Py\cdot ArSO_3H + Py\cdot HCl$$

Quinoline is a useful base and solvent for the preparation of low-boiling, aliphatic isonitriles, since its high boiling point facilitates the isolation of the reaction product [71] by distillation.

Some examples of preparations by the sulfochloride method are described in references [45a, 70–72].

4.14 The Phosphorus Oxychloride Method

The synthesis of isonitriles from *N*-monosubstituted formamides using phosphorus oxychloride as the dehydrating agent requires more work and material than when phosgene is used. This may be important in the preparation of large quantities of isonitriles. Moreover, the phosgene method generally gives higher yields. Nevertheless, in laboratories where safety provisions are inadequate for safe handling of the extremely poisonous, volatile phosgene, the choice must fall on phosphorus oxychloride, or even on a sulfochloride, as the dehydrating agent.

Aliphatic or araliphatic isonitriles can be prepared from the corresponding formamide simply by a combination of phosphorus oxychloride and pyridine [48, 49, 73, 73a].

$$2\,R\text{-}NHCHO + POCl_3 + 4\,Py \rightarrow 2\,R\text{-}NC + Py\cdot HPO_3 + 3\,Py\cdot HCl$$

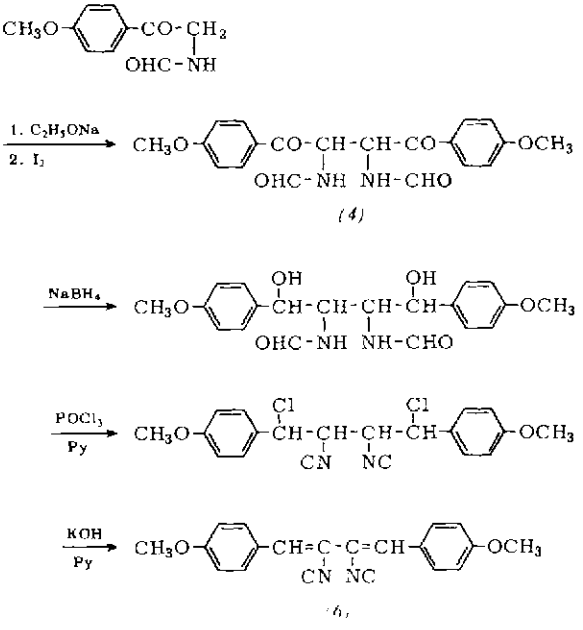
This method gives 58–95% yields of aliphatic isonitriles but only 7–54% of aromatic isonitriles [48, 74].

The elimination of water from *N*-arylformamides by phosphorus oxychloride proceeds satisfactorily, however, if potassium t-butoxide is used as the base. The reason for this is probably that the anion formed from *N*-arylformamides by the t-butoxide [75] is more readily *O*-acylated by phosphorus oxychloride than the starting material itself.

$$2\,[R\text{-}N\text{:}\,CH\,\,O]^{\ominus}K^{\oplus} + POCl_3 + 2(CH_3)_3COK \rightarrow 2\,RNC + KPO_3 + 3\,KCl + 2(CH_3)_3COH$$

It is possible in this way to prepare mono- and diisonitriles in 56–88% yield [48, 76].

The phosphorus oxychloride method can also be used for the dehydration of *N*-formylhydrazones to form isocyanamide derivatives [77], and for the preparation of aliphatic β-oxo-, β-hydroxy-, and β-chloro-isonitriles. α,β-Unsaturated isonitriles are accessible by dehydrochlorination of β-chloro-isonitriles [77, 78]. The last steps in the recent synthesis [77, 79] of *O,O'*-dimethylxanthocillin *(6)* (cf. Section 4.1) correspond to this type of reaction.



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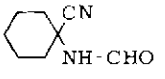
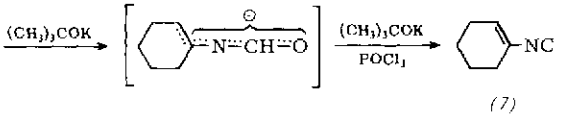
(6)

The synthesis of 2-cyclohexenyl isonitrile *(7)* (57% yield [80]) from *N*-(1-cyanocyclohexyl)formamide *(8)* represents another variant of the phosphorus oxychloride method.



(8)



(7)

4.2. The Thermolysis of N,N'-Diaryl-N-hydroxyformamides

In the course of his investigations on cycloadditions, *Ingold* observed that nitrosobenzene and *p*-chloronitrosobenzene form stable adducts with *N*-methylenaniline or its *p*-bromo, *p*-chloro, or *p*-methyl derivatives [81].

These adducts were found to be *N,N'*-diaryl-*N*-hydroxyformamidines *(9)*, instead of the expected 1,4-diaryl-

[71] *J. Casanova, E. R. Schuster*, and *N. D. Werner*, J. chem. Soc. (London) *1963*, 4280.

[72] *M. Lipp, F. Dallacker*, and *I. Meier zu Köcker*, Mh. Chem. *90*, 41 (1959).

[73] *I. Ugi, R. Meyr, M. Lipinski, F. Bodesheim*, and *F. K. Rosendahl*, Org. Syntheses *41*, 13 (1961).

[73a] *F. Lautenschläger* and *G. F. Wright*, Canad. J. Chem. *41*, 863 (1963).

[74] Belgian Published Patent Application 625036 (Nov. 19th, 1962/May 20th, 1963), Philips' Gloeilampenfabricken.

[75] *J. Hine* and *M. Hine*, J. Amer. chem. Soc. *74*, 5266 (1952).

[76] *I. Ugi* and *R. Meyr*, Org. Syntheses *41*, 101 (1961).

[77] *I. Hagedorn*, Angew. Chem. *75*, 305 (1963).

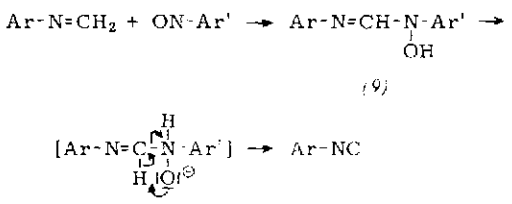
[78] *I. Hagedorn* and *H. Elting*, Angew. Chem. *73*, 26 (1961).

[79] *I. Hagedorn* and *U. Eholzer*, Angew. Chem. *74*, 215 (1962); Angew. Chem. internat. Edit. *1*, 514 (1962); German Published Patent Application 1167332 (July 6th, 1961/Apr. 9th, 1964), Farbenfabriken Bayer AG., inventors: *I. Hagedorn* and *H. Etling*; *I. Hagedorn, U. Eholzer*, and *H. Etling*, Chem. Ber. *98*, 193 (1965). *I. Hagedorn* and *U. Eholzer*, ibid. *98*, 202 (1965).

[80] *I. Ugi* and *F. K. Rosendahl*, Liebigs Ann. Chem. *666*, 65 (1963).

[81] *C. K. Ingold*, J. chem. Soc. (London) *125*, 87 (1924).

1,2,4-oxadiazetidines [82]. They decompose on heating to form isonitriles, presumably by α-elimination *via* a cyclic mechanism.

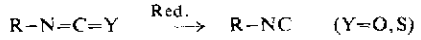


(9)

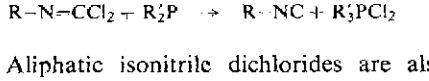
5. Redox Reactions

The reduction of readily available derivatives of iminocarbonic acid could provide a valuable addition to the above methods for the preparation of isonitriles, if it could be made to proceed under mild conditions and in high yield. Usually, however, drastic reaction conditions are required, and the yields are only moderate.

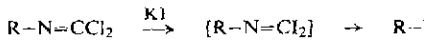
Isocyanates are reduced by heating with triethyl phosphite (17–57% yield [83]), whereas isothiocyanates can be reduced with triethylphosphine [84], triphenyltin hydride [84b], copper [84a], or by photolysis [85].



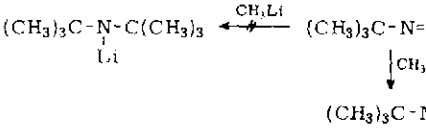
Tertiary phosphines dehalogenate isonitrile dichlorides [86].



Aliphatic isonitrile dichlorides are also reduced by iodide. The intermediate isonitrile diiodide is unstable and dissociates spontaneously into isonitrile and iodine [87].



Isonitrile halides can also be converted to isonitriles by organometallic compounds. Attempts to obtain di-t-butylamine by the reaction of t-butyl isocyanide di-



(10)

(11)

chloride with methyl-lithium [88] led to the formation of t-butyl isocyanide *(11)*, probably by halogen-metal exchange and subsequent α-elimination. Tetrabromo-*N,N'*-dimethylenehydrazine *(12)* cannot be reduced by metals to diisocyanogen [89].

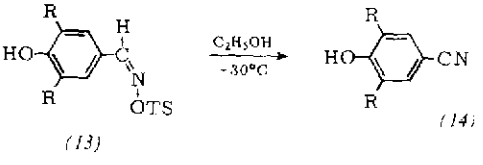
(12)

During the oxidation of 1-cyclohexyl [34] and 1-phenyl [90] thiosemicarbazides with sodium chlorite or hypochlorite or with mercuric oxide, small amounts of isonitriles are formed.

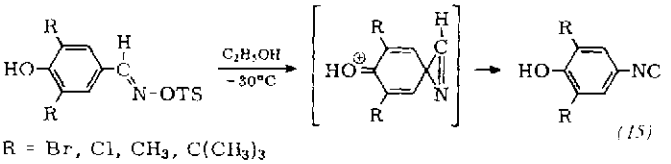
Brackman and *Smit* [90a] believe that the oxidation of n-butylamine/methanol with oxygen, which is catalysed by copper(II) chloride, leads to n-butyl isonitrile. A reaction of this type would necessarily proceed *via* *N*-methylene-n-butylamine, and would be a counterpart to the reduction of iminocarbonic acid derivatives.

6. Abnormal Beckmann Rearrangements

According to *Müller* and *Narr* [91], the *O*-tosyl oximes of 3,5-disubstituted 4-hydroxybenzaldehydes *(13)* and of *p*-dimethylaminobenzaldehyde, which are obtained from the sodium salts of the oximes and *p*-toluenesulfonyl chloride, give mixtures of the corresponding nitriles *(14)* and isonitriles *(15)* in 40 to 92% yield on elimination of *p*-toluenesulfonic acid. The formation of the nitriles corresponds to nucleophilic β-elimination of a proton and a tosylate anion [92], whereas the isonitrile is formed from the *syn*-isomer by an abnormal Beckmann rearrangement [93–95].



(13) *(14)*



(15)

R = Br, Cl, CH_3, $C(CH_3)_3$

A similar interpretation can be given for the reaction of the *syn*-oximes of benzaldehyde, *p*-methylbenzaldehyde,

[82] *M. D. Farrow* and *C. K. Ingold*, J. chem. Soc. (London) *125*, 2543 (1924); cf. also *G. N. Burkhardt*, *A. Lapworth* and *E. B. Robinson*, J. chem. Soc. (London) *127*, 2234 (1925).

[83] *T. Mukaiyama*, *H. Nambu*, and *M. Okamoto*, J. org. Chemistry *27*, 3651 (1962).

[84] *A. W. Hofmann*, Ber. dtsch. chem. Ges. *3*, 766 (1870).

[84a] *W. Weith*, Ber. dtsch. chem. Ges. *6*, 210 (1873).

[84b] *D. H. Lorenz* and *E. I. Becker*, J. org. Chemistry *28*, 1707 (1963).

[85] *U. Schmidt* and *K. H. Kabitzke*, Angew. Chem. *76*, 687 (1964); Angew. Chem. internat. Edit. *3*, 641 (1964).

[86] German Published Patent Application 1158501 (May 23rd, 1962/Dec. 5th, 1962), Farbenfabriken Bayer AG., inventors: *H. Malz* and *E. Kühle*.

[87] *K. A. Petrov* and *A. A. Nejmyševa*, Zhur. obshch. Khim. *29*, 2165 (1959).

[88] *I. Ugi* and *F. K. Rosendahl*, unpublished work.

[89] *C. Grundmann*, personal communication.

[90] *K. Ley* and *U. Eholzer*, personal communication.

[90a] *W. Brackman* and *P. J. Smit*, Recueil Trav. chim. Pays-Bas *82*, 757 (1963).

[91] *E. Müller* and *B. Narr*, Z. Naturforsch. *16* B, 845 (1961).

[92] Review: *P. Kurtz* in *Houben-Weyl*: Methoden der organischen Chemie. Thieme, Stuttgart 1952, Vol. 8, pp. 247, 325; cf. also *J. F. Bunnett*, Angew. Chem. *74*, 731 (1962); Angew. Chem. internat. Edit. *1*, 225 (1962).

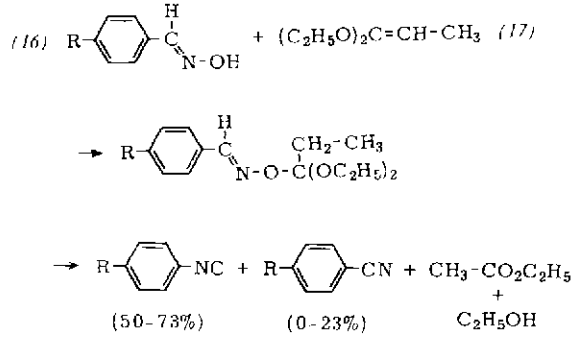
[93] *A. Werner* and *A. Piquet*, Ber. dtsch. chem. Ges. *37*, 4295 (1904).

[94] See also: *E. Beckmann* and *A. Köster*, Liebigs Ann. Chem. *274*, 1 (1893).

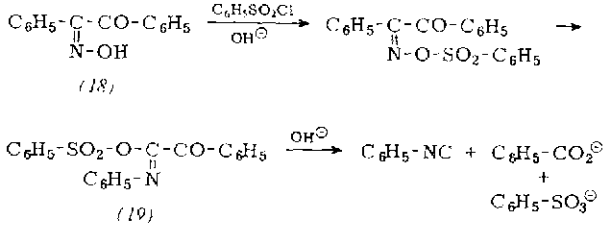
[95] *A. H. Blatt* and *R. P. Barnes*, J. Amer. chem. Soc. *56*, 1148 (1934); J. org. Chemistry *24*, 580 (1959); *A. Ferris*, ibid. *25*, 12 (1960); *A. F. Ferris*, *G. S. Johnson* and *F. E. Gould*, ibid. *25*, 1813 (1960); Reviews: *C. A. Grob*, Bull. Soc. chim. France *1960*, 1360; *P. A. S. Smith* in *P. de Mayo*: Molecular Rearrangements. Interscience Publishers, New York 1963, p. 457.

and *p*-nitrobenzaldehyde *(16)* with methylketene diethylacetal *(17)* [96], which is catalysed by boron trifluoride/mercuric oxide.

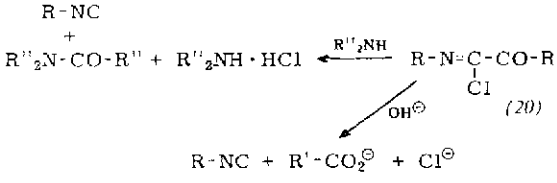
Similar treatment of the *anti*-oximes yields only the nitriles (60–80%) [92].



On attempting to carry out a Beckmann rearrangement of γ-benzil monoxime *(18)* by the action of benzenesulfonyl chloride and alkali, *Werner* and *Piquet* [93] obtained products containing benzoic acid, phenyl isonitrile, and a sulfur compound which was decomposed by alkali to yield benzoic acid and phenyl isonitrile. The reaction was interpreted as a Beckmann rearrangement of the γ-benzil monoxime *O*-benzenesulfonate to phenylglyoxyl anilide *O*-benzenesulfonate *(19)*, followed by



alkaline cleavage of the latter [93,94]. This interpretation is supported by the α-fragmentation of α-ketocarboxylic imide chlorides *(20)* by alkali [5–5b,61,97] and by amines [61,97].

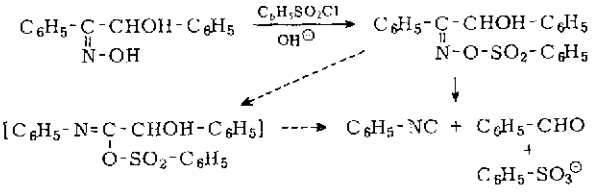


It is not yet known whether the α-fragmentation occurs during or after the abnormal Beckmann rearragement of *p*-benzoin oxime [98].

[96] *T. Mukaijama, K. Tonooka*, and *K. Inoue*, J. org. Chemistry *26*, 2202 (1961); see also: *T. Mukaijama* and *T. Hata*, Bull. chem. Soc. (Japan) *33*, 1382 (1960).

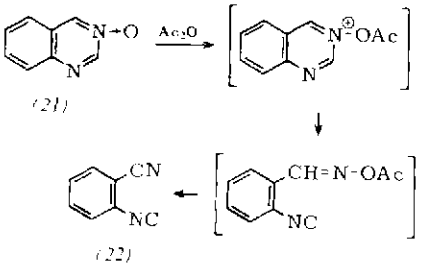
[97] *I. Ugi, F. Beck*, and *U. Fetzer*, Chem. Ber. *9*, 126 (1962).

[98] *A. Werner* and *T. Detscheff*, Ber. dtsch. chem. Ges. *38*, 69 (1905).

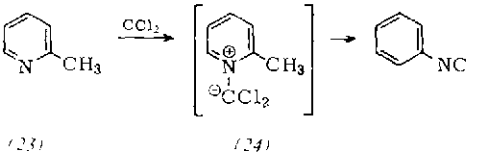


7. Ring-Cleavage Reactions of Heterocyclic Compounds

The cleavage of heteroaromatic rings to form isonitriles may be regarded as a further indication of the strong tendency of the isonitriles to be formed (*i.e.* isonitriles are thermodynamically favorable and a large number of reactions with suitable activation energies are available). Quinazoline 3-oxide *(21)* is converted by acetic anhydride into 2-isocyanobenzonitrile *(22)* [99].



According to *Ploquin*, 2-methylpyridine *(23)* reacts with dichlorocarbene, *via* the ylide *(24)*, to form phenyl isonitrile by ring cleavage followed by ring closure in a new arrangement [41].



Indole reacts with nitrosobenzene to form phenyl isonitrile [100]. The reaction is assumed to proceed *via* intermediates *(25)* and *(26)* [101], corresponding to those postulated by *Grundmann* to explain the tetramerization of phenyl isonitrile to indigo dianil *(27)* [103].

No investigations have as yet been carried out, to our knowledge, to find whether indigo dianil can also be prepared "directly" from indole and nitrosobenzene.

The anomalous Hofmann degradation of β-arylglycidamides *(28)* is an example of the formation of isonitriles by ring cleavage of nonaromatic heterocyclic systems.

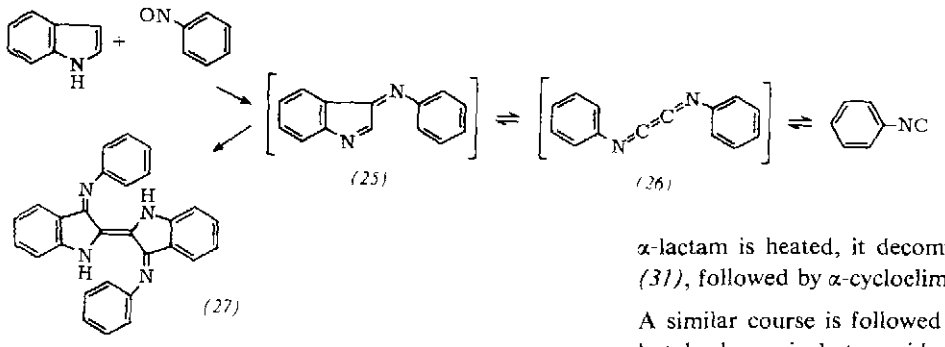
[99] *T. Higashino*, Chem. pharmac. Bull. (Tokyo) *9*, 635 (1961).

[100] *W. Madelung* and *M. Tencer*, Ber. dtsch. chem. Ges. *48*, 953 (1915).

[101] "Dimeric phenyl isocyanide", which may exist in small quantities in equilibrium with phenyl isocyanide, can probably also be regarded as an intermediate in the synthesis of 2-hydroxy-1-naphthylglyoxal [102].

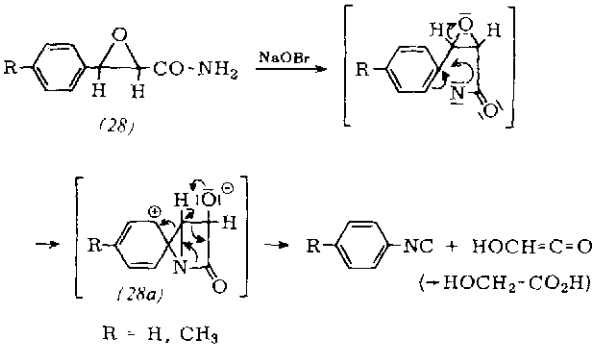
[102] *M. Passerini*, Gazz. chim. ital. *54*, 185, 633 (1924); *55*, 555 (1925); *M. Passerini* and *A. Neri*, ibid. *64*, 934 (1934).

[103] *C. Grundmann*, Chem. Ber. *91*, 1380 (1958).



(25) (26) (27)

As an alternative to the mechanism proposed by *Abraham* and *Hajela* [104] an intermediate *(28a)* may be assumed [105] (a differentiation between these mechanisms could be made by labelling with ^{14}C).

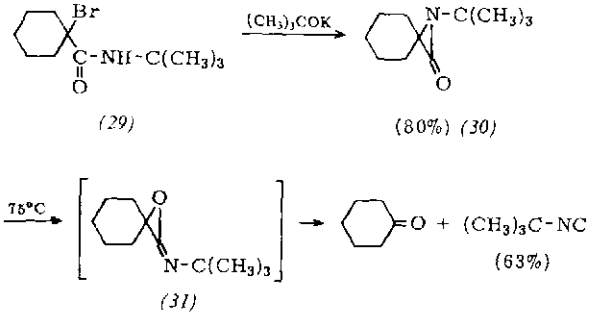


(28) (28a)

R = H, CH_3

8. Ring-Closure Reactions of α-Halogenoacylamines Followed by α-Cycloelimination

According to *Sheehan* and *Lengyel* [106], *N*-t-butyl-1-bromocyclohexanecarboxamide *(29)* can be cyclized to the α-lactam *(30)* by potassium t-butoxide. When the



(29) (80%) (30) (31)

[104] *N. A. Abraham* and *N. Hajela*, C. R. hebd. Séances Acad Sci. *255*, 3192 (1962).

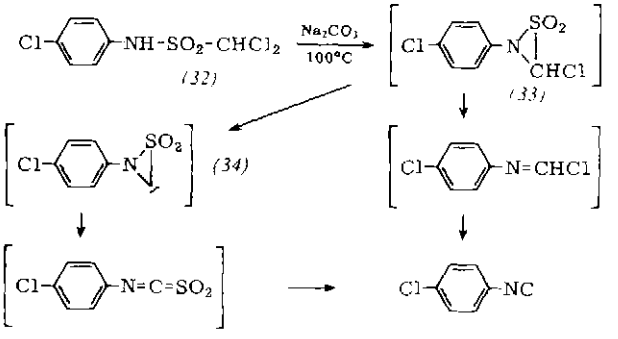
[105] Cf. *M. S. Newman* and *C. Courduvelis*, J. Amer. chem. Soc. *86*, 2942 (1964).

[106] *J. C. Sheehan* and *I. Lengyel*, J. Amer. chem. Soc. *86*, 746 (1964).

α-lactam is heated, it decomposes by isomerization to *(31)*, followed by α-cycloelimination.

A similar course is followed in the conversion of *N*-t-butyl-α-bromoisobutyramide to 1-t-butyl-2,2-dimethylaziridin-3-one (54%) and the thermal dissociation of the latter into acetone (12%), t-butyl isonitrile (12%), and *N*-t-butylmethacrylamide (65%) [106a].

Reactions proceeding by related mechanisms are the formation of small quantities of cyclohexyl isonitrile from *N*-cyclohexyldichloroacetamide and potassium t-butoxide [107] and the formation of 4-chlorophenyl isonitrile from the sodium salt of *N*-(4-chlorophenyl)dichloromethylsulfonamide [108]. It is not yet known whether, in the latter reaction, the intermediate α-sultam *(33)* decomposes by α-cycloelimination followed by α-dehydrochlorination, or whether the opening of a three-membered carbene ring *(34)* [109] is followed by cleavage of the cumulative double-bond system.



(32) (33) (34)

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German version: Angew. Chem. *77*, 492 (1965)
Translated by Express Translation Service, London

[106a] *J. C. Sheehan* and *I. Lengyel*, J. Amer. chem. Soc. *86*, 1356 (1964).

[107] *I. Ugi*, unpublished work.

[108] *W. V. Farrar*, J. chem. Soc. (London) *1960*, 3058.

[109] *W. v. E. Doering* and *P. M. La Flamme*, Tetrahedron *2*, 75 (1958); *W. R. Moore* and *H. R. Ward*, J. org. Chemistry *25*, 2073 (1960); *27*, 4129 (1962); *L. Skattebøl*, Tetrahedron Letters *1961*, 167; *T. J. Logan*, ibid. *1961*, 173; *W. J. Ball* and *S. R. Landor*, Proc. chem. Soc. (London) *1961*, 143; J. chem. Soc. (London) *1962*, 2298; *P. D. Gardner* and *M. Narayana*, J. org. Chemistry *26*, 3518 (1961); *W. R. Moore* and *R. C. Bertelson*, ibid. *27*, 4182 (1962).

Equilibrium and Transport Properties of Concentrated Electrolyte Solutions

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A historical survey is followed by a discussion of a number of problems associated with concentrated solutions of electrolytes containing two ion constituents: general thermodynamic properties, dissociation equilibria, phase separation, analytical representation of the thermodynamic functions over the entire range of concentrations, and general relationships in electrical conductivity, diffusion, and sedimentation. A number of relationships valid at all concentrations is formulated, and known relationships pertaining to dilute solutions are derived from these as special cases. The discussion of concentrated solutions is illustrated by numerical examples, most of which are based on recent results.

I. Introduction

The beginnings of physical chemistry are closely linked with the experimental and theoretical study of the equilibrium and transport properties of electrolyte solutions, a field which also covers investigation of galvanic cells. Consider, for example the contributions made during the second half of the last century by *Arrhenius*, *Gibbs*, *Helmholtz*, *Hittorf*, *Kohlrausch*, *Nernst*, *Ostwald*, *Planck*, and *van't Hoff*.

The properties in question were described in these early investigations on the basis of the theory of ideal dilute solutions. In this simple approximation, the electrolyte solutions are assumed to be so dilute that the interactions between the ions are negligible. Consequently, the only thermodynamic difference between such electrolyte solutions and ideal dilute non-electrolyte solutions is the increase in the number of solute particles as a result of dissociation in the former case. The dissociation equilibrium is described by the classical law of mass action. An effect of the approximation is that the dependence of the equivalent conductivity on the concentration appears to be due only to changes in the degree of dissociation of the electrolyte, whilst the mobilities of the ions are independent of concentration. This statement, together with the classical law of mass action, leads to *Ostwald*'s dilution law, which was confirmed for dilute aqueous solutions of weak electrolytes, *e.g.* dilute acetic acid, to within the experimental accuracy possible at that time (*Ostwald* 1888). The diffusion coefficient of the electrolyte in an ideal dilute solution also can easily be related to the ionic mobilities (*Nernst* 1888).

It soon became clear, however, that even at very high dilutions, solutions of strong electrolytes (*e.g.* hydrochloric or sulfuric acid or salts in water) exhibit such wide deviations from the laws known at that time that the equations for ideal dilute solutions could no longer be regarded as being applicable. These deviations were even observed for concentrations at which non-electrolyte solutions still show approximately ideal behaviour. Thus these "anomalies of strong electrolytes" are undoubtedly connected with the relatively high concentrations, and consequent interactions, of the ions. Quantitative description of these interactions was soon attempted. It was not until 1923, however, that a useful molecular statistical theory was evolved by *Debye* and *Hückel*. This theory was later extended and re-stated by *Onsager* (1926–1927) for application to electrical conductivity. Some consequences of these laws had already been discovered empirically, by *Kohlrausch* (1869–1880) in the case of conductivity, and by *Bjerrum* (1916), *Brönsted* (1922), *Lewis* (1921–1923), and others in the case of the thermodynamic functions.

It is now known that the equations proposed by *Debye*, *Hückel*, and *Onsager* are themselves limiting laws: they correspond to the first approximation beyond the laws of ideal dilute solutions. The molecular concepts on which they are based are as follows:

The electrolyte solution consists of a system of charged particles embedded in a non-conducting medium with the same density, dielectric constant, and viscosity as the solvent. The ion concentration is so small that elimination of the charges would yield an ideal dilute solution. The ions move in a disordered manner (Brownian movement). When transport processes take place, an ordered motion is superposed on the thermal movement; in particular, during conduction of electricity, cations and anions migrate in opposite directions, giving rise to relaxation and electrophoretic effects, the complete mathematical treatment of which is extremely complicated.

The present molecular theories of the equilibrium and transport properties of electrolyte solutions still reduce to the limiting laws of *Debye*, *Hückel*, and *Onsager* at sufficiently low concentrations. The range of validity has been extended to include higher electrolyte concentrations by taking into account such factors as incomplete dissociation and ion association or solvation. However, general applicability of the equations to electrolyte solutions of any concentration is ruled out right from the start by the fundamental simplification of the theory, according to which ions and aggregates of ions are regarded as discrete entities and the solvent as a structureless continuum.

If it is desired to cover the entire range of concentrations from pure solvent to pure liquid electrolyte, as is possible experimentally *e.g.* with the systems water/acetic

acid, water/hydrochloric acid, or water/sulfuric acid, we cannot base our considerations on the theoretical or semi-empirical equations which have been used in the past. Instead, we must build up an entirely new picture in which (at least for the equilibrium properties) the non-electrolyte and the electrolyte are no longer regarded as the "solvent" and the "solute", respectively, but as equivalent components. In this new scheme, which is essentially empirical at the moment, and which will be developed below for thermodynamic functions, the *Debye-Hückel* limiting law retains its validity. This law, together with *Onsager*'s limiting law, is one of the few results of the molecular theory of electrolyte solutions which has been accepted as reliable by all research workers.

Our discussion of the equilibrium and transport properties of concentrated electrolyte solutions is confined to solutions of a single electrolyte containing two ion constituents, *e.g.* $CaCl_2$, H_2SO_4, or H_3PO_4, in an inert solvent, *e.g.* H_2O.

For the sake of simplicity we exclude electrolytes with three or more ion constituents (*e.g.* $KHSO_4$), mixed electrolyte solutions, and fused salts. Moreover, we cannot concern ourselves with details of liquid-vapor and liquid-solid equilibria or osmotic phenomena, since although these are important for experimental determinations of thermodynamic functions, they are not limited to electrolytes. It will also be necessary, in our consideration of transport processes, to omit discussion of viscosity and non-isothermal processes (thermal conduction, thermal diffusion, etc.), as well as of galvanic cells.

II. Equilibrium Properties

1. General

Consider a binary liquid mixture, in which component 1 is a non-electrolyte ("solvent"), and component 2 an electrolyte containing two ion constituents. At high electrolyte concentrations we therefore have at least four types of particles present: non-electrolyte molecules, undissociated electrolyte molecules, and at least one kind of cation and one kind of anion.

We assume for the moment that the liquid is free from electric potential or concentration gradients, *etc.*, since we are at present concerned only with equilibrium properties.

As independent variables with which to describe the macroscopic state of the liquid mixture, we choose the absolute temperature T, the pressure P, and a single concentration variable, which we take to be either the stoichiometric mole fraction x of the electrolyte or the molality m (moles electrolyte per kg solvent). The quantities x and m are related as shown in Equation (1), where M_1 is the kilogram-molecular weight of the non-electrolyte.

$$m = \frac{x}{M_1 \cdot (1-x)} \quad \text{or} \quad x = \frac{M_1 \cdot m}{1 + M_1 \cdot m} \tag{1}$$

The pure solvent is described according to Eq. (1) by $x = 0$ or $m = 0$, and the pure liquid electrolyte by $x = 1$ or $m \to \infty$. The pure liquid electrolyte corresponds to a real state only in systems such as H_2O/HCl or H_2O/H_2SO_4; for systems with a saturation limit, e.g. $H_2O/NaCl$, it represents a hypothetical state (*e.g.* "fused sodium chloride at 25 °C and 1 atm"). Nevertheless, the two components are treated in principle as equivalent.

It is possible to calculate all equilibrium properties of the electrolyte solution, with the exception of the dissociation constant, provided that we know the chemical potentials μ_1 and μ_2 of the two components or the molar Gibbs free energy, $\overline{G} = (1-x)\mu_1 + x\mu_2$, of the liquid mixture as a function of T, P, and x. We need not know the absolute values of μ_1, μ_2, and $\overline{G}$, but simply the differences between these quantities and their values for the pure liquid components. Let μ_{0i} be the chemical potential of the pure liquid component i at the given values of T and P, and R the gas constant. We then make use of the dimensionless quantities defined by equations (2) and (3), which we consider as functions of T, P, and x.

$$\psi_1 \equiv \frac{\mu_1 - \mu_{01}}{RT} \; ; \; \psi_2 \equiv \frac{\mu_2 - \mu_{02}}{RT} \tag{2}$$

$$\Gamma \equiv (1-x)\cdot\psi_1 + x\cdot\psi_2 = \frac{(1-x)(\mu_1 - \mu_{01}) + x\cdot(\mu_2 - \mu_{02})}{RT}$$

$$= \frac{\overline{G} - (1-x)\cdot\mu_{01} - x\cdot\mu_{02}}{RT} \tag{3}$$

The function ψ_1 is related to the "activity" a_1 of component 1 (which we do not require in this discussion) by the equation $\psi_1 = \ln a_1$.

Equations (4) and (5) follow from the Gibbs-Duhem equation.

$$(1-x)\left(\frac{\delta\psi_1}{\delta x}\right)_{T,P} + x\left(\frac{\delta\psi_2}{\delta x}\right)_{T,P} = 0 \tag{4}$$

$$\psi_1 = \Gamma - x\left(\frac{\delta\Gamma}{\delta x}\right)_{T,P}; \psi_2 = \Gamma + (1-x)\left(\frac{\delta\Gamma}{\delta x}\right)_{T,P} \tag{5}$$

The other properties of the quantities ψ_1 and ψ_2 or Γ, *e.g.* those relating to the conditions for stability and coexistence, are also similar to those of the chemical potentials μ_1 and μ_2 or the molar free energy $\overline{G}$.

Two other quantities are generally used in the literature instead of ψ_1, ψ_2, and Γ: these are the osmotic coefficient φ of the solvent and the conventional activity coefficient γ of the electrolyte, which are considered as functions of T, P, and m.

Let ν_+ and ν_- respectively be the number of cations and anions which result from complete dissociation of one molecule of electrolyte (*e.g.* H_2SO_4: $\nu_+ = 2$, $\nu_- = 1$; H_3PO_4: $\nu_+ = 3$, $\nu_- = 1$). Moreover, let $\mu_2^{\ominus}$ be a standard value of the chemical potential of the electrolyte, depending, like μ_{01} and μ_{02}, only on T and P.

The functions φ and γ can then be defined as follows.

$$\varphi \equiv \frac{\psi_1}{\nu \cdot M_1 \cdot m} \tag{6}$$

$$\nu \cdot \ln(\nu_+ \cdot m \cdot \gamma) \equiv \psi_2 + C_2 \tag{7}$$

with

$$\nu = \nu_+ + \nu_- \; ; \; \nu_\pm^\nu \equiv \nu_+^{\nu_+} \cdot \nu_-^{\nu_-} \tag{8}$$

and

$$C_2 \equiv \frac{\mu_{02} - \mu_2^{\ominus}}{RT} \tag{9}$$

In the case of electrolytes such as HCl or Na_2SO_4, which give only two types of ions on dissociation, irrespective of the concentration, it is possible to use the degree of dissociation α of the electrolyte and the mean ionic activity coefficient $\gamma_\pm$ [on the molality (m) scale] in accordance with Equation (10). The quantity which can be measured directly is γ, not $\gamma_\pm$.

$$\gamma = \alpha \cdot \gamma_\pm \quad (10)$$

Whereas φ, C_2, and α are dimensionless, γ and $\gamma_\pm$ as defined in equations (7) and (10) have the same dimensions as 1/m and M_1, namely kg/mole. In this connection, we use the following abbreviations:

$$m\dagger \equiv 1 \text{ mole/kg}; \gamma\dagger \equiv M\dagger \equiv 1 \text{ kg/mole}.$$

An ideal dilute electrolyte solution is characterized by the condition $\gamma_\pm = \gamma\dagger$. Furthermore, if the electrolyte in such a solution is completely dissociated, then $\varphi = 1$; $\alpha = 1$; $\gamma_\pm = \gamma = \gamma\dagger$.

Using Equations (1), (4), (6), and (7), and integrating between $m = 0 (\varphi = 1; \gamma = \gamma\dagger)$ and $m = m (\varphi = \varphi; \gamma = \gamma)$ at constant temperature and pressure, we obtain Equations (11) and (12), which are important for the evaluation of experimental data.

$$\varphi = 1 + \frac{1}{m} \cdot \int_0^m m \cdot d \ln \frac{\gamma}{\gamma\dagger} \quad (11)$$

$$\ln \frac{\gamma}{\gamma\dagger} = \varphi - 1 + \int_0^m \frac{\varphi - 1}{m} \cdot dm \quad (12)$$

If both components are volatile, the quantities ψ_1 and ψ_2 can be found from the partial vapor pressures, and these are used together with Equations (6) and (12) to find the functions φ and γ. If only the solvent is volatile, then vapor pressure measurements (generally by the indirect isopiestic method) lead to ψ_1, and hence to φ and γ, but not to ψ_2. If only the electrolyte is volatile, then only ψ_2 can be obtained from the vapor pressure. One can also find φ, and hence ψ_1 and γ, from freezing point determinations. E.m.f. measurements lead to the quantity γ, from which φ can be determined by Equation (11), and hence ψ_1 by Equation (6). The constant C_2 for volatile electrolytes can be obtained from γ and ψ_2 with the aid of Equation (7).

2. Dissociation Equilibria

A dissolved electrolyte such as HCl or Na_2SO_4 yields only two types of ions, irrespective of the concentration, *e.g.*

$$Na_2SO_4 \rightleftarrows 2\,Na^+ + SO_4^{2-}. \quad (13)$$

Electrolytes such as H_2SO_4 or H_3PO_4, on the other hand, dissociate in two or three stages. We shall disregard these more complicated cases in the present discussion.

A single-step dissociation of the type (13) can be described by the general equilibrium condition (14) [1].

$$\frac{\nu_+^\nu \cdot m^{\nu-1} \cdot \gamma^\nu}{(1-\alpha) \cdot \gamma_u} = K_m \quad (14)$$

[1] *R. Haase*, Z. physik. Chem. N.F. *39*, 360 (1963).

In the above equation, γ_u is the activity coefficient of the undissociated electrolyte and K_m the dissociation constant of the electrolyte (both quantities on the m scale). K_m is dimensionless and depends only on T and P.

For our example (13), we have: $\nu = 3$; $\nu_\pm = 4^{1/3}$. However, the dissociation equilibria discussed below are of the simplest type (15).

$$HNO_3 \rightleftarrows H^+ + NO_3^-. \quad (15)$$

Here $\nu = 2$; $\nu_\pm = 1$, so that Equation (14) reduces to

$$\frac{m \cdot \gamma^2}{(1-\alpha)\gamma_u} = K_m \quad (16)$$

Since

$$\lim_{m \to 0} \gamma_u = \gamma\dagger \quad (17)$$

it follows from Equation (16) [2, 3] that

$$\lim_{m \to 0} \left[\ln \frac{m \cdot \gamma^2}{(1-\alpha)\gamma\dagger} \right] = \ln K_m \quad (18)$$

Using Equation (18), therefore, we can find the dissociation constant K_m at given pressure for any temperature, provided that $\gamma(m)$ and $\alpha(m)$ are known. The standard values of the affinity $A^\ominus$, the heat of dissociation $h_{TP}^\ominus$, and the entropy of dissociation $s_{TP}^\ominus$ (on the m scale) can be obtained from K_m by means of Equations (19), (20), and (21).

$$A^\ominus = RT \ln K_m \quad (19)$$

$$h_{TP}^\ominus = RT^2 \left(\frac{\partial \ln K_m}{\partial T} \right)_P = -R \left(\frac{\partial \ln K_m}{\partial (1/T)} \right)_P \quad (20)$$

$$Ts_{TP}^\ominus = h_{TP}^\ominus + A^\ominus \quad (21)$$

We also have

$$T \left(\frac{\partial s_{TP}^\ominus}{\partial T} \right)_P = \left(\frac{\partial h_{TP}^\ominus}{\partial T} \right)_P \quad (22)$$

Whereas some method can always be found for the measurement of the activity coefficient γ, the experimental determination of the degree of dissociation α presents a problem. The usual methods, particularly for strong electrolytes, depend on assumptions, *e.g.* that of a certain concentration dependence of the electrical conductivity. It was a great advance, therefore, when several authors, and *Redlich* in particular, pointed out the possibility of determining the concentrations of ions by the relatively direct spectroscopic methods. Thus values of the function $\alpha(m)$, obtained from Raman [3] and nuclear resonance spectra [4], are now available for aqueous nitric and perchloric acids at several temperatures. We base our calculations on the results reported by *Hood* and *Reilly* [4], since these appear to be the most precise so far.

We have determined the activity coefficients from partial vapor pressure and isopiestic measurements, for the

[2] *R. Haase, K.-H. Dücker*, and *H. A. Küppers*, Ber. Bunsenges. physik. Chem., in press.

[3] *O. Redlich* and *J. Bigeleisen*, J. Amer. chem. Soc. *65*, 1883 (1943); *O. Redlich, E. K. Holt*, and *J. Bigeleisen*, J. Amer. chem. Soc. *66*, 13 (1944); *O. Redlich*, Chem. Reviews *39*, 333 (1946); Mh. Chem. *86*, 329 (1955).

[4] *G. C. Hood, O. Redlich*, and *C. A. Reilly*, J. chem. Physics *22*, 2067 (1954); *G. C. Hood* and *C. A. Reilly*, ibid. *32*, 127 (1960).

systems H_2O/HNO_3 and $H_2O/HClO_4$, as far as possible in the concentration and temperature range for which the degrees of dissociation are known. These activity coefficients were used to calculate K_m, $A^{\ominus}$, $h^{\ominus}_{TP}$, and $s^{\ominus}_{TP}$ [2] with the aid of equations (18) to (21) at atmospheric pressure. The results are listed in Table 1. HNO_3 and $HClO_4$ are strong acids of comparable strengths. The quantity $h^{\ominus}_{TP}$ and hence also [by Eq. (22)] $s^{\ominus}_{TP}$, is found to be practically constant over the temperature range studied.

Table 1. Dissociation constant K_m and standard values of the affinity $A^{\ominus}$, heat of dissociation $h^{\ominus}_{TP}$, and entropy of dissociation $s^{\ominus}_{TP}$, for aqueous nitric and perchloric acids [2].

Temp. [°C]	K_m		$A^{\ominus}$ [kcal/mole]		$h^{\ominus}_{TP}$ [kcal/mole]		$s^{\ominus}_{TP}$ [cal·deg^{-1} mole^{-1}]	
	HNO_3	$HClO_4$	HNO_3	$HClO_4$	HNO_3	$HClO_4$	HNO_3	$HClO_4$
10		41.1		+2.09		−1.99		0.36
25	33.5	34.5	+2.08	+2.10	−3.51	−1.99	−4.81	0.36
40		29.3		+2.10		−1.99		0.36
50	20.3		+1.94		−3.51		−4.81	
75	14.5		+1.85		−3,51		−4.81	

We then used the values of $\alpha(m)$, $\gamma(m)$, and K_m for both acids, together with Equations (10) and (16), to determine the mean ionic activity coefficient $\gamma_{\pm}(m)$ and the activity coefficient $\gamma_u(m)$ of the undissociated acid [2]. By way of example, Fig. 1 shows the three functions $\gamma(m)$, $\gamma_{\pm}(m)$, and $\gamma_u(m)$ for aqueous perchloric acid at 25 °C.

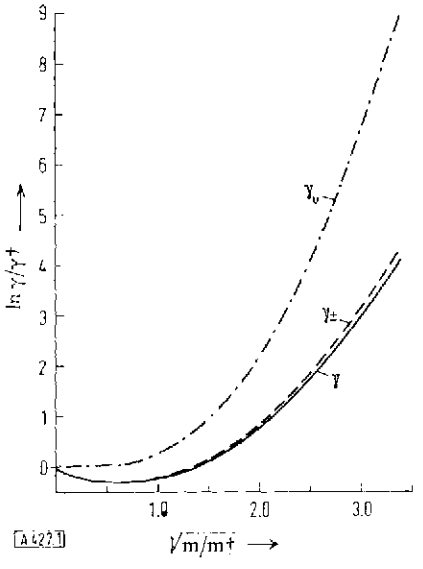

Fig. 1. The system $H_2O/HClO_4$ at 25 °C: Logarithms of the conventional activity coefficient γ, the mean ionic activity coefficient $\gamma_{\pm}$, and the activity coefficient γ_u of the undissociated electrolyte, *vs.* the square root of the molality m, according to [2].
($\gamma\dagger \equiv 1$ kg/mole, $m\dagger \equiv 1$ mole/kg).

Remarkably high values are found for γ_u in concentrated acids, in contrast to the values of about 1 kg/mole found for dilute acids. For example, 16 molal aqueous perchloric acid at 25 °C has $\gamma_u \approx 5 \times 10^5$ kg/mole. On the other hand, the highest conventional activity coefficient previously known, *i.e.* that of 35 molal hydrobromic acid at 25 °C, is $\gamma \approx 4800$ kg/mole, obtained from vapor pressure measurements [5].

[5] *R. Haase, H. Naas,* and *H. Thumm,* Z. physik. Chem. N.F. *37*, 210 (1963).

3. Phase Separation

In a two-component liquid mixture, phase separation results in two coexistent binary liquid mixtures with different compositions in equilibrium with each other. This phenomenon is relatively rare in electrolyte solutions, and is usually not mentioned even in modern monographs on electrolytes.

As early as 1888, *Bakhuis Roozeboom* [6] observed phase separation at high acid concentrations in the systems H_2O/HCl and H_2O/HBr. The former system has been quantitatively investigated [7] over the entire miscibility gap, together with the solid-liquid equilibria which occur at low temperatures. We have verified these early results with the aid of vapor pressure measurements [5], supplemented them by quantitative investigations on the H_2O/HBr system, and showed that phase separation also occurs in the system H_2O/HI.

All three of these systems exhibit miscibility gaps without accessible critical temperatures for phase separation. Thus the upper limit of the range in which the two liquids coexist is formed by the critical point for evaporation (which almost coincides with the critical point of the pure hydrogen halide), and the lower limit is fixed by equilibrium with a solid hydrate. All the phase separation curves are extremely unsymmetrical, one phase always containing almost pure acid.

The miscibility gaps found for the three systems are given in Table 2. The results relate to the pressures at which the three phases coexist (*i.e.* the vapor pressure over the two liquid phases), but the values at atmospheric pressure should be practically the same. We can therefore construct two isobaric phase separation diagrams from the data given in Table 2 (x″ and x‴ as functions of T at constant P).

Table 2. Phase separation in aqueous hydrogen halides. Stoichiometric mole fractions x″ and x‴ of the acid in the water-rich and acid-rich phases respectively, as functions of temperature.

System	Temp. [°C]	x″		x‴	
		from [7]	from [5]	from [7]	from [5]
H_2O/HCl	5	0.485	0.478	0.9990	
	10	0.480	0.473	0.9985	
	15	0.475	0.468	0.9982	
	20	0.470	0.464	0.9980	
	25	0.465	0.459	0.9977	
	30	0.460	0.454	0.9975	
	35	0.455	0.450	0.9972	
H_2O/HBr	15		0.423		0.999
	20		0.418		0.999
	25		0.411		0.998
	30		0.403		0.996
	35		0.400		0.994
H_2O/HI	25		0.346		0.995

The occurrence of a miscibility gap in any binary system can be seen from the form of the function $\Gamma(x)$ for given values of T and P. If the entire curve of $\Gamma(x)$ is convex towards the x-axis, miscibility is complete. If phase separation occurs, the curve contains two points of inflection and a bend which allows the construction of a double tangent (*cf.* Fig. 4 below). The range of concentrations over which Γ is concave towards the x-axis corresponds to labile (absolutely unstable) states.

[6] *H. W. Bakhuis Roozeboom,* Z. physik. Chem. *2*, 449 (1888).
[7] *F. F. Rupert,* J. Amer. chem. Soc. *31*, 851 (1909).

The limits of stability are given by the points of inflection. The region between the points of inflection and the points of contact of the double tangent correspond to metastable states. All other concentrations correspond to stable one-phase systems. The points of contact of the double tangent show the compositions (x'' and x''' in Table 2) of the two coexistent liquid phases. If these points of contact are found from the Γ-x curves for various temperatures at a given pressure and transferred to a T-x diagram, the isobaric phase separation diagram results.

We shall give some examples of the shapes of Γ-x curves which have been obtained from experimental results for aqueous electrolyte solutions at 25 °C and 1 atm.

4. Analytical Representation of the Equilibrium Properties

To obtain an analytical representation of the equilibrium properties of an electrolyte solution at any concentration, it is best to start with the function Γ (T, P, x). All other thermodynamic quantities can then be obtained by differentiation.

We express function Γ in the form of Equation (23) [1, 8], which is valid for solutions of an electrolyte with two ion constituents over the entire range of concentrations from $x = 0$ to $x = 1$.

$$\Gamma = (1-x)\cdot\ln(1-x) + \nu\cdot x\cdot\ln x + (C+\nu-1)\cdot x - \frac{2}{3}B_0\cdot x^{3/2} \quad (23)$$
$$+ \frac{1}{2}B_1\cdot x^2 + \frac{2}{5}B_2\cdot x^{5/2} + \frac{1}{3}B_3\cdot x^3 + \frac{2}{7}B_4\cdot x^{7/2} + \frac{1}{4}B_5\cdot x^4 + \ldots.$$

In equation (23), C, B_0, B_1, B_2, ... are dimensionless parameters depending only on T and P and related by Equation (24).

$$\frac{1}{2}B_1 + \frac{2}{5}B_2 + \frac{1}{3}B_3 + \frac{2}{7}B_4 + \frac{1}{4}B_5 + \ldots = \nu - 1 + C + \frac{2}{3}B_0 \quad (24)$$

Differentiation of (23) with respect to T or P gives the corresponding expressions for the dependence of the entropy of mixing and heat of mixing, or of the volume effects, on concentration.

The first three terms on the right-hand side of Equation (23) correspond to the equations for ideal solutions of fully dissociated electrolytes. The constant C appearing in the third term is given by the general expression (25), where C_2 has the same meaning as in Equations (7) and (9). For volatile electrolytes, C_2 can be derived directly from the experimental results (cf. Section II, 1), so that we can immediately find C.

$$C = C_2 - \nu\cdot\ln\nu_+ + \nu\cdot\ln\frac{M_1}{M_l} \quad (25)$$

The fourth term of Equation (23), which contains B_0, corresponds to the Debye-Hückel limiting law. Thus B_0 is related to the Debye-Hückel coefficient a by

$$B_0 = -\frac{a}{\sqrt{M_1}}\cdot z_+\cdot z_-\cdot\nu\cdot\sqrt{\frac{I}{2}(z_+^2\cdot\nu_- + z_-^2\cdot\nu_-)} \quad (26)$$

In this equation, z_+ and z_- are the electrochemical valences of the cations and the anions respectively, formed from the electrolytes in the last stage of dissociation (*e.g.* $CaCl_2$: $z_+ = 2$; $z_- = -1$; H_2SO_4: $z_+ = 1$; $z_- = -2$). Consequently B_0 is always known at the outset.

If component 1 is water, then at 25 °C and 1 atm:

$$M_1 = 18.016 \times 10^{-3}\ \text{kg/mole};\quad a = 1.176\ \text{kg}^{1/2}/\text{mole}^{1/2} \quad (27)$$

Equation (27), together with Equations (25) and (26), gives for aqueous electrolyte solutions at 25 °C and 1 atm the Equations (28) and (29). Numerical values of C and B_0 are given in Table 3.

$$C = C_2 - \nu\cdot\ln\nu_- + \nu\cdot\ln(18.016\cdot10^{-3}) \quad (28)$$

$$B_0 = -\frac{17.53\, z_+\cdot z_-\cdot\nu}{2}\sqrt{\frac{I}{2}(z_+^2\nu_+ + z_-^2\cdot\nu_-)}. \quad (29)$$

The terms in Equation (23) which contain B_1, B_2, ... *etc.* are empirical terms corresponding to a continuation of the expansion of Γ (x) in fractional powers of x. If the electrolyte is not volatile, there are n independent parameters (B_1, B_2, ... B_n), and the quantity C is determined from Eq. (24). For volatile electrolytes (*e.g.* HCl, HBr, HI, HNO_3), C can be determined from vapor pressure data, so that Equation (24) gives a relationship between B_1, B_2, ... B_n. We then have (n-1) independent parameters. If $\nu = 1$, $B_0 = 0$, $B_2 = 0$, $B_4 = 0$, ... etc., Equation (23) reduces to the ordinary power series for binary solutions of non-electrolytes.

Using Equations (1), (5), (6), and (7), it is possible to derive expressions for ψ_1, ψ_2, φ, and γ from Equation (23) [1, 8]. We shall confine ourselves here to giving the equation (30) for the activity coefficient γ, which is derived from (1), (5), (7), (23), and (25).

$$\nu\cdot\ln\frac{\gamma}{\gamma\dagger} = \nu\cdot\ln(1-x) - B_0\cdot x^{1/2} + (B_1 - \nu + 1)\cdot x$$
$$+ \left(\frac{1}{3}B_0 + B_2\right)\cdot x^{3/2} + \left(B_3 - \frac{1}{2}B_1\right)\cdot x^2 + \left(B_4 - \frac{3}{5}B_2\right)\cdot x^{5/2}$$
$$+ \left(B_5 - \frac{2}{3}B_3\right)\cdot x^3 - \frac{5}{7}B_4\cdot x^{7/2} - \frac{3}{4}B_5\cdot x^4 - \ldots. \quad (30)$$

As can be seen from Equation (30), which does not involve C, the slope of the curve of $\ln(\gamma/\gamma\dagger)$ against $x^{1/2}$ at $x = 0$ is $-B_0/\nu$. This corresponds to the Debye-Hückel limiting law.

Table 3 shows the values of the adjustable parameters B_1, B_2, ... *etc.* for aqueous solutions of 17 electrolytes at 25 °C and 1 atm, as obtained by us [2, 8] from experimental data. These are practically the only electrolyte solutions for which reliable data covering a wide range of concentrations exist. The constants ν, C, and B_0 are also included in Table 3. The C values for the hydrogen halides and nitric acid were determined from experimental values of C_2, using Equation (28), that for perchloric acid (in brackets) was subsequently determined from B_0, B_1, B_2, etc., with the aid of Equation (24). It can be seen that three, four, or five independent parameters are required.

Measurements extending to pure liquid electrolyte ($x = 1$) are possible in only a few cases (*e.g.* sulfuric acid). The continuation of the investigations up to $x = 1$ usually is prevented by fundamental or practical difficulties, *e.g.* a miscibility gap in the case of the hydrogen halides, a

[8] *R. Haase, H. Naas,* and *K.-H. Dücker,* Z. physik. Chem. N.F. *39*, 383 (1963).

Table 3. Values of the constants in Equations (23) and (30), for concentrated aqueous electrolyte solutions at 25 °C and 1 atm [2, 8].

Electrolyte	C	B_0	B_1	B_2	B_3	B_4	B_5
HCl	10.33	17.53	191.5	− 923.8	2908	− 3898	1765
HBr	16.17	17.53	206.8	− 1044	3515	− 4786	2156
HI	13.99	17.53	238.6	− 1335	4712	− 6784	3325
HNO_3	4.15	17.53	151.8	− 487.3	768.5	− 417.5	
$HClO_4$	(128.3)	17.53	161.7	− 449.4	719.7		
H_2SO_4		91.08	476.9	− 798.2	490.4		
NaOH		17.53	117.8	− 236.9	250.4		
KOH		17.53	163.8	− 738.6	2406	− 3660	2170
LiCl		17.53	142.2	− 316.9	380.2		
CsCl		17.53	134.7	− 957.5	4483	−10320	8996
$CaCl_2$		91.08	1473	−13020	63720	−14430	12090
LiBr		17.53	149.0	− 345.2	484.1		
$LiNO_3$		17.53	189.2	− 1115	4449	− 8906	6842
NH_4NO_3		17.53	108.5	− 563.3	1662	− 2505	1502
$AgNO_3$		17.53	96.91	− 761.2	3171	− 6439	5063
$Ca(NO_3)_2$		91.08	721.6	− 2121	2165		
$Pb(ClO_4)_2$		91.08	1469	−12640	60500	−13630	11480

saturation limit in the case of bases and salts, or decomposition of the electrolyte in the cases of nitric and perchloric acids.

Fig. 2 shows a plot of $\ln(\gamma/\gamma\dagger)$ as a function of $m^{1/2}$ for hydrochloric acid. The calculated values agree closely with the experimental results. The measurements on which the experimental curve of Fig. 2 is based [5] extend as far as the miscibility limit (cf. Table 2).

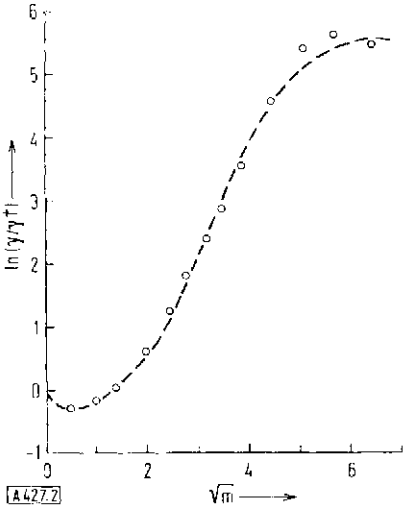

Fig. 2. The system H_2O/HCl at 25 °C: Logarithm of the conventional activity coefficient γ *vs.* the square root of the molality m according to [8]. Experimental: (ooo); calculated from Equations (1) and (30), using the constants in Equation (27) and Table 3: (— —). ($\gamma\dagger \equiv$ 1 kg/mole, $m\dagger \equiv$ 1 mole/kg).

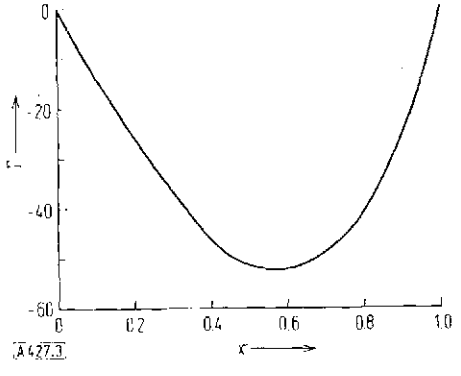

Fig. 3. The system H_2O/$HClO_4$ at 25 °C: Γ (x) as a function of the stoichiometric mole fraction x of the electrolyte, as calculated by Equation (23) using the constants in Table 3.

With the constants listed in Table 3, a miscibility gap for the hydrogen halides and complete miscibility for the other systems can be predicted. In the example of Fig. 3 (perchloric acid), the course of the Γ–x curve is characteristic of complete miscibility. Fig. 4, on the other hand, shows a typical example (hydrochloric acid) of the Γ–x curve in a system which exhibits phase separation. The

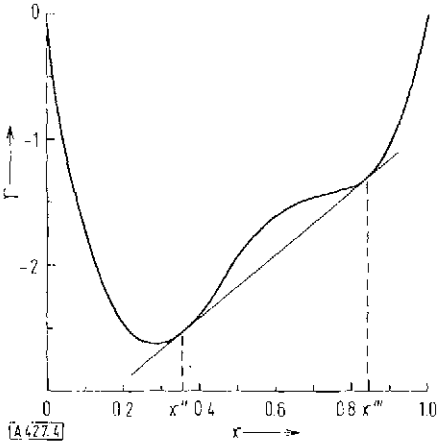

Fig. 4. The system H_2O/HCl at 25°C: Γ (x) as a function of the stoichiometric mole fraction x of the electrolyte, according to [8], calculated by Equation (23) using the constants in Table 3 (x'', x''': values of x for the two coexistent liquid phases).

compositions of the two coexisting liquid phases ($x'' = 0.35$ and $x''' = 0.84$) as obtained from the points of contact of the double tangent are reasonably close to the values obtained by direct measurement (Table 2: $x'' = 0.46$ and $x''' = 0.998$). Similar results were found for hydrobromic and hydriodic acids [8].

III. Electrical Conductivity

1. General

In an electrolyte solution which is situated in an external electric field, but which is otherwise homogeneous, *i.e.* exhibits no gradients other than the potential gradient, conduction of electricity occurs, associated with migration of the ions. If we discregard extremely high field strengths, Ohm's law expressed in the form (31) applies to each volume element.

$$\vec{I} = \varkappa \vec{\mathfrak{E}} = -\varkappa \operatorname{grad} \varphi \quad (31)$$

In Equation (31), the vectors $\vec{I}$ and $\vec{\mathfrak{E}}$ are the electric current density and field strength, respectively, φ is the electric potential, and $\varkappa$ is the specific conductivity.

The result of the mutual opposition of the electrostatic force on the ions and the resistance of the medium (resistance due to friction and electrostatic interaction whith other ions) is that, after a brief acceleration, an ion moves at a constant average velocity with respect to the solvent. If the magnitude of this velocity of migration is divided by the magnitude of the electric field, we obtain a positive quantity u_i, the mobility of ions of type i. Within the range of validity of Ohm's law, u_i is inde-

pendent of the field strength, but is a function of the intensive variables of the system (temperature, pressure, concentration). It is convenient to replace u_i by the ionic conductivity λ_i of the ions of type i, as defined in Equation (32); F is the Faraday constant.

$$\lambda_i \equiv F \cdot u_i \tag{32}$$

It can be shown [9] that, provided that Ohm's law is valid, the relationship (33) must always be satisfied. In this equation, $|z_i|$ is the magnitude of the electrochemical valence and c_i the molarity of ions of type i. The summation must be carried out over all types of ions present.

$$\varkappa = F \cdot \sum_i z_i c_i \cdot u_i = \sum_i z_i c_i \cdot \lambda_i \tag{33}$$

When more than two types of ions are present, the discussion of equation (33) becomes complicated. In the next section, therefore, we shall confine ourselves to solutions of electrolytes containing two types of ions (*e.g.* HCl or Na_2SO_4). We shall also assume, for the sake of simplicity, that the solvent (*e.g.* H_2O) does not form ions. After the discussion of transport numbers, we shall also examine whether the ionic mobilities and conductivities can be derived from experimental data in this case.

2. Equivalent Conductivities

We shall now deal with electrolyte solutions containing two types of ions, using either the molarity c or the equivalent concentration c* of the electrolyte as the macroscopic concentration variable. We then have [cf. Equation (1)]:

$$c = \frac{\rho \cdot m}{1 + M_2 \cdot m} \; ; \; c^* = z_+ \nu_+ c = z_- \nu_- c \tag{34}$$

In this equation ρ is the density of the solution and M_2 is the formula weight of the electrolyte.

We also have

$$c_+ = \nu_+ \cdot \alpha \cdot c; \; c_- = \nu_- \cdot \alpha \cdot c \tag{35}$$

which, together with Equation (34), gives

$$z_+ c_+ = z_- \cdot c_- = \alpha \cdot c^* \tag{36}$$

Equation (37) defines the equivalent conductivity Λ

$$\Lambda \equiv \varkappa / c^* \tag{37}$$

which can be measured. This relationship, together with Equations (33) and (36), leads to a fundamental equation

$$\Lambda = F \cdot \alpha \cdot (u_+ + u_-) = \alpha \cdot (\lambda_+ + \lambda_-) \tag{38}$$

for the electrical conductivity in electrolyte solutions containing two types of ions.

For infinite dilution, Equation (38) becomes

$$\lim_{c \to 0} \Lambda = \Lambda^0 = F \cdot (u_+^0 + u_-^0) = \lambda_+^0 + \lambda_-^0 \tag{39}$$

in which the superscript ^{0} signifies the limiting value of the quantity in question when $c \to 0$. According to the law of independent migration of ions, first formulated by *Kohlrausch* in 1893 and repeatedly verified since that time, u_i^0 (or λ_i^0) is characteristic of ions of the type i in a given solvent at a given temperature and pressure, independent of the oppositely charged ion. Thus Λ^0 is a sum of contributions due to the individual ions.

For very dilute solutions of weak electrolytes, we can put $\lambda_i = \lambda_i^0$ in Equation (38). We then obtain from (38) and (39) that $\Lambda/\Lambda^0 = \alpha$. This relationship leads to Ostwald's dilution law when it is combined with the classical law of mass action for dissociation equilibria of type (15), *i.e.* with Equations (10) and (16) and $\gamma_\pm \quad \gamma_u = \gamma\dagger$.

For very dilute solutions of strong electrolytes, on the other hand, $\alpha = 1$, and λ_+, λ_-, and Λ contain terms proportional to $c^{1/2}$ which can be calculated from the valences of the ions and properties of the solvent, using Onsager's limiting law. An extension of the theoretical treatment of electrical conduction in dilute solutions of strong electrolytes beyond the square root law has recently been developed by *Onsager* and *Fuoss* [10], again on the basis of the relaxation and the electrophoretic effects.

Concentrated electrolyte solutions show a complicated dependence of α, λ_+, λ_-, and Λ on concentration which is at present not amenable to theoretical treatment. We have determined Λ over a wide range of concentrations for the systems H_2O/HNO_3 and $H_2O/HClO_4$, for which α-values are available from spectroscopic data [11].

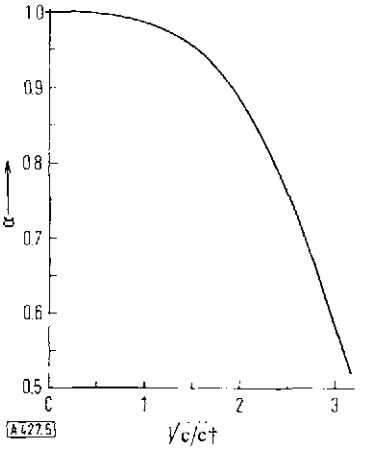

Fig. 5. The system H_2O/HNO_3 at 25 °C: Degree of dissociation α of the electrolyte as a function of the square root of the molarity c according to [4]. ($c\dagger \equiv 1$ mole/l).

Fig. 5 shows the degree of dissociation α of the electrolyte, Fig. 6 the measured values of Λ, together with the values of $(\lambda_+ + \lambda_-)$ calculated with Equation (38), as functions of $c_{1/2}$ for aqueous nitric acid (at 25 °C and 1 atm). Aqueous perchloric acid presents a similar picture [11]. The effect of incomplete dissociation at high concentrations can be clearly recognized.

In order to obtain an analytical representation for the entire concentration range from $x = 0$ to $x = 1$ (for which experimental values are available for aqueous nitric acid

[9] *R. Haase*: Thermodynamik der irreversiblen Prozesse. Steinkopff, Darmstadt 1963, p. 281 ff.

[10] *R. M. Fuoss* and *F. Accascina*: Electrolytic Conductance. Interscience, New York-London 1959.

[11] *R. Haase, P.-F. Sauermann*, and *K.-H. Dücker*, Z. physik. Chem. N.F. *43*, 218 (1964).

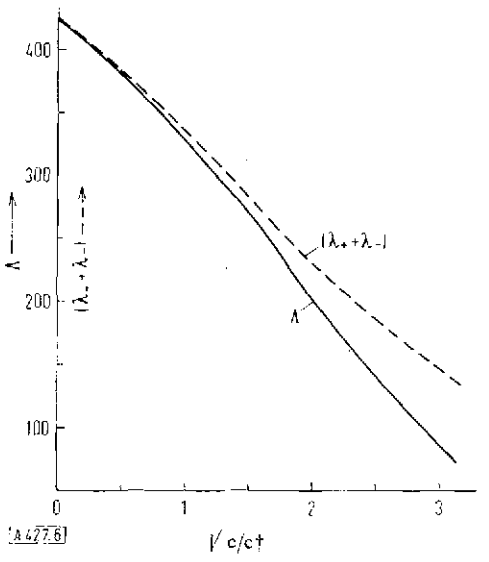

Fig. 6. The system H_2O/HNO_3 at 25 °C: Equivalent conductivity Λ and sum $(\lambda_+ + \lambda_-)$ of the ionic conductances, according to [11] (units ohm^{-1} cm^2 eq^{-1}; $c^\dagger$ = 1 mole/l).

and sulfuric acid [11], it would be necessary to find empirical expressions for $\Lambda(x)$ or $\lambda_+(x)$ and $\lambda_-(x)$ which would reduce, at high dilution, to the equations of *Onsager* and *Fuoss* [10] (cf. the method used in the case of equilibrium properties, Section II.4). No attempt has so far been made in this direction, partly owing to the complicated form of the *Onsager-Fuoss* equations, and partly because of the difficulties encountered in the experimental determination of the fundamental quantities λ_+ and λ_- in concentrated solutions (cf. Section III.4).

3. Transport Numbers

Contrary to widely held beliefs, neither the Hittorf transport number nor the true transport number of an ion can be measured at all electrolyte concentrations [9]. The quantity measured is the transport number of an ion constituent, which corresponds to the Hittorf transport number only at sufficiently high dilutions [9]. This fact can be demonstrated for each of the methods used for the determination of transport numbers, *i.e.* Hittorf's method [12], the moving boundary method [13], and e.m.f. measurements in concentration cells [9, 12] and in gravity or centrifugal cells [9].

For the sake of simplicity, let us again consider solutions of a single electrolyte containing two types of ions. The transport numbers of the cation and anion constituents respectively are ϑ_+ and $\vartheta_- = (1-\vartheta_+)$. ϑ_+ and ϑ_- are equal to the number of equivalents of the cation and anion constituents, respectively, passing through a reference plane which is stationary with respect to the solvent, during the passage of 1 faraday of electricity through the solution. The term "ion constituent" refers to the parts (atoms or radicals) of the electrolyte molecule which can form ions, irrespective of the extent to which these components are actually present as ions.

Thus in an aqueous solution of sodium sulfate, the atom Na and the radical SO_4 are the cation and anion constituents respectively: Na occurs in the species Na^+ and Na_2SO_4, and sulfate occurs as SO_4^{2-} and Na_2SO_4.

If dissociation of an electrolyte is incomplete, it is necessary to take into account transport of the undissociated electrolyte molecules, relative to the solvent, in the electric field. This relative migration of the undissociated electrolyte may be either direct (association of the neutral electrolyte molecules with ions) or indirect (solvation of ions and consequent movement of the solvent relative to the electrolyte molecules). Corresponding to the mobility u_i and the ionic conductance λ_i, therefore, we also introduce the mobility u_u of the undissociated electrolyte and the quantity $\lambda_u = F.u_u$.

$$\vartheta_+ = \frac{u_+}{u_+ + u_-} \pm \frac{1-\alpha}{\alpha} \cdot \frac{u_u}{u_+ + u_-} = \frac{1}{\lambda_+ + \lambda_-}\left(\lambda_+ \pm \frac{1-\alpha}{\alpha}\cdot\lambda_u\right) \quad (40)$$

$$\vartheta_- = 1-\vartheta_+ = \frac{u_-}{u_+ + u_-} \mp \frac{1-\alpha}{\alpha}\frac{u_u}{u_+ + u_-}$$

$$= \frac{1}{\lambda_+ + \lambda_-}\left(\lambda_- \mp \frac{1-\alpha}{\alpha}\cdot\lambda_u\right) \quad (41)$$

The general expressions (40) and (41) can be derived for the dimensionless quantities ϑ_+ and ϑ_- [13].

The upper (lower) sign applies when the undissociated electrolyte molecules migrate in the same direction as the cations (anions). It can be seen that, when dissociation is complete ($\alpha = 1$) or if transport of the undissociated electrolyte is negligible ($u_u = 0$; $\lambda_u = 0$), ϑ_+ and ϑ_- reduce to the Hittorf transport numbers t_+ and $t_- = (1-t_+)$ of the cations and the anions, respectively. At infinite dilution ($c \to 0$; $\alpha \to 1$), we have

$$\vartheta_+^0 = t_+^0 = \frac{u_+^0}{u_+^0 + u_-^0} = \frac{\lambda_+^0}{\lambda_+^0 + \lambda_-^0} \quad (42)$$

$$\vartheta_-^0 = t_-^0 = \frac{u_-^0}{u_+^0 + u_-^0} = \frac{\lambda_-^0}{\lambda_+^0 + \lambda_-^0} \quad (43)$$

in which ϑ_i^0 and t_i^0 are the limiting values of the transport numbers at infinite dilution.

We have determined transport numbers for concentrated aqueous solutions of HNO_3, $HClO_4$, and $AgNO_3$ at 25 °C, using the moving boundary method [14]. Fig. 7

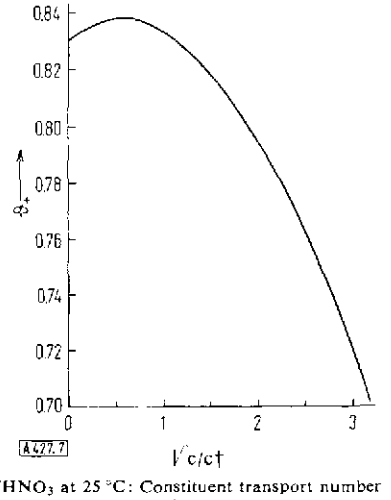

Fig. 7. The system H_2O/HNO_3 at 25 °C: Constituent transport number ϑ_+ of the cation vs. $c^{1/2}$, according to [11]. ($c^\dagger \equiv 1$ mole/l).

[12] *M. Spiro*, J. chem. Educat. *33*, 464 (1956); Trans. Faraday Soc. *55*, 1207 (1959); *A. Weissberger*: Physical Methods of Organic Chemistry, Part IV. Interscience, New York 1960, p. 3049.

[13] *R. Haase*, Z. physik. Chem. N.F. *39*, 27 (1963).

[14] *R. Haase, G. Lehnert*, and *H.-J. Jansen*, Z. physik. Chem. N.F. *42*, 32 (1964).

shows the curve of ϑ_+ against $c^{1/2}$ for aqueous nitric acid. A significant feature is the maximum, which is also found with aqueous perchloric acid.

4. Ionic Conductivities

We have seen that, in solutions of a single electrolyte containing two ionic species, it is possible to measure the following quantities: the equivalent conductivity Λ, the stoichiometric transport numbers ϑ_i, and in some cases the degree of dissociation α. Experimental data can also be used to find the limiting values Λ^0 and t_i^0.

It is therefore possible to determine the limiting values λ_+^0 and λ_-^0 of the ionic conductivities, using Equation (44), which is derived from Equations (39), (42), and (43).

$$\lambda_+^0 = t_+^0 \cdot \Lambda^0; \quad \lambda_-^0 = t_-^0 \cdot \Lambda^0 \tag{44}$$

These quantities, which were mentioned earlier, are tabulated in modern monographs and reference books for many ions at various temperatures.

The equations

$$\lambda_+^* \equiv \vartheta_+ \cdot \Lambda; \quad \lambda_-^* \equiv \vartheta_- \cdot \Lambda \tag{45}$$

$$\lambda_+' \equiv \frac{\vartheta_+ \cdot \Lambda}{\alpha}; \quad \lambda_-' \equiv \frac{\vartheta_- \cdot \Lambda}{\alpha} \tag{46}$$

can be used for all concentrations with the experimental values of ϑ_+ and Λ or of ϑ_i, Λ, and α.

From (38), (40), (41), (45), and (46), we find [11]:

$$\lambda_+^* = \alpha \cdot \lambda_+ + (1-\alpha) \cdot \lambda_u \tag{47}$$

$$\lambda_-^* = \alpha \cdot \lambda_- + (1-\alpha) \cdot \lambda_u \tag{48}$$

$$\lambda_+' = \lambda_+ + \frac{1-\alpha}{\alpha} \cdot \lambda_u \tag{49}$$

$$\lambda_-' = \lambda_- \mp \frac{1-\alpha}{\alpha} \cdot \lambda_u \tag{50}$$

from which we obtain the identities:

$$\lambda_-^* + \lambda_+^* = \Lambda \tag{51}$$

$$\lambda_+' + \lambda_-' = \lambda_+ + \lambda_- \tag{52}$$

In accordance with Equation (51), λ_+^* and λ_-^* may be referred to as the equivalent conductivities of the cation and anion constituents of the electrolyte respectively. According to Equations (49) and (50), λ_+' and λ_-' may be identified with the ionic conductivities λ_+ and λ_- only if dissociation is complete ($\alpha = 1$), or if the migration of undissociated electrolyte in the electric field is negligible ($\lambda_u = 0$). Consequently, at high concentrations λ_+ and λ_- cannot be separately determined. Provided that experimental data for α are available, however, it is possible to find the sum $(\lambda_+ + \lambda_-)$, using Equation (38) or (52) (cf. Fig. 6).

Fig. 8 shows values of λ_+^*, λ_+', λ_-^*, and λ_-' for aqueous nitric acid at 25 °C, over a wide range of concentrations. These values were determined from the data of Figs. 5, 6, and 7, using Equations (45) and (46). A similar picture is found with aqueous perchloric acid [11]. A striking feature is the strong dependence of λ_+^* and λ_+' (for H^+) on concentration, compared with that of λ_-^* and λ_-' (NO_3^- and ClO_4^-). This feature is related to the proton jump mechanism of the migration of H^+ ions, which becomes increasingly noticeable with increasing dilution.

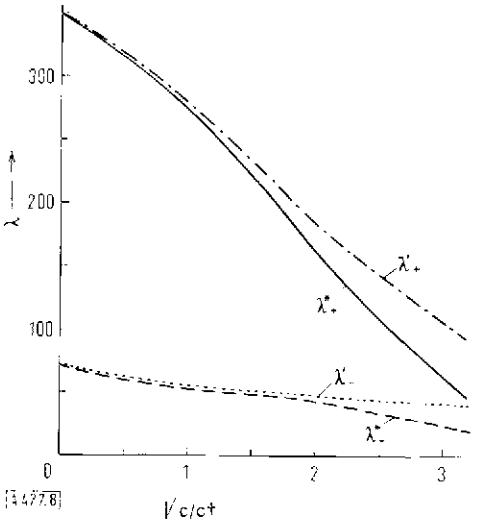

Fig. 8. The H_2O/HNO_3 system at 25 °C: The quantities λ_+^*, λ_+', λ_-^*, and λ_-' as functions of the square root of the molarity c [mole/l], according to [11] (units $ohm^{-1}\,cm^2\,eq^{-1}$; $c^\dagger = 1$ mole/l).

Sufficient data for the determination of λ_i^* over a wide range of concentrations are available for only a few other electrolyte systems (*e.g.* aqueous hydrochloric acid [11], silver nitrate [14,15], and silver perchlorate [15]).

IV. Diffusion

Diffusion is the transport of matter in a mixture, caused by concentration gradients. Let us again consider a solution of a single electrolyte containing two ion constituents. As a result of the conditions of electroneutrality and local dissociation equilibrium (which normally are satisfied by every volume element, even in a medium in which transport processes are taking place), all electrolyte particle types move at the same average velocity. Apart from the (average) velocity of the solvent molecules (vector $\vec{v}_1$), therefore, there is only one other independent velocity, *i.e.* the common (average) velocity $\vec{v}_2$ of the ions and undissociated electrolyte molecules (*e.g.* the species H^+, HSO_4^-, SO_4^{2-}, and H_2SO_4 in aqueous sulfuric acid). We also have only one independent concentration variable, for which (as in the case of electrical conductivity) we shall choose for the moment the molarity c of the electrolyte.

The transport of matter is characterized by a vector $(\vec{v}_2 - \vec{v}_1)$ or $c(\vec{v}_2 - \vec{v}_1)$. The latter quantity is the diffusion current density of the electrolyte in the "solvent-fixed" frame of reference, ("Hittorf's reference system") and is denoted by $\vec{J}_2$. Thus

$$\vec{J}_2 \equiv c \cdot (\vec{v}_2 - \vec{v}_1). \tag{53}$$

[15] *A. N. Campbell* and *K. P. Singh*, Canad. J. Chem. *37*, 1959 (1959).

In this reference system, the velocity of the solvent $\vec{v}_1$ is taken as the reference velocity. There are also other reference systems, such as that in which the reference velocity is the mean volume velocity $\vec{w}$ (Fick's reference system). The corresponding vector for the diffusion current density is

$$_w\vec{J}_2 \equiv c\cdot(\vec{v}_2 - \vec{w}). \tag{54}$$

Hittorf's system is related to Fick's system by equation (55) [9], where $\bar{V}$ is the molar volume of the mixture, V_1 and V_2 are the partial molar volumes of the solvent and the electrolyte respectively, and x is the stoichiometric mole fraction of the electrolyte.

$$_w\vec{J}_2 = (1 - c\cdot V_2)\cdot {}_1\vec{J}_2 = \frac{(1-x)\cdot V_1}{V}\cdot {}_1\vec{J}_2 \tag{55}$$

The above discussion is true not only for diffusion but also for other transport processes which occur in the absence of an electric current, *e.g.* sedimentation (cf. Section V) and thermal diffusion. For the present, however, we shall confine our discussion to pure diffusion, *i.e.* we shall ignore external force fields, as well as pressure and temperature gradients. In Section V we shall consider pressure gradients in addition to concentration gradients.

For pure diffusion in a solution of an electrolyte containing two ion constituents, each volume element obeys Fick's law in the form

$$_w\vec{J}_2 = -D\cdot \operatorname{grad} c \tag{56}$$

in which D is the diffusion coefficient. Equation (56) is analogous to Ohm's law (31), and is always valid unless the concentration gradients are extremely high. As the electric conductivity $\varkappa$ in Equation (31), so the diffusion coefficient D in Equation (56) is a measurable positive quantity (in stable mixtures not at their critical points), which depends on the intensive (local) variables of state (temperature, pressure, concentration).

It is often desirable to convert from Fick's reference system to Hittorf's system, and from the molarity c to the molality m. From Equation (34), it is possible to derive

$$\operatorname{grad} c = \frac{c\cdot(1-c\cdot V_2)}{m}\cdot \operatorname{grad} m \tag{57}$$

Combination of Equations (55), (56), and (57) gives Equation (58), which is Fick's law expressed in Hittorf's system.

$$_1\vec{J}_2 = -D\cdot\frac{c}{m}\cdot \operatorname{grad} m \tag{58}$$

We shall now restrict the discussion to completely dissociated electrolytes containing two ionic species. Thus we exclude compounds such as H_2SO_4 or H_3PO_4, and set $\alpha = 1$. The solution then contains only three types of particles: non-electrolyte molecules, cations, and anions. The condition $\alpha = 1$ stipulates dilute solutions of strong electrolytes. Application of the thermodynamics of irreversible processes to such systems leads to the general equation (59) for the diffusion coefficient D [9, 16, 17].

$$D = b\cdot q^2\cdot\frac{\nu\cdot RT}{c}\left[1 + m\left(\frac{\partial \ln \gamma}{\partial m}\right)_{T,P}\right] \tag{59}$$

$$q \equiv \frac{z_+ - z_-}{\nu} = \frac{z_+}{\nu_-} = \frac{-z_-}{\nu_+} \tag{60}$$

$$b \equiv \frac{a_{11}\cdot a_{22} - a_{12}^2}{z_+^2\cdot a_{11} + 2 z_+\cdot z_-\cdot a_{12} + z^2\cdot a_{22}} \tag{61}$$

In the above equations, a_{11}, a_{22}, and a_{12} are phenomenological coefficients related to the ionic conductivities λ_+ and λ_- by Equations (62) and (63).

$$\lambda_+ = \frac{F^2}{\nu_+\cdot c}\, z_+\cdot a_{11} + z_-\cdot a_{12} \tag{62}$$

$$\lambda_- = \frac{F^2}{\nu_-\cdot c}\, z_+ a_{12} + z_-\cdot a_{22} \tag{63}$$

As previously mentioned, in diffusion the ions move at the same average speed and in the same direction, namely opposite to the direction of the chemical potential gradient. Consequently, in contrast to the conduction of electricity, only the electrophoretic effect is active, the relaxation effect being absent. The coefficients a_{11}, a_{22}, and a_{12} in (61) must therefore lead to elimination of the relaxation effect which is still accounted for in Equations (62) and (63). Thus if we have a kinetic molecular theory of electrolytic conduction with explicit expressions for λ_+ and λ_-, the condition of non-occurrence of the relaxation effect in Equation (61), together with Equations (62) and (63), provide the three equations required for the calculation of a_{11}, a_{22}, and a_{12} from molecular-physical data. Consequently, any kinetic treatment of electrical conduction in dilute solutions of strong electrolytes, combined with Equation (59), leads to an explicit expression for D. *Onsager* and *Fuoss* [18] first reported such an expression. At higher concentrations, the molecular-kinetic theory of diffusion, like that of electrical conduction, meets with difficulties which cannot at present be overcome.

For very dilute, but not necessarily ideal dilute solutions (in the thermodynamic sense), the kinetic theory shows [18] that it is possible to disregard the electrophoretic effect, and use the approximation:

$$a_{12} = 0;\ \lambda_+ = \lambda_+^0;\ \lambda_- = \lambda_-^0 \tag{64}$$

From Equation (64), together with (59)–(63), we obtain Equation (65) [18, 19],

$$D = \frac{RT}{F^2}\cdot\left(\frac{1}{z_+} - \frac{1}{z_-}\right)\cdot\frac{\lambda_+^0\cdot\lambda_-^0}{\lambda_+^0 + \lambda_-^0}\left[1 + m\left(\frac{\partial \ln \gamma}{\partial m}\right)_{T,P}\right] \tag{65}$$

which relates the diffusion coefficient in very dilute solutions of strong electrolytes to the limiting values λ_+^0 and λ_-^0 of the ionic conductances and to thermodynamic properties of the electrolyte solution.

At infinite dilution ($m \to 0$), combination of (66) with (65) gives the limiting law (67):

$$\lim_{m\to 0} D = D^0;\ \lim_{m\to 0}\left[m\cdot\left(\frac{\partial \ln \gamma}{\partial m}\right)_{T,P}\right] = 0 \tag{66}$$

[16] *R. Haase*, Trans. Faraday Soc. *49*, 724 (1953), footnote on p. 728.

[17] *R. Haase*: Thermodynamik der Mischphasen. Springer, Berlin-Göttingen-Heidelberg 1956, p. 579.

[18] *L. Onsager* and *R. M. Fuoss*, J. physic. Chem. *36*, 2689 (1932).

[19] *G. S. Hartley*, Philos. Mag. J. Sci. *12*, 473 (1931).

$$D^0 = \frac{RT}{F^2} \cdot \left(\frac{1}{z_+} - \frac{1}{z_-} \right) \frac{\lambda_+^0 \cdot \lambda_-^0}{\lambda_+^0 + \lambda_-^0} \qquad (67)$$

proposed by *Noyes* in 1908. For 1:1 electrolytes ($z_+ = -z_- = 1$) Equation (67) reduces to

$$D^0 = \frac{2\,RT}{F^2} \cdot \frac{\lambda_+^0 \cdot \lambda_-^0}{\lambda_+^0 + \lambda_-^0} \qquad (68)$$

given by *Nernst* in 1888.

V. Sedimentation

Sedimentation is the transport of matter in a mixture caused by gravitational or centrifugal fields. If we confine the discussion to solutions of a single electrolyte containing two ion constituents, then the general considerations regarding concentration variables, velocities, and diffusion current densities as discussed in Section IV are still valid.

Consider first an electrolyte solution subject to no fields other than the external force field (gravitational or centrifugal acceleration $\vec{g}$), and no gradients other than the pressure gradient (grad P). We may assume local mechanical equilibrium, so that if ρ is the density of the solution, then

$$\rho \cdot \vec{g} = \text{grad } P \qquad (69)$$

Moreover, if we disregard extremely high force fields, each volume element satisfies the equation

$$\vec{v}_2 - \vec{w} = s \cdot \vec{g} \qquad (70)$$

or, combining this with Equations (54) and (69):

$${}_w\vec{J}_2 = c \cdot s \cdot \vec{g} = s \cdot \frac{c}{\rho} \cdot \text{grad } P, \qquad (71)$$

or with Equations (1), (34), and (55):

$${}_1\vec{J}_2 = s \cdot \frac{M_1 \cdot m}{\bar{V}_1} \cdot \vec{g} = s \cdot \frac{M_1 \cdot m}{\bar{V}_1 \cdot \rho} \cdot \text{grad } P. \qquad (72)$$

Equations (71) and (72) correspond respectively to (56) and (58). The measurable quantity s is the sedimentation coefficient. It may be either positive or negative, and (like the diffusion coefficient D) depends on the intensive variables of the volume element.

Sedimentation in a mixture initially uniform in concentration gives rise to a concentration gradient, which in turn leads to diffusion. In general, therefore, we must consider the simultaneous occurrence of a pressure gradient and a concentration gradient, and hence a superposition of the two transport processes (diffusion and sedimentation). Experience has shown that this superposition is linear. Starting with Equations (58) and (72), we can therefore write

$${}_1\vec{J}_2 = -D \cdot \frac{c}{m} \cdot \text{grad } m + s \cdot \frac{M_1 \cdot m}{\bar{V}_1} \cdot \vec{g} \qquad (73)$$

Equation (73) describes the simultaneous occurrence of diffusion and sedimentation in the solvent-fixed reference system.

After sufficient time, the opposing effects of sedimentation ("separation") and diffusion ("mixing") lead to the establishment of a steady state characterized by ${}_1\vec{J}_2 = 0$, which under the conditions assumed (uniform temperature) corresponds to an equilibrium state. According to classical thermodynamics [9], this sedimentation equilibrium is described by

$$(M_2 - \bar{V}_2) \cdot \rho \cdot \vec{g} = \left(\frac{\partial \mu_2}{\partial m} \right)_{T,P} \cdot \text{grad } m \qquad (74)$$

On the other hand, by applying the condition ${}_1\vec{J}_2 = 0$ to Equation (73), we obtain

$$s \cdot \frac{M_1 \cdot m}{\bar{V}_1} \cdot \vec{g} = D \cdot \frac{c}{m} \cdot \text{grad } m \qquad (75)$$

The equilibium conditions (74) and (75) immediately lead to

$$\frac{D}{s} = \frac{M_1 \cdot m^2 \cdot (\partial \mu_2 / \partial m)_{T,P}}{c \cdot \bar{V}_1 \cdot (\bar{M}_2 - \bar{V}_2 \rho)} \qquad (76)$$

Equations (1), (2), (7), and (9) give the following relationships:

$$\frac{M_1 \cdot m^2}{c} = m \cdot (1 + M_1 \cdot m) \cdot \bar{V} \qquad (77)$$

$$\left(\frac{\partial \mu_2}{\partial m} \right)_{T,P} = \frac{\nu \cdot RT}{m} \left[1 + m \cdot \left(\frac{\partial \ln \frac{\gamma}{\gamma_\pm}}{\partial m} \right)_{T,P} \right] \qquad (78)$$

and from these, together with Equation (76), we obtain

$$\frac{D}{s} = \frac{(1 + M_1 \cdot m) \cdot \bar{V}}{\bar{V}_1 \cdot (M_2 - \bar{V}_2 \cdot \rho)} \cdot \nu \cdot RT \left[1 + m \left(\frac{\partial \ln \frac{\gamma}{\gamma_\pm}}{\partial m} \right)_{T,P} \right] \qquad (79)$$

Equation (79) is valid at all concentrations, and relates the transport coefficients D and s. The quantities on the right-hand side can be found from equilibrium data alone, *i.e.* from experimental values of $\rho(m)$ and $\gamma(m)$. Equivalent expressions were derived earlier by various methods [9, 20]. Our derivation [21] has the advantage of generality and simlicity. The above form of Equation (79) is particularly suitable for electrolyte solutions. For other purposes, however, particularly for high molecular weight non-eletrolytes, other forms of this relationship, which can also be derived from Equation (76), are more suitable [9, 20].

Creeth [22] has recently confirmed experimentally an equation corresponding to (79) (but using the "c" scale and not involving $\bar{V}$ and V_1) for aqueous solutions of Tl_2SO_4 at 25 °C at electrolyte concentrations of 8 to 50 g/l. The functions $V_2(m)$ and $\rho(m)$ were determined by density measurements, $\gamma(m)$ by e.m.f. measurements,

[20] For a review containing historical data, see *R. Haase* in *J. W. Williams*: Ultracentrifugal Analysis in Theory and Experiment. Academic Press, New York-London 1963, p. 13.

[21] *R. Haase*, Z. physik. Chem. N.F. *25*, 26 (1960); *R. Haase* and *H. Schönert*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *64*, 1155 (1960).

[22] *J. M. Creeth*, J. physic. Chem. *66*, 1228 (1962); *J. M. Creeth* and *B. E. Peter*, J. physic. Chem. *64*, 1502 (1960).

D(m) from diffusion experiments, and s(m) from experiments with the ultracentrifuge. The order of magnitude of the diffusion coefficient D is 10^{-5} cm²/sec in this system, and that of s is 10^{-13} sec.

Equation (65) applies to very dilute solutions of strong electrolytes containing two ionic species. In this case we can also apply the approximations

$$M_1 \cdot m \ll 1 ; V \approx V_1 \tag{80}$$

Thus from Equations (65) and (79) we obtain

$$s = \frac{M_2^* \cdot (1-\tilde{V}_2 \cdot \rho)}{F^2} \cdot \frac{\lambda_+^0 \cdot \lambda^0}{\lambda_+^0 + \lambda_-^0} \tag{81}$$

in which M_2^* is the equivalent weight of the electrolyte, defined by

$$M_2^* \equiv \frac{M_2}{z_+ \nu_+} = \frac{M_2}{z_- \nu_-} \tag{82}$$

and in which we have made use of (60) and

$$V_2 = M_2 \cdot \tilde{V}_2 \tag{83}$$

($\tilde{V}_2$ is the partial specific volume of the electrolyte).

In the limit $m \to 0$, we find from Equations (81) and (79), together with Equations (66), (80), and (83):

$$\lim_{m \to 0} s = \frac{M_2^* \cdot (1-\tilde{V}_2^0 \cdot \rho_{01})}{F^2} \cdot \frac{\lambda_+^0 \cdot \lambda_-^0}{\lambda_+^0 + \lambda_-^0} \tag{84}$$

$$\lim_{m \to 0} \frac{D}{s} = \frac{\nu \cdot RT}{M_2 \cdot (1-\tilde{V}_2^0 \cdot \rho_{01})} \tag{85}$$

In Equations (84) and (85), $\tilde{V}_2^0$ is the limiting value of the partial specific volume of the electrolyte at infinite dilution, and ρ_{01} is the density of the pure solvent. The limiting law (85) is known as Svedberg's equation (*Svedberg* 1925), particularly under the condition $\nu = 1$, (non-electrolyte solutions). This relationship can be used to determine the quantity M_2/ν. Equation (85) can also be derived from Equations (67) and (84) using (60) and (82).

Since the molecular theory of sedimentation is fundamentally simpler than that of diffusion, Equation (79) is useful in calculating D from s. On the other hand, D is the more easily measured quantity, so that (79) will also be used for the reverse calculation.

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Chemistry and Stereochemistry of Fluorophosphoranes [*]

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Fluorophosphoranes are a recently discovered new type of phosphorus compound derived from phosphorus pentafluoride by substitution of fluorine atoms with various groups. Synthesis, chemistry, and stereochemistry of this class of compounds containing phosphorus in the comparatively rare coordination number 5 will be discussed.

A. Introduction

Until recently, relatively few examples of pentacoordination were known; some halides of group V elements were recognized as typical representatives of pentacoordinated species. For phosphorus in particular, pentacoordinated halides with trigonal-bipyramidal configuration (in the gas phase) have long been known, *e.g.* PBr_5, PCl_5 (covalent form), PF_5, and the covalent forms of the halofluorides PX_nF_{5-n} (X = Cl, Br; n = 2,3,4). The chemistry of P(V)-halofluorides, which are distinguished in several instances by the interconversion of covalent and ionic forms, has recently been reviewed [1–3].

In the present article, a review is presented on chemical and stereochemical aspects of a further class of phosphorus-halogen compounds containing pentacoordinate phosphorus. The compounds of this type are derived from phosphorus pentafluoride by substitution of fluorine atoms with various groups. The following types of these "fluorophosphoranes" will be considered:

1. Fluorophosphoranes containing hydrocarbon groups as substituents, R_nPF_{5-n} (n = 1,2,3).
2. Aryltrifluorophosphorus hydrides, $ArPF_3H$. Compounds of this type are not true fluorophosphoranes within the scope of this article. Because of the stereochemical relationship to other fluorophosp horanes, however, aryltrifluorophosphorus hydrides will also be considered here.
3. Arylchlorotrifluorophosphoranes, $ArPF_3Cl$.
4. Alkyl(aryl)-dialkylaminotrifluorophosphoranes, $R(Ar)PF_3NR'_2$.
5. Dialkylaminofluorophosphoranes, $(R_2N)_nPF_{5-n}$ (n = 1,2).
6. Perhaloalkyldihalodifluorophosphoranes, $R_{Hal}PF_2X_2$ (Hal = F,Cl; X = Cl, Br).

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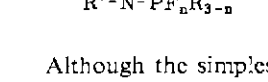
[1] *D. S. Payne*, Quart. Rev. *15*, 173 (1961).

[2] *R. R. Holmes*, J. chem. Educ. *40*, 125 (1963).

[3] *L. Kolditz*, Z. Chem. *2*, 291 (1963).

7. Fluoro-1,3,2,4-diazadiphosphetidines *(1)* (n = 2,3; R,R' = hydrocarbon groups).



(1)

Although the simplest fluorophosphorane, the "parent compound" PF_5, is known since 1876, since well before the discovery of elemental fluorine, a fluorophosphorane within the scope of the above definition was first referred to in the patent literature in 1955 [4,5]. Fluorophosphoranes were not isolated and characterized in detail until 1958–59 when *A. B. Burg* and his co-workers [6] and *W. C. Smith* [7] reported some perfluoroalkyl derivatives [6] and phenyl- and isooctenyl-tetrafluorophosphorane [7]. Numerous publications on synthesis and chemistry of fluorophosphoranes have appeared since then.

B. Synthesis of Fluorophosphoranes

I. Compounds of Composition R_nPF_{5-n}

1. The first preparative method to be reported involves fluorination of the readily accessible complexes of PCl_3 or alkyldichlorophosphines with alkyl halides and $AlCl_3$ using HF [4,5,8], AsF_3, SbF_3 [8,9], or KF [8].

$$[R_nPCl_{4-n}][AlCl_4] \rightarrow R_nPF_{5-n}\ (n = 1,2) \qquad (a)$$

2. Dichlorophosphines react with SbF_5 or a mixture of stoichiometric amounts of $SbCl_5$ and SbF_3 with formation of tetrafluorophosphoranes according to (b) and (c):

$$3\,RPCl_2 + 3\,SbF_5 \rightarrow 3\,RPF_4 + SbF_3 + 2\,SbCl_3 \qquad (b)$$

$$3\,RPCl_2 + 3\,SbCl_5 + 4\,SbF_3 \rightarrow 3\,RPF_4 - 7\,SbCl_3 \qquad (c)$$

3. Especially straightforward is the reaction (d) of chlorophosphines with group V trifluorides, in particular AsF_3 and SbF_3. In a simultaneous halogen exchange and oxidation-reduction reaction, elemental As or Sb and the corresponding trichloride, $AsCl_3$ or $SbCl_3$, are formed besides fluorophosphoranes. This method was discovered during attempts at the synthesis of fluorophosphines, R_nPF_{3-n} [8,10–12].

$$3\,R_nPCl_{3-n} + (5-n)\,MF_3 \rightarrow 3\,R_nPF_{5-n} + 2\,M + (3-n)\,MCl_3$$

$$M = As, Sb;\ n = 1,2 \qquad (d)$$

The course of reaction (d) is independent of whether the chlorophosphine is added to the fluorinating agent, or *vice versa*. AsF_3 is particularly suitable for the preparation of higher-boiling fluorophosphoranes (the highest boiling by-product is $AsCl_3$, b.p. 131 °C), whereas for low-boiling compounds (b.p. <200 °C) SbF_3 is preferred (b.p. of $SbCl_3$ 225 °C).

No oxidation-reduction reaction takes place when electronegative substituents are attached to the trivalent phosphorus. Perfluoroalkylhalogenophosphines [6,13–17] or CCl_3PCl_2 [18], for instance, react with SbF_3 with exclusive formation of fluorophosphines. The influence of the substituents is expecially illustrative on comparing CH_3PCl_2 with $ClCH_2PCl_2$: whereas the former reacts with SbF_3 under mild conditions to give the tetrafluorophosphorane [11], the latter is converted in high yield to the difluorophosphine, which is spontaneously flammable in air [10,19]. Only when the strong oxidizing agent SbF_5 is used can $ClCH_2PCl_2$ be converted into $ClCH_2PF_4$ [10,11].

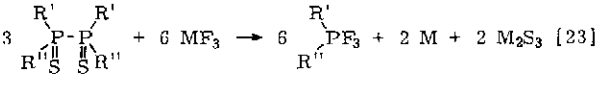
The formation of fluorophosphoranes by the reaction of chlorophosphines with SbF_3 (or AsF_3) presumably proceeds *via* the fluorophosphines. Reaction (e), for example, was shown to occur almost quantitatively [20]. $C_6H_5PF_3H$ also reduces SbF_3 to elemental Sb [32].

$$3\,C_6H_5PF_2 + 2\,SbF_3 \rightarrow 3\,C_6H_5PF_4 + 2\,Sb \qquad (e)$$

Dialkylaminodichlorophosphines, R_2NPCl_2 [21], and chlorophosphites, $(RO)_nPCl_{3-n}$ (n=1,2), [22] undergo only halogen exchange with SbF_3, and no oxidation-reduction reactions were noted. Dihaloarsines are converted to difluoroarsines by SbF_3 [11].

The above methods are very useful wherever the required halophosphines are readily accessible. Such is usually not the case for monochlorophosphines, R_2PCl. Dialkyltrifluorophosphoranes are readily available, however, by an alternate route based on a different starting material.

4. Tetraalkyldiphosphine disulfides *(2)*, which are readily obtained from Grignard reagents and $PSCl_3$, react smoothly with the group V trifluorides AsF_3 and especially SbF_3.



(2) M = As, Sb

Tertiary phosphine sulfides react similarly with SbF_3 with formation of difluorophosphoranes and Sb_2S_3:

$$3\,R^1R^2R^3P{=}S + 2\,SbF_3 \rightarrow 3\,R^1R^2R^3PF_2 + Sb_2S_3 \qquad (f)$$

[4] *H. Coates* and *P. R. Carter* (to Ministry of Supply, London), Brit. Pat. 734187 (July 27th, 1955).

[5] *H. Coates* and *P. R. Carter* (to Ministry of Supply, London): U.S. Pat. 2853515 (Sept. 23rd, 1958).

[6] *A. B. Burg, G. Brendel, A. P. Caron, G. L. Juvinall, W. Mahler, K. Mödritzer*, and *P. J. Slota*, WADC Report 56–82, Part III, April 1958.

[7] *W. C. Smith* (to E. I. duPont de Nemours and Co., Inc.): U.S. Pat. 2904588 (Sept. 15th, 1959).

[8] *I. P. Komkov, S. Z. Ivin, K. V. Karawanov*, and *L. Je. Smirnov*, Zhur. Obshch. Khim. *32*, 301 (1962).

[9] *R. Schmutzler*, unpublished work.

[10] *R. Schmutzler*, Chem. and Ind. *1962*, 1868.

[11] *R. Schmutzler*, Inorg. Chem. *3*, 410 (1964).

[12] *L. M. Yagupol'skii* and *Zh. M. Ivanova*, Zhur. Obshch. Khim. *29*, 3766 (1959).

[13] *A. B. Burg, G. Brendel, A. P. Caron, G. L. Juvinall, W. Mahler, K. Mödritzer*, and *P. J. Slota*, WADC Report 56-82, Part II (1958).

[14] *A. B. Burg* and *G. Brendel*, J. Am. chem. Soc. *80*, 3198 (1958).

[15] *A. B. Burg* and *G. Brendel* (to American Potash and Chemicals Corp.): U.S. Pat. 2959620 (Nov. 8th, 1960).

[16] *V. N. Kulakova, Yu. M. Zinov'ev*, and *L. Z. Soborovskii*, Zhur. Obshch. Khim. *29*, 3957 (1959).

[17] *R. N. Sterlin, R. D. Yatsenko, L. N. Pinkina*, and *I. L. Knunyants*, Nauka i Prom. *4*, 810 (1959) [Chem. Abstr. *54*, 10838 (1960)]; Izvest. Akad. Nauk S.S.S.R., Otdel. Khim. Nauk *1960*, 1991.

[18] *J. F. Nixon*, Chem. and Ind. *1963*, 1555.

[19] *R. Schmutzler*, American Chemical Society Advances in Chemistry Series, *37*, 150 (1963).

[20] *R. Schmutzler*, Chem. Ber. *98*, 552 (1965).

[21] *R. Schmutzler*, Inorg. Chem. *3*, 416 (1964).

[22] *R. Schmutzler*, Chem. Ber. *96*, 2435 (1963).

Not all types of P=S bonds react with SbF_3 in an analogous manner. Thus, no reaction is observed between thiophosphates, $(RO)_3P=S$ [23], or tris(dialkylamino)phosphine sulfides, $(R_2N)_3P=S$ [24], and SbF_3, the hitherto unknown compounds $(RO)_3PF_2$ and $(R_2N)_3PF_2$, respectively, being expected. The phosphonothioic dihalide $ClCH_2PSCl_2$ reacts readily with SbF_3 to give $ClCH_2PSF_2$ in high yield; no $ClCH_2PF_4$ is formed [25]. On the other hand, only a 25 % yield is obtained in the fluorination of $C_6H_5PSCl_2$ with SbF_3, possibly owing to formation of $C_6H_5PF_4$ [26].

5. Some perhaloalkyl derivatives as well as some aromatic fluorophosphoranes were obtained by fluorination of the products resulting from addition of chlorine to dichlorophosphines [6, 8, 12, 27–29]:

$$R_nPCl_{3-n} \xrightarrow{Cl_2} R_nPCl_{5-n} \xrightarrow{SbF_3} R_nPF_{5-n} \quad (n = 1,2) \qquad (g)$$

6. An interesting method of synthesis employs sulfur tetrafluoride as a fluorinating agent. The various possible reactions are illustrated by Equations (h)–(m).

$$RPO(OH)_2 + 3\,SF_4 \rightarrow RPF_4 + 2HF + 3\,SOF_2 \quad [30,31] \quad (h)$$

$$R_2PO(OH) + 2\,SF_4 \rightarrow R_2PF_3 + HF + 2\,SOF_2 \quad [31] \quad (i)$$

$$RPOF_2 + SF_4 \rightarrow RPF_4 + SOF_2 \quad [30,31] \quad (k)$$

$$2\,R_3P + SF_4 \rightarrow 2\,R_3PF_2 + S \quad [27,31] \quad (l)$$

$$R_3PO + SF_4 \rightarrow R_3PF_2 + SOF_2 \quad [23,31] \quad (m)$$

The reaction of phosphonic acids with SF_4 can also be directed to give predominantly phosphonic difluorides, $RPOF_2$. All reactions are conducted under autogenous pressure with excess SF_4 at temperatures ranging between 50 and 150 °C. Reactants containing aliphatic substituents require lower reaction temperatures than aromatic compounds [23].

In an extension of this reaction to aromatic arsonic acids and arsines, arylarsenic(V) fluorides, Ar_nAsF_{5-n}, were obtained [31].

Table 1. Tetrafluorophosphoranes RPF_4.

Compound	Method of preparation [*]	B.p. [**] [°C/mm Hg] (m.p. [°C])	J_{P-F} [c.p.s.]	Ref.
CH_3PF_4	I 1) 3) 5)	11–13 (−50)	967	[8, 10, 11, 60]
$ClCH_2PF_4$	I 2)	47	997	[10, 11, 60]
CCl_3PF_4	I 1) 5)	68–70	1124	[8, 29]
CF_3PF_4	I 5)	−35 to −39 (−113 to −117)	1103	[6, 27, 28, 60]
$C_6H_5CH_2PF_4$	I 3)	53/15	1002	[10, 11, 60]
$C_2H_5PF_4$	I 1) 3)	32–34.5	987	[8, 10, 11, 60]
$C_6H_5CH=CHPF_4$	I 3)	97.5–98/23	940	[10, 11, 60]
$i\text{-}C_3H_7PF_4$	I 1)	54–55		[8]
$CH_2=CHCH_2PF_4$	I 3)	48.5–49		[8]
$n\text{-}C_4H_9PF_4$	I 3)	85–86	990	[10, 11, 60]
$i\text{-}C_8H_{15}PF_4$	I 2) 3)	60/3; 43/19; 156	955	[7, 10, 11, 60]
$C_2F_5PF_4$			1175	[61]
$n\text{-}C_3F_7PF_4$			1090	[29]
$C_6H_5PF_4$	I 2) 3) 5) 6)	133–136	963	[7, 8, 10–12, 30, 31, 60]
m- and *p*-$CH_3C_6H_4PF_4$	I 3) 5)	161–162; 55/8	960	[10, 11, 12, 60]
m- and *p*-$(CH_3)_2CHC_6H_4PF_4$	I 3)	64/8	960	[10, 11, 60]
m- and *p*-$ClC_6H_4PF_4$	I 3) 5)	49/9; 163–164	960	[10, 11, 12, 60]
m- and *p*-$CH_3OC_6H_4PF_4$	I 3)	79–81/10; 95–96/20		[10, 11]
2,5-$(CH_3)_2C_6H_3PF_4$	I 3)	56/9	960	[10, 11, 60]
m-$CF_3C_6H_4PF_4$	I 3)	64/40	965	[9, 63]
p-$CF_3C_6H_4PF_4$	I 3)	140–141		[45]

[*] In this and the following tables, this column contains references to the relevant sections of Chapter B, "Synthesis of Fluorophosphoranes".

[**] Upper and lower limits often formed from values given by different authors. — Values in parentheses are melting points.

Table 2. Trifluorophosphoranes $R'RPF_3$.

Compound	Method of preparation	B.p. [°C/mm Hg] (m.p. [°C])	Ref.
$(CH_3)_2PF_3$	I 1) 3) 4)	60–62	[8, 10, 11, 23]
$(CF_3)_2PF_3$	I 5) $(CF_3)_2PI/SF_4$	−4.7 to −5 (−74 to −76.2)	[6, 28]
$CH_3(C_2H_5)PF_3$	I 3)	81–82	[8]
$(C_2H_5)_2PF_3$	I 3) 4) 5)	50/100; 104–105	[8, 10, 11, 23]
$(n\text{-}C_4H_9)_2PF_3$	I 4)	71/10	[23]
$(CH_2)_4PF_3$ *(8)*	I 3) 4)	61–62/90	[11, 23]
$(CH_2)_5PF_3$ *(9)*	I 4)	64–65/40	[23]
$CH_3(C_6H_5)PF_3$	I 4)	64/9	[23]
$(C_6H_5)_2PF_3$	I 3) 6)	92–93/0.4; 106–107/2	[10, 11, 31]

[23] *R. Schmutzler*, Inorg. Chem. *3*, 421 (1963).

[24] *R. Schmutzler*, unpublished work.

[25] *R. Schmutzler*, J. inorg. nucl. Chem. *25*, 335 (1963).

[26] *L. M. Yagupol'skii* and *Zh. M. Ivanova*, Zhur. Obshch Khim. *30*, 1284 (1960).

[27] *W. Mahler*, Paper presented at the 2nd International Symposium on Fluorine Chemistry, Estes Park, Colorado, U.S.A., July 17th–20th, 1962; Abstr. p. 441.

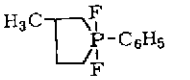
[28] *W. Mahler*, Inorg. Chem. *2*, 230 (1963).

[29] *J. F. Nixon*, J. inorg. nucl. Chem. *27*, (1965), in the press, and personal communication.

[30] *W. C. Smith* (to E. I. duPont de Nemours and Co., Inc.): U.S. Pat. 2950306 (Aug. 23rd, 1960).

[31] *W. C. Smith*, J. Amer. chem. Soc. *82*, 6176 (1960).

Table 3. Difluorophosphoranes $R'R_2PF_3$.

Compound	Method of preparation	B.p. [°C/mm Hg] (m.p. [°C])	^{19}F-NMR J_{P-F} [c.p.s.]	J_{PF-CH} [c.p.s.]	Ref.
$(CH_3)_3PF_2$	I 6)	–	545	11	[60]
$(C_2H_5)_3PF_2$	I 4)	53/20	575	11	[23, 60]
$(n\text{-}C_4H_9)_3PF_2$	I 4); $(n\text{-}C_4H_9)_3P$/2,2,4,4-Tetrakis(trifluoromethyl)-dithietane	71–72/0.4; 76–77/0.6	585	16	[23, 46, 60]
	I 6)	89/0.4	630		[23, 60]
$C_6H_5(n\text{-}C_4H_9)_2PF_2$	I 4)	80/0.08			[23]
$(CH_3)_2F_2PCH_2-CH_2F_2P(CH_3)_2$	I 4)	ca. 80/5 (47.1–48.4)			[23]
$(C_6H_5)_3PF_2$	I 6); $[(CF_3)_2CF]_2S_2/(C_6H_5)_3P$	(136–146)	695		[31, 46, 60]
$(CF_3)_3PF_2$	I 6)	20 (–102)	988	16 [a]	[27, 28, 60]

[a] J_{PF-CF}.

II. Aryltrifluorophosphorus Hydrides

The known representatives of this class of compounds were obtained by the reaction of the corresponding dichlorophosphines with KHF_2 [32]:

$$ArPCl_2 + 2\ KHF_2 \rightarrow ArPF_3H + 2\ KCl + HF \qquad (n)$$

Table 4. Aryltrifluorophosphorus hydrides $ArPF_3H$ [32].

Compound	Method of preparation	B.p. [°C/mm Hg]
$C_6H_5PF_3H$	II	57–58/20
$p\text{-}CH_3C_6H_4PF_3H$	II	90–91/40
$p\text{-}ClC_6H_4PF_3H$	II	90–91/35

III. Arylchlorotrifluorophosphoranes

The few compounds of this type known so far were obtained by chlorination of the respective hydrides.

$$ArPF_3H + Cl_2 \rightarrow ArPF_3Cl + HCl \qquad (o)$$

Instead of pure $ArPF_3Cl$, mixtures of the composition $ArPF_{4-n}Cl_n$ ($n \geq 1$) are usually formed [32, 33].

IV. Dialkylaminofluorophosphoranes

1. Secondary amines react with PF_5 in toluene to give 1:1 adducts which decompose at 100 °C with the formation of R_2NPF_4 [Eq. (p)]. $(CH_3)_2NPF_4$ (but not the ethyl or propyl compound, presumably owing to steric hindrance) forms another adduct with $(CH_3)_2NH$, which is pyrolysed to $[(CH_3)_2N]_2PF_3$ [34, 35] [Eq. (q)]. Under the conditions employed thus far, no further reaction of $(R_2N)_2PF_3$ with secondary amine was observed [34].

$$R_2NH + PF_5 \xrightarrow{\text{toluene}} R_2HN{\rightarrow}PF_5 \xrightarrow{100\,^\circ C} R_2NPF_4 \qquad (p)$$

$$(CH_3)_2NH + (CH_3)_2NPF_4 \rightarrow (CH_3)_2HN{\rightarrow}PF_4N(CH_3)_2 \xrightarrow{100\,^\circ C} [(CH_3)_2N]_2PF_3 \qquad (q)$$

2. PF_5 reacts with *N,N*-dialkylaminotrimethylsilanes [36, 37, 40]:

$$R_2NSi(CH_3)_3 + PF_5 \rightarrow R_2NPF_4 + (CH_3)_3SiF \qquad (r)$$

$$R_2NPF_4 + R_2NSi(CH_3)_3 \rightarrow (R_2N)_2PF_3 + (CH_3)_3SiF \qquad (s)$$

Whereas the reactions with PF_5 (r) proceed with evolution of heat, heating to about 150 °C is necessary with the presumably weaker Lewis acid R_2NPF_4 (s). In the reaction of PF_5 with $(CH_3)_3SiN(CH_3)_2$, formation of a 1:1 adduct was found to occur, which decomposes irreversibly even at –78 °C according to Equation (r) [36].

Table 5. Dialkylaminofluorophosphoranes $(R_2N)_nPF_{5-n}$ (n = 1, 2).

Compound	Method of preparation	B.p. [°C/mm Hg]	J_{P-F} [c.p.s.]	Ref.
$(CH_3)_2NPF_4$	IV 1) 2)	60	836	[34, 36]
$(C_2H_5)_2NPF_4$	IV 2)	99–100	25 °C: 851 –85 °C: 793 (ax); 916 (eq)	[40, 61]
$[(CH_3)_2N]_2PF_3$	IV 1)	21/4	752 (ax); 871 (eq)	[34]
$[(C_2H_5)_2N]_2PF_3$	IV 2)	79/14	751 (ax); 875 (eq)	[40, 61]

V. Alkyl(Aryl)dialkylaminotrifluorophosphoranes

1. Arylchlorotrifluorophosphoranes react with secondary amines in benzene at 5–10 °C [33].

$$ArPF_3Cl + 2\ R_2NH \rightarrow ArPF_3NR_2 + R_2NH_2Cl \qquad (t)$$

2. Particularly simple is the dialkylaminolysis of tetrafluorophosphoranes in ether, which proceeds smoothly at 0 °C [38].

$$2\ RPF_4 + 2\ R'_2NH \rightarrow RPF_3NR'_2 + [R'_2NH_2]^{\oplus}[RPF_5]^{\ominus} \qquad (u)$$

[32] *Zh. M. Ivanova* and *A. V. Kirsanov*, Zhur. Obshch. Khim. *31*, 3991 (1961).

[33] *Zh. M. Ivanova* and *A. V. Kirsanov*, Zhur. Obshch. Khim. *32*, 2592 (1962).

[34] *D. H. Brown, G. W. Fraser*, and *D. W. A. Sharp*, Chem. and Ind. *1964*, 367.

[35] *R. Schmutzler*, unpublished work.

[36] *G. C. Demitras, R. A. Kent*, and *A. G. MacDiarmid*, Chem. and Ind. *1964*, 1712; *G. C. Demitras* and *A. G. MacDiarmid*, personal communication.

[37] *R. Schmutzler*, unpublished work.

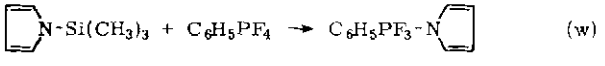
[38] *R. Schmutzler* and *G. S. Reddy*, Inorg. Chem. *4*, 191 (1965).

3. Dialkylaminochlorophosphines, $R(Ar)PClNR'_2$, react with trifluorides of group V elements, *e.g.* AsF_3 or SbF_3, analogously to mono- and dichlorophosphines, R_nPCl_{3-n} [39] [Eq. (v)].

$$3\ R(Ar)PClNR'_2 + 3\ MF_3 \rightarrow 3\ R(Ar)PF_3NR'_2 + 2\ M + MCl_3 \quad [M = As, Sb]. \qquad (v)$$

4. Tetrafluorophosphoranes split the Si–N bond in *N,N*-dialkylaminotrimethylsilanes [40]:

$$RPF_4 + R'_2NSi(CH_3)_3 \rightarrow RPF_3NR'_2 + (CH_3)_3SiF$$



$$+ (CH_3)_3SiF \qquad (w)$$

$$2\ RPF_4 + (R'_2N)_2Si(CH_3)_2 \rightarrow 2\ RPF_3NR'_2 + (CH_3)_2SiF_2$$

Table 6. Alkyl(aryl)dialkylaminotrifluorophosphoranes $R(Ar)PF_3NR'_2$.

Compound	Method of preparation	B.p. [°C/mm Hg]	Ref.
$CH_3PF_3N(CH_3)_2$	V 3)	85	[39]
$C_2H_5PF_3N(C_2H_5)_2$	V 2)	66.5/30	[38]
$C_6H_5PF_3N(CH_3)_2$	V 1) 2) 3) 4)	88/6.5; 48–49/0.4	[47] [38–40]
$C_6H_5PF_3NHCH_3$	V 2)	42/0.25	[38]
$C_6H_5PF_3N(C_2H_5)_2$	V 1) 2) 3) 4)	78–82/2; 81/1.35; 70/0.5	[33, 38–40]
$C_6H_5PF_3N[CH_2CH(CH_3)_2]_2$	V 1)	107–108/2	[33]
$C_6H_5PF_3N(C_2H_5)C_6H_5$	V 1)	141–143/3	[33]
$C_6H_5PF_3$-Piperidino	V 1) 2)	115–116/2; 69/0.05	[33, 38]
$C_6H_5PF_3$-Morpholino	V 1)	108–109/2	[33]
$C_6H_5PF_3$-*N*-Pyrrolyl	V 4)	73–74/0.35	[40]
p-$ClC_6H_4PF_3N(C_2H_5)_2$	V 1)	96–97/2	[33]
p-$ClC_6H_4PF_3N[CH_2CH(CH_3)_2]_2$	V 1)	138–140/3	[33]
p-$ClC_6H_4PF_3$-Piperidino	V 1)	128–130/2	[33]
p-$ClC_6H_4PF_3$-Morpholino	V 1)	132–134/2	[33]

VI. Perhaloalkyldihalodifluorophosphoranes

The known compounds of this type have all been made by addition of elemental halogen to the corresponding fluorophosphine [29,41]:

$$R_{Hal}PF_2 + X_2 \rightarrow R_{Hal}PF_2X_2 \qquad (X = Cl, Br)$$

Table 7. Perhaloalkyldihalodifluorophosphoranes, $RHalPF_2X_2$.

Compound	Method of Preparation	J_{P-F} [c.p.s.]	Properties	Ref.
$CCl_3PF_2Cl_2$	VI	1106	White, crystalline solid, volatile in vacuum.	[18, 29]
$CCl_3PF_2Br_2$	VI	1109	White, crystalline solid, volatile in vacuum.	[18, 29]
n-$C_3F_7PCl_2F_2$	VI	1105	Volatile solid.	[29]

[39] *R. Schmutzler*, Angew. Chem. *76*, 570 (1964); Angew. Chem. internat. Edit. *3*, 513 (1964).

[40] *R. Schmutzler*, Angew. Chem. *76*, 893 (1964); Angew. Chem. internat. Edit. *3*, 753 (1964).

[41] *J. F. Nixon*, personal communication.

VII. Fluoro-1,3,2,4-diazadiphosphetidines

1. This novel type of compound was obtained in the following reactions (x) which proceed highly specifically with respect to ring size [36,42].

$$2\ PF_5 + 2\ [(CH_3)_3Si]_2NCH_3 \rightarrow \begin{matrix} F_3P\text{-}N\text{-}CH_3 \\ | \quad | \\ H_3C\text{-}N\text{-}PF_3 \end{matrix} + 4\ (CH_3)_3SiF \qquad (x)$$

$$2\ R(Ar)PF_4 + [(CH_3)_3Si]_2NCH_3 \rightarrow \begin{matrix} (Ar)RF_2P\text{-}N\text{-}CH_3 \\ | \quad | \\ H_3C\text{-}N\text{-}PF_2R(Ar) \end{matrix} + 4\ (CH_3)_3SiF$$

2. Small yields of $[F_3PNCH_3]_2$ were also obtained by fluorination of the corresponding chloride with KSO_2F in nitrobenzene [43].

3. A further method of preparation of $[F_3PNCH_3]_2$ involves reaction of PF_5 with CH_3NH_2 in the presence of trimethylamine [43] according to (y).

$$6\ PF_5 + 2\ CH_3NH_2 + 4\ (CH_3)_3N \rightarrow \begin{matrix} F_3P\text{-}N\text{-}CH_3 \\ | \quad | \\ H_3C\text{-}N\text{-}PF_3 \end{matrix} + 4\ (CH_3)_3NH^+PF_6^- \qquad (y)$$

4. The 1:1 adduct between aniline and PF_5 reacts at 10–25 °C in benzene with the 1:1 adduct of $(C_2H_5)_3N$ with PF_5, the *N*-phenyl compound $[C_6H_5NPF_3]_2$ being formed [44] [Eq. (z)].

$$2\ C_6H_5NH_2 \cdot PF_5 + 4\ (C_2H_5)_3N \cdot PF_5 \rightarrow \begin{matrix} F_3P\text{-}N\text{-}C_6H_5 \\ | \quad | \\ H_5C_6\text{-}N\text{-}PF_3 \end{matrix} + 4\ (C_2H_5)_3NH^{\oplus}PF_6^{\ominus} \qquad (z)$$

Table 8. Fluoro-1,3,2,4-diazadiphosphetidines.

Compound	Method of preparation	B.p.[°C/mm Hg] (m.p. [°C])	Ref.
$[F_3PNCH_3]_2$	VII 1) 2) 3)	87.9–89/760 (−8.3; −11)	[36,42,43]
$[F_3PNC_6H_5]_2$	VII 4)	[a]	[44]
$[(ClCH_2)F_2PNCH_3]_2$	VII 1)	68/0.05 (47–48)	[42]
$[(C_2H_5)F_2PNCH_3]_2$	VII 1)	42/1	[42]
$[(C_6H_5)F_2PNCH_3]_2$	VII 1)	(162) [a]	[42]

[a] Sublimes in vacuum.

VIII. Miscellaneous Ways of Formation of Fluorophosphoranes

An unusual mode of formation of CH_3PF_4 was observed during the disproportionation of CH_3PF_2, which proceeds slowly at room temperature in accordance with

[42] *R. Schmutzler*, Chem. Comm. (London) *1965*, 19.

[43] *P. Haasemann*, Doctorate Dissertation, Technische Hochschule Stuttgart (Germany), 1963; *J. Goubeau*, personal communication.

[44] *J. J. Harris* and *B. Rudner*, Paper presented at the 145th Meeting, American Chemical Society, Philadelphia 1964; *J. J. Harris*, personal communication.

[45] *L. M. Yagupol'skii* and *Zh. M. Ivanova*, Zhur. Obshch. Khim. *30*, 4026 (1960).

(a'). The rate of conversion may be increased by heating. The related $ClCH_2PF_2$ apparently undergoes a similar transformation [29].

$$10\,CH_3PF_2 \rightarrow 5\,CH_3PF_4 + (CH_3P)_5 \qquad [16] \qquad (a')$$

Bis(trifluoromethyl)trifluorophosphorane is formed on contact of SF_4 with $(CF_3)_2PI$ at room temperature [28]. Also unusual is the formation of $(C_6H_5)_3PF_2$ in the reaction of bis(perfluoroisopropyl)disulfide *(3)* with $(C_6H_5)_3P$ [46]:

$$(CF_3)_2CF\text{-}S\text{-}S\text{-}CF(CF_3)_2 + (C_6H_5)_3P \rightarrow 2\,(CF_3)_2C{=}S + (C_6H_5)_3PF_2$$

$(n\text{-}C_4H_9)_3PF_2$ is obtained in good yield upon reaction of hexafluorothioacetone with tributylphosphine [46].

C. Physical and Chemical Properties of Fluorophosphoranes

1. General

All fluorophosphoranes are sufficiently stable to be handled in glass apparatus, but glass frequently is attacked slowly if moisture is not rigorously excluded. Fluorophosphoranes are stable indefinitely in containers made of inert materials such as stainless steel or Teflon®. Upon standing of tetra- and trifluorophosphoranes in glass containers, they are converted to phosphonyl or phosphinyl fluorides, respectively, which on prolonged contact with glass or with excess water may be converted to the corresponding acids [7, 10, 11, 23]:

$$R_nPF_{5-n} \xrightarrow[-HF]{H_2O} R_nPOF_{3-n} \xrightarrow[-HF]{H_2O} R_nPO(OH)_{3-n} \qquad (b')$$

The hydrolytic stability of fluorophosphoranes with hydrocarbon substituents may be classified qualitatively as follows:

$$R_3PF_2 > R_2ArPF_2 \approx Ar_2PF_3 > RArPF_3 > R_2PF_3 > R(Ar)PF_4\ (> PF_5)$$

A difluorophosphorane such as $(n\text{-}C_4H_9)_3PF_2$, for example, is unchanged in glass over at least one year, whereas during the synthesis of dialkyltrifluorophosphoranes from tetraalkyldiphosphine disulfides and SbF_3, formation of phosphinic fluorides, $R_2P(=O)F$, even with careful exclusion of moisture, cannot be suppressed completely. In contrast to other difluorophosphoranes, the compound $(CH_3)_2PF_2CH_2CH_2PF_2(CH_3)_2$ is hydrolysed with extreme ease to give $(CH_3)_2P(=O)CH_2CH_2P(=O)(CH_3)_2$.

Little is known about the hydrolytic behavior of fluorophosphoranes containing substituents other than hydrocarbon groups. Aryltrifluorophosphorus hydrides, for instance, react with excess water in accordance with (c').

$$ArPF_3H + 2\,H_2O \rightarrow 3\,HF + ArPO_2H_2 \qquad [32] \qquad (c')$$

The hydrolysis of aryldialkylaminotrifluorophosphoranes with excess water has been shown to proceed as in (d') [33]. Conceivably this hydrolysis involves an

$$ArPF_3NR_2 + 2\,H_2O \rightarrow 2\,HF + R_2NH_2^{\oplus}\,ArPO_2F^{\ominus} \xrightarrow{\text{aniline}} \text{anilinium salt} \qquad (d')$$

$ArPOFNR_2$ intermediate. Formation of the anionic species $ArPO_2F^{\ominus}$ was also observed when (aryl)tetrafluorophosphoranes were brought in contact with aniline or *p*-toluidine in the presence of atmospheric moisture [12] [Eq. (e')].

$$ArPF_4 + 2\,H_2O + 4\,Ar'NH_2 \rightarrow 3\,Ar'NH_3F + Ar'NH_3^{\oplus} + ArPO_2F^{\ominus}$$

$$(Ar = C_6H_5, p\text{-}ClC_6H_4;\ Ar' = C_6H_5, p\text{-}CH_3C_6H_4) \qquad (e')$$

Phosphonyl difluorides, $ArPOF_2$, also enter this type of reaction. This fact suggests their intermediate role [12].

Fluorophosphoranes containing the 1,3,2,4-diazadiphosphetidine ring system are remarkably stable towards hydrolysis. For instance, $[C_6H_5PF_2NCH_3]_2$ could be recovered to an extent of 83% after having been boiled with water for 3 hours [42].

The majority of the known fluorophosphoranes is thermally stable. There were no indications for any disproportionation on heating $C_6H_5PF_4$ to 350 °C for 8 h in a sealed vessel [31]. Thus, with regard to thermal stability, fluorophosphoranes are significantly different from the only formally analogous chlorophosphoranes, R_nPCl_{5-n}. The latter usually are thermally unstable and salt-like, thus being comparable to the "parent compound" PCl_5 ($[PCl_4][PCl_6]$). Chlorophosphoranes usually cannot be volatilized without decomposition [48].

It was noted, however, that the thermal stability of certain fluorophosphoranes is limited, too. The perfluoroalkyl compound $(CF_3)_3PF_2$, for instance, may undergo a reversible transformation to $(CF_3)_2PF_3$ with elision of difluorocarbene, CF_2. $(CF_3)_2PF_3$ undergoes further transformations until the stage of the stable PF_5 is reached [27, 28] [Eqs. (f')].

$$\begin{aligned} (CF_3)_3PF_2 &\rightleftharpoons (CF_3)_2PF_3 + CF_2 \\ (CF_3)_2PF_3 &\rightleftharpoons CF_3PF_4 + CF_2 \\ CF_3PF_4 &\rightleftharpoons PF_5 + CF_2 \end{aligned} \qquad (f')$$

At 25 °C, $(CF_3)_2PF_3$ disproportionates to the extent of 10% per day with formation of $(CF_3)_3PF_2$ and CF_3PF_4. The latter undergoes a similar but slower disproportionation to give $(CF_3)_3PF_2$, $(CF_3)_2PF_3$, and PF_5. The reaction of excess PF_5 with $(CF_3)_3PF_2$ (100 °C/4 h) is a good method of synthesis of CF_3PF_4 [27, 28].

In the absence of other reagents, CF_2 originating from CF_3-substituted fluorophosphoranes is converted irreversibly to the dimer, $CF_2{=}CF_2$, trimer (hexafluorocyclopropane), and to higher polymers. By means of suitable reagents, CF_2 formed in the decomposition of $(CF_3)_3PF_2$, usually at 100 °C, may be intercepted. Reactions with I_2, HCl, and O_2, leading to CF_2I_2, HCF_2Cl, and COF_2, respectively, have been reported, for example. A reaction with hydrogen was not observed, whereas UF_6 and MoF_6 were reduced. Reaction with Cl_2 proceeds in a more complicated manner, all three possible chlorofluoromethanes being formed. No reaction with CF_2 was observed when $(CF_3)_3PF_2$ was pyrolysed at

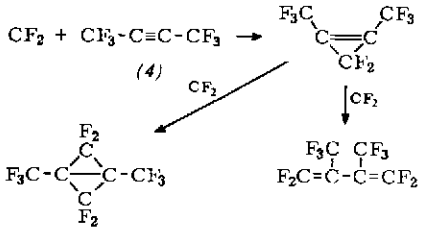
[46] *W. J. Middleton*, personal communication.

[47] *R. Schmutzler*, unpublished work.

[48] *W. Kuchen, H. Buchwald, K. Strolenberg*, and *J. Metten*, Liebigs Ann. Chem. *652*, 28 (1962).

120 °C in the presence of BF_3, NO, NF_3, N_2O, PF_3, CS_2, SO_2, or CF_3I [27, 28].

It is of special interest that a bicyclobutane derivative is formed when the pyrolysis of $(CF_3)_3PF_2$ is conducted in the presence of hexafluorobut-2-yne *(4)*. The main line of reaction may be represented as follows [49]:



II. Chemistry of Fluorophosphoranes

The chemistry of the tetrafluorophosphoranes, RPF_4, is characterized and determined by their electron acceptor (Lewis acid) properties which are similar to those of the parent compound, PF_5 [50].

The acceptor strength of tetrafluoropbosphoranes is lower than that of PF_5, although $C_6H_5PF_4$, for instance, reacts with some typical Lewis bases, such as dimethylformamide or pyridine, with formation of 1:1 adducts. Alkyltetrafluorophosphoranes also react with organic donor molecules, but no complexes stable enough to be isolated at room temperature are obtained [51]. ^{19}F-NMR spectroscopy gives no evidence that R_2PF_3 and R_3PF_2, which are presumably very weak electron acceptors, interact with donors at all. There is an increase in hydrolytic stability of the fluorophosphoranes with decreasing Lewis acidity (cf. C.I).

According to ^{19}F-NMR studies, tetrafluorophosphoranes undergo an interesting transformation in solutions in dimethyl sulfoxide. At first, formation of a solvated fluorophosphonium cation *(5)*, besides $RPF_5^{\ominus}$, was thought to have occurred:

$$2RPF_4 \cdot OS(CH_3)_2 \rightleftharpoons \{RPF_3[OS(CH_3)_2]_2\}^{\oplus} + RPF_5^{\ominus} \qquad (5)$$

It was subsequently found, however, that the presumed cation decomposes with formation of $H^{\oplus}$ and $RPOF_2$. The identity of $[RPF_5]^{\ominus}$ (R = C_6H_5) as an octahedral species with four fluorine atoms (F_e) in equatorial and one (F_a) in axial position was established from the following NMR parameters: $J_{P-Fe} \approx 830$ c.p.s., $J_{P-Fa} \approx 680$ c.p.s., $J_{FaFe} = 41$ c.p.s., $\delta_{FaFe} = 3.7$ p.p.m. The ^{19}F-NMR spectrum consists of a doublet of doublets (F_e) and a doublet of quintets (F_a). Similarly, the species $[CH_3PF_5]^{\ominus}$ (besides CH_3POF_2) was detected in the system $CH_3PF_4/(CH_3)_2SO$. The following NMR parameters were found for $[CH_3PF_5)]^{\ominus}$:

$J_{P-Fe} = 830$ c.p.s., $J_{P-Fa} = 691$ c.p.s., $J_{FaFe} = 39$ c.p.s., $J_{H\ Fe} = 8$ c.p.s., $\delta_{FaFe} = 10.3$ p.p.m. [51].

It may be noted that use has been made of the Lewis acids $C_6H_5PF_4$ and $i\text{-}C_8H_{15}PF_4$ in the polymerization of tetrahydrofuran [7, 30].

Stable salts containing alkyl(aryl)pentafluorophosphate anions were obtained according to (g') [38].

$$2\ R(Ar)PF_4 + 2\ R_2'NH \xrightarrow[0-10\,^{\circ}C]{\text{ether}} R(Ar)PF_3NR_2' + [R_2'NH_2][R(Ar)PF_5]. \qquad (g')$$

Formation of an organopentafluorophosphate was also observed when $C_6H_5PF_3N(CH_3)_2$ was allowed to stand at room temperature over prolonged periods [52]:

$$2\ C_6H_5PF_3N(CH_3)_2 \rightarrow C_6H_5PF[N(CH_3)_2]_2^{\oplus}\ [C_6H_5PF_5]^{\ominus}. \qquad (h')$$

The course of this interesting reaction is independent of the method of preparation of $C_6H_5PF_3N(CH_3)_2$. It is noteworthy that the closely related $C_6H_5PF_3N(C_2H_5)_2$, even after prolonged storage, does not show any indication of such a transformation.

The identity of the ion $[C_6H_5PF_5]^{\ominus}$ is confirmed especially by ^{31}P- and ^{19}F-NMR spectroscopy [52]. The ^{31}P spectra of the transformation product in acetonitrile show a doublet at low field (85 % H_3PO_4 reference) due to the cation. At high field there is another doublet ($J_{P-Fa} = 697$ c.p.s.), each of whose components are split into a quintet as a result of spin-spin coupling between ^{31}P and the four equatorial fluorine atoms of the octahedral $[C_6H_5PF_5]^{\ominus}$ ($J_{P-Fe} = 816$ c.p.s.). Particularly revealing is the high positive value of the ^{31}P chemical shift (+136.0 p.p.m.), which is only slightly lower than that for the highly symmetrical $PF_6^{\ominus}$ (+143.7 p.p.m.) [52]. The ^{19}F-NMR spectrum is also in agreement with the C_{4v} symmetry suggested for $[C_6H_5PF_5]^{\ominus}$ ($J_{P-Fe} = 818$ c.p.s.; $J_{P-Fa} = 690$ c.p.s.; $J_{FaFe} = 41$ c.p.s.). Identical data were obtained for a series of further dialkylammonium-RPF_5 salts [38]. The facile formation of the $[RPF_5]^{\ominus}$ ion is noteworthy in view of the paucity of hexacoordinate phosphorus species, aside from the well known ions $PF_6^{\ominus}$ (and $PCl_6^{\ominus}$).

$C_6H_5PF_4$, like PF_5, forms a 1:1 adduct with NOF, which is not very stable thermally, in contrast to $NO^{\oplus}PF_6^{\ominus}$. Various reactions, *e.g.* (i')–(l'), suggest the structure $NO^{\oplus}[C_6H_5PF_5]^{\ominus}$ for the adduct.

$$NO^{\oplus}[C_6H_5PF_5]^{\ominus} + BF_3 \rightarrow NOBF_4 + C_6H_5PF_4 \qquad (i')$$

$$NO^{\oplus}[C_6H_5PF_5]^{\ominus} + CH_3OH \rightarrow ClH_3ONO, C_6H_5P(:O)F_2 \qquad (k')$$

$$NO^{\oplus}[C_6H_5PF_5]^{\ominus} + 2,4\text{-}(CH_3)_2C_6H_3NH_2 \rightarrow 2,4\text{-}(CH_3)_2C_6H_3F\ \textit{etc.} \qquad (l')$$

Of particular interest is the reaction with secondary amines which proceeds smoothly in accordance with (m').

$$NOF \cdot C_6H_5PF_4 + 2\ R_2NH \rightarrow R_2N \cdot NO + [R_2NH_2]^{\oplus}\ [C_6H_5PF_5]^{\ominus} \qquad (m')$$

Again, formation of stable dialkylammonium phenylpentafluorophosphates is observed [38].

Hydrolysis of $NOF \cdot C_6H_5PF_4$ gives phenylphosphonic acid as the only product, and an attack of the NO group on the aromatic ring may be excluded from consideration.

In contrast to NOF, NO_2F reacts with $C_6H_5PF_4$ even at −30 °C exclusively with nitration of the aromatic ring. The substitution takes place presumably in the *p*-position, since hydrolysis of the nitration product leads to the stable *p*-nitrophenylphosphonic acid [38].

[49] *W. Mahler*, J. Amer. chem. Soc. *84*, 4600 (1962).

[50] *E. L. Muetterties, T. A. Bither, M. W. Farlow*, and *D. D. Coffman*, J. inorg. nucl. Chem. *16*, 52 (1960).

[51] *E. L. Muetterties* and *W. Mahler*, Inorg. Chem. *4*, 119 (1965).

[52] *R. Schmutzler*, J. Amer. chem. Soc. *86*, 4500 (1964).

Among further reactions related to the Lewis acid character of fluorophosphoranes, the smooth cleavage of oxygen bridges is especially worth noting. Such reactions occur particularly readily with tetrafluorophosphoranes, whereas $(C_6H_5)_2PF_3$, the only trifluorophosphorane to enter this type of reaction, reacts much less readily. The following examples are typical[11,53]:

$$RPF_4 + (R'CO)_2O \rightarrow RPF_2O + 2\ R'COF$$

$$C_6H_5PF_4 + \text{(cyclic anhydride)} \xrightarrow{10h;\ 100°C} C_6H_5PF_2O + \text{polymers} \quad (89\%)$$

$$C_6H_5PF_4 + \text{(cyclic anhydride)} \rightarrow F\text{-}CO\text{-}CH_2\text{-}CH_2\text{-}CO\text{-}F + C_6H_5PF_2O$$

$$RPF_4 + R'_3Si\text{-}O\text{-}SiR'_3 \rightarrow RPF_2O + 2\ R'_3SiF$$

$$(C_6H_5)_2PF_3 + R'_3Si\text{-}O\text{-}SiR'_3 \rightarrow (C_6H_5)_2PFO + 2\ R'_3SiF$$

$$RPF_4 + R'_3Si\text{-}OR'' \rightarrow RPF_2O + R'_3SiF + R''F$$

$$(C_6H_5)_2PF_3 + R_3Si\text{-}OR' \rightarrow (C_6H_5)_2PFO + R_3SiF + R'F$$

The decrease in reactivity in going from RPF_4 to $(C_6H_5)_2PF_3$ is evident in all these reactions. Whereas the former type of compound usually reacts fast and exothermally, similar reactions of $(C_6H_5)_2PF_3$ require prolonged heating. In the case of carboxylic anhydrides, open-chain compounds react much more readily than maleic or succinic anhydride.

The reaction of RPF_4 or $(C_6H_5)_2PF_3$ [(o') and (p')] with trialkylsilyl ethers was originally devised for the preparation of the alkyl(aryl)alkoxytrifluorophosphoranes RPF_3OR', which were expected to be of interest with regard to their stereochemistry.

$$RPF_4 + R'_3SiOR'' \rightarrow RPF_3OR'' + R'_3SiF \qquad (o')$$

$$(C_6H_5)_2PF_3 + R_3SiOR' \rightarrow (C_6H_5)_2PF_2OR' + R_3SiF \qquad (p')$$

The observed instability of such compounds reflects the marked tendency of phosphorus to avoid the coordination number 5 by stabilization with formation of tetracoordinated species, such as RPF_2O and $(C_6H_5)_2PFO$. Formation of the polar phosphoryl group presumably enhances this tendency.

All reactions between fluorophosphoranes and Si–O compounds proceed in high yields in accordance with the above equations. In a similar manner, fluorophosphoranes react with Si–N compounds. This reaction provides a rather general approach toward the synthesis of various types of phosphorus-fluorine-nitrogen compounds [36,40,42] (cf. Sections B IV, V, VII). PF_5 and RPF_4 react with dialkylaminotrimethylsilanes in accordance with (q') and (r').

$$PF_5 + (CH_3)_3SiNR_2 \rightarrow R_2NPF_4 + (CH_3)_3SiF \qquad (q')$$

$$RPF_4 + (CH_3)_3SiNR'_2 \rightarrow RPF_3NR'_2 + (CH_3)_3SiF, \textit{etc.} \qquad (r')$$

[53] *R. Schmutzler*, J. chem. Soc. (London) *1964*, 4551.

The reaction of the above phosphorus fluorides with *N*-substituted hexamethyldisilazanes leads to formation of 1,3,2,4-diazafluorodiphosphetidines. It may also be noted that $C_6H_5PF_4$ and $(C_6H_5)_2PF_3$ react with hexamethyldisilazane with formation of polymeric phenyliminophosphonic and -phosphinic fluorides, respectively. Phosphonitrilic type compounds result on removal of HF from the latter, *e.g.* by means of CsF [54].

$$C_6H_5PF_4 + [(CH_3)_3Si]_2NH \xrightarrow[-2(CH_3)_3SiF]{} [C_6H_5PF_2(NH)]_n \rightarrow \xrightarrow[(CsF)]{-HF} [(C_6H_5)(F)P{=}N]_n \qquad (s')$$

$$(C_6H_5)_2PF_3 + [(CH_3)_3Si]_2NH \xrightarrow[-2(CH_3)_3SiF]{} [(C_6H_5)_2PF(NH)]_n \rightarrow \xrightarrow[(CsF)]{-HF} [(C_6H_5)_2P{=}N]_3 \qquad (t')$$

The reactions between fluorophosphoranes and Si–N compounds presumably proceed with an electrophilic attack of phosphorus on the silazane nitrogen. Subsequent nucleophilic attack of fluorine on the silicon leads to simultaneous cleavage of the Si–N bond.

$$\begin{array}{ccccc} R'_3SiNR''_2 & & R'_3Si\text{-}NR''_2 & & R'_3SiF \\ + & \rightarrow & FPF_{4-n} & \rightarrow & + \\ R_nPF_{5-n} & & R_n\ (6) & & R_nPF_{4-n}NR''_2 \end{array}$$

R = Alkyl, Aryl; R', R'' = Alkyl; n = 0,1

The presumed intermediate $RNPF_{3-n}$ (n = 0, 1) in the case of the *N*-substituted hexaalkyldisilazanes is obtained exclusively as the dimer [42].

The course of the reaction is markedly determined by the Lewis acidity of the phosphorus fluoride. A limit in reactivity is reached with $(C_6H_5)_2PF_3$, and $(CH_3)_2PF_3$ does not react with Si–N compounds even under forcing conditions. There is also no reaction between phosphorus trifluoride and heptamethyldisilazane [42], whereas a reaction between the closely related *N*-ethylhexamethyldisilazane and PCl_3 has been observed [55].

Based on the experience with SF_4 [56a,b], and $C_6H_5SF_3$ [57a,b] as unusual fluorinating agents, consideration has been given to employing fluorophosphoranes for this purpose. As the majority of the known fluorophosphoranes are liquids at room temperature, they are easier to handle than the gaseous SF_4. Although a reaction between carbonyl compound and fluorophosphorane was observed in almost every instance, the expected fluorination did not take place, and polymers were the predominant products. The only clear example of a carbonyl fluorination was observed in the system $(C_6H_5)_2PF_3/C_6H_5CHO$ [11] [Eq. (u')].

$$(C_6H_5)_2PF_3 + C_6H_5CHO \rightarrow (C_6H_5)_2PFO + C_6H_5CHF_2 \qquad (u')$$

The reaction of tetrachlorophosphoranes, obtained by the chlorination of dichlorophosphines, with SO_2 is one of the most important methods for the preparation of phosphonic dichlorides. As to the reaction of SO_2 with tetrafluorophos-

[54] *R. Schmutzler*, Z. Naturforsch. *19b*, 1101 (1964).

[55] *E. W. Abel* and *G. Willey*, Proc. chem. Soc. (London) *1962*, 308.

[56] (a) *W. C. Smith* (to E. I. du Pont de Nemours and Co., Inc.): U.S. Pat. 2859245 (Nov. 4th, 1958); (b) *W. C. Smith*, *W. R. Hasek*, and *V. A. Engelhardt*, J. Amer. chem. Soc. *82*, 543 (1960).

[57] (a) *W. A. Sheppard*, J. Amer. chem. Soc. *82*, 4751 (1960); (b) *W. A. Sheppard*, ibid., *84*, 3058 (1962).

phoranes, two somewhat conflicting observations have been reported: CH_3PF_4 has been found to react with SO_2 at 100 °C to give $CH_3P(=O)F_2$ [4, 5], whereas $C_6H_5PF_4$, under identical conditions, does not react with SO_2 [12].

Upon reaction of $C_6H_5PF_4$ with diazomethane, followed by hydrolysis, fluoromethylphenylphosphinic acid *(7)* is formed [45].

$$C_6H_5PF_4 \xrightarrow[2.\ H_2O]{1.\ CH_2N_2;\ -30\,^\circ C} \begin{matrix} C_6H_5 \\ CH_2F \end{matrix}\!\!>\!P(=O)\text{-}OH \quad (7)$$

Fluorides of phosphono- or phosphinothioic acids are formed on passing alkyl-tetra- and -trifluorophosphoranes over elemental sulfur, K_2S, ZnS, Al_2S_3, As_2S_3, PbS, SnS_2, Sb_2S_5, P_2S_3, or CS_2 [8].

Aryltrifluorophosphorus hydrides react with sulfur in 90% yield in accordance with (v') [32].

$$ArPF_3H + S \rightarrow ArPSF_2 + HF \qquad (v')$$

Finally, the reactions (w') and (x') of $C_6H_5PF_4$ with a carboxylic acid or its lithium salt may be mentoined.

$$C_2H_5COOH + C_6H_5PF_4 \rightarrow C_2H_5COF + C_6H_5POF_2 + HF \quad (w')$$

$$C_2H_5COOLi + C_6H_5PF_4 \rightarrow C_2H_5COF + C_6H_5POF_2 + LiF \quad [26]. \qquad (x')$$

III. Electron-Donor Properties of Fluorophosphoranes

Fluorophosphoranes form a number of crystalline, colorless 1:1 adducts with electron-acceptor molecules such as BF_3 or SbF_5, *e.g.* $(CH_3)_2PF_3 \cdot SbF_5$, $C_2H_5PF_4 \cdot SbF_5$, $(CH_3)_2PF_3 \cdot BF_3$ (dissociation pressure 1 mm at 25 °C). In general, dialkyltrifluorophosphoranes form more stable complexes with acceptor molecules than tetrafluorophosphoranes.

The formation of complexes of fluorophosphoranes with PF_5 as an acceptor molecule was established tensimetrically. The dissociation pressure of $CH_3PF_4 \cdot PF_5$, for instance, is given by the equation log p(mm) = 9.89 − 1882/T [51].

The donor properties of fluorophosphoranes may be due either to ionization,

$$R_nPF_{5-n} \rightleftharpoons [R_nPF_{4-n}]^{\oplus}F^{\ominus} \qquad (n = 1,2)$$

or to the presence of lone electron pairs on the ligands. No such properties have been observed for unsubstituted PF_5.

The complexes of fluorophosphoranes with acceptor molecules possibly contain fluorophosphonium cations, $RPF_3^{\oplus}$ or $R_2PF_2^{\oplus}$, besides the corresponding acceptor anions, such as $BF_4^{\ominus}$ or $SbF_6^{\ominus}$ [51].

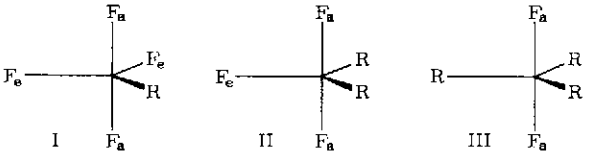
D. Stereochemistry of Fluorophosphoranes

I. General

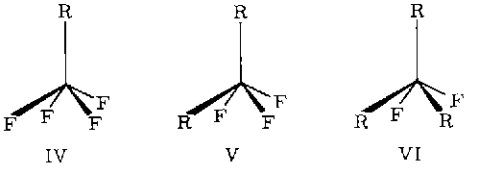
Whereas in the related molecules PCl_5 and $SbCl_5$ two different bond lengths, corresponding to equatorial and axial positions, have been observed, only one P–F bond distance has been found for PF_5 [*]. Likewise, in the ^{19}F-NMR spectrum of PF_5 only a single line is observed, split into a doublet by coupling between ^{19}F and ^{31}P [58]. The ^{19}F-NMR spectrum of PF_5 is independent of the temperature over a wide range [59], and there are no indications for intermolecular fluorine exchange.

These findings cannot be rationalized readily by either the trigonal-bipyramidal or square-pyramidal model generally accepted for pentacoordinate molecules. It is interesting to note that the ^{19}F- and ^{31}P-NMR spectra of the monosubstituted derivatives of PF_5 also indicate equivalence of the fluorine atoms over a wide temperature range [60–62].

The bonding in pentacoordinate molecules is characterized by the presence of five sp^3d hybrid orbitals. In case of combination with the d_{z^2} orbital, a trigonal-bipyramidal configuration results. The hybrid orbitals are directed towards the corners of a square pyramid if the $d_{x^2-y^2}$ orbital is used. Assuming that significant steric interactions occur between groups at an angle of 90° only, and that the ligand repulsion increases in the order F–F < F–R < R–R, the models I–III may be considered as the most likely configurations of trigonal-bipyramidal fluorophosphoranes.



Similar considerations for square-pyramidal arrangements lead to models IV to VI [60]:



II. Experimental Observations

1. Compounds of the Type R_3PF_2

In all compounds of this type NMR-spectroscopic equivalence of fluorine atoms and R groups is observed. Equivalence of fluorine atoms due to an intermolecular

[*] Note added in proof (April 25th, 1965): Previous electron diffraction studies on PF_5 indicated a single value for all P–F bond lengths [*H. Braune* and *P. Pinnow*, Z. physik. Chem. *B 35*, 239 (1937); *L. O. Brockway* and *J. Y. Beach*, J. Amer. chem. Soc. *60*, 1836 (1938)]. In a recent investigation, however, two different P–F bond lengths were observed: P–F (equatorial) = 1.499 ± 0.004 Å; P–F (axial) = 1.549 ± 0.005 Å (*O. L. Hersh*, Dissertation, University of Michigan 1963.

[58] *H. S. Gutowsky, D. W. McCall*, and *C. P. Slichter*, J. chem. Physics *21*, 279 (1953).

[59] *R. J. Gillespie*, personal communication.

[60] *E. L. Muetterties, W. Mahler*, and *R. Schmutzler*, Inorg. Chem. *2*, 613 (1963).

[61] *E. L. Muetterties, W. Mahler, K. J. Packer*, and *R. Schmutzler*, Inorg. Chem. *3*, 1298 (1964).

[62] *J. F. Nixon* and *R. Schmutzler*, Spectrochim. Acta *20*, 1835 (1964).

exchange process is ruled out since F–H coupling is observed. Intramolecular exchange is also unlikely because of the size of the substituents, and especially because of the internal consistency of the ^{19}F chemical shifts in the various types of compounds, as will be discussed below.

The remarkable variation in the P–F coupling constants of R_3PF_2 seems to be due mainly to differences in electronegativity of the substituents, which are also reflected in the P–F stretching frequencies in the infrared spectra [60], *e.g.* in

R_3PF_2 (R = alkyl)	ν_{P-F} – ca. 620 cm^{-1}
R_2ArPF_2 (R = alkyl, Ar = aryl)	ν_{P-F} 640 cm^{-1}
$(CF_3)_3PF_2$	ν_{P-F} = 855 cm^{-1}.

Similar shifts in the P–F stretching frequencies as a result of the presence of different substituents are also noted in the infrared spectra of R_2PF_3 and RPF_4 [60].

2. Compounds of the Type R_2PF_3

The ^{19}F-NMR spectra of these compounds indicate the presence of two kinds of fluorine atoms, the remaining two substituents occupying equivalent positions [38–40, 60,61].

For instance, the spectrum of the simplest compound, $(CH_3)_2PF_3$, comprises two (P–F coupling) triplets of intensity one at high field (equatorial fluorine atom), and a multiplet of intensity two at low field (axial fluorine atom). The multiplet comprises two (J_{P-Fe}) doublets (J_{FaFe}), whose components are further split due to coupling between the axial fluorine atoms and the H atoms of the alkyl groups. Thus in the case of $(CH_3)_2PF_3$, a septet fine structure is observed.

These data are in accord with model II. A square-pyramidal arrangement cannot be ruled out, however, but is rendered unlikely on the basis of the internal consistency of the ^{19}F chemical shifts to be discussed below.

The spectra of the other trifluorophosphoranes differ from that of $(CH_3)_2PF_3$ only in the details of the low-field multiplets. A quartet fine structure is observed for $(CH_3)(C_6H_5)PF_3$, for instance, and in $(C_6H_5)_2PF_3$ the low field resonance signals are doublets. Further, there is much stronger coupling between the hydrogens of (equatorial) alkyl groups and axial fluorine atoms than with those in equatorial positions, *e.g.* in $(CH_3)(C_6H_5)PF_3$: J_{Fa-CH_3} = 12.9 c.p.s., J_{Fe-CH_3} = 1.9 c.p.s. A comparison of the ^{19}F-NMR spectra of various R_2PF_3 compounds shows that, as a rule, axial P–F coupling constants are about 100–200 c.p.s. smaller than equatorial ones. This finding, as well as the observed infrared P–F frequencies, suggest that axial P–F bonds are longer than equatorial bonds. Likewise, the axial bond lengths in R_3PF_2 seem to be larger than in R_2PF_3. The predictions of *Pauling*'s valence-bond theory are in contrast to this finding, axial bonds in the trigonal bipyramid having been suggested to be stronger than equatorial ones. The experimental data available for some other trigonal-bipyramidal molecules, such as PCl_5, also suggest equatorial bonds to be stronger than axial bonds. The situation has been represented correctly in a recent M.O. calculation, using Slater orbitals [64]; c.f. also [65].

[63] *R. Schmutzler*, unpublished work.

[64] *F. A. Cotton*, J. chem. Physics *35*, 228 (1961).

[65] *R. J. Gillespie*, J. chem. Soc. (London) *1963*, 4672.

Of special interest among trifluorophosphoranes is the stereochemistry of the cyclic compound *(8)*. The ^{19}F spectrum at room temperature is a simple doublet (P–F coupling), suggesting equivalence of fluorine atoms.

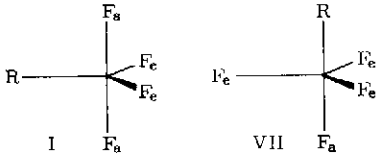
(8) *(9)*

Both lines are split into a quintet as a result of coupling between fluorine and the four α-protons. When a solution of $(CH_2)_4PF_3$ in toluene is cooled, a broadening of the resonance signals is first observed, and below −70 °C the typical R_2PF_3 spectrum appears. Apparently the strain in the PC_4 ring system lowers the energy of activation for the fluorine-exchange process. In accord with this assumption, a similar exchange process is not observed in the presumably less strained ring system *(9)*, even at temperatures up to 100 °C [60].

P–F and C–F fluorine atoms in the perfluoroalkyltrifluorophosphoranes $(CF_3)_2PF_3$ [60] and $(C_2F_5)_2PF_3$ [61] are found to be equivalent at room temperature. Possibly all three fluorine atoms in these compounds occupy identical positions. NMR-spectroscopic equivalence is also observed in the spectra of Cl_2PF_3 and Br_2PF_3 at room temperature. The equivalence in these cases, however, is due to a temperature-dependent exchange process [60]. C_{2v} symmetry has been proved for Cl_2PF_3 (and also for H_2PF_3 [68]) by infrared and Raman spectroscopy [68,69]. Two fluorine atoms occupy axial positions, one is equatorial.

3. Compounds of the Type RPF_4

The ^{19}F-NMR spectra of all compounds investigated thus far show the fluorine atoms to be equivalent at room temperature [29,34,60,61]. This suggests a square-pyramidal structure with four fluorine atoms occupying equatorial positions. The equivalence of fluorine atoms in the RPF_4 spectra is not compatible with either one of the two trigonal-bipyramidal models I and VII except on



the assumption of intramolecular positional exchange taking place. This kind of an intramolecular pseudorotation process, in which the position of one of the five ligands is retained, was proposed originally for the parent compound PF_5 [66]. In the case of the tetrafluorophosphoranes, the exchange process is independent of temperature over a wide range. It is of

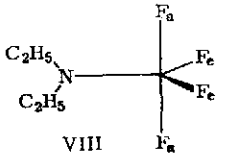
[66] *R. S. Berry*, J. chem. Physics *32*, 933 (1960).

[67] *K. Moedritzer, L. Maier*, and *L. C. D. Groenweghe*, J. chem. Engng. Data *7*, 307 (1962).

[68] *J. Goubeau*, personal communication.

[69] *J. E. Griffiths, R. P. Carter*, and *R. R. Holmes*, J. chem. Physics *41*, 863 (1964).

special interest, therefore, that for the recently synthesized tetrafluorophosphorane $(C_2H_5)_2NPF_4$ [40], nonequivalence of fluorine atoms has been found in the ^{19}F-NMR spectrum at low temperature [61]. Two doublets have been observed, each component showing triplet fine structure. This finding is in accord with the trigonal-bipyramidal model VIII in which a fast intramolecular exchange process takes place. The energy of activation for the fluorine exchange has been estimated as 12.8 ±2 kcal/mole [61].



VIII

Chemical shifts for equatorial fluorine atoms in trifluorophosphoranes are found between −10 to +16 p.p.m., and extreme values are noted only for a few perfluoroalkyl derivatives. Strongly negative values are observed for δ_F of axial fluorine atoms, usually between −35 and −75 p.p.m., and only the perfluoroalkyl derivatives and some dialkylaminofluorophosphoranes show more positive values. ^{19}F chemical shifts in R_2PF_3 mostly fall in the region −39 to −73 p.p.m., *i.e.* in the same region as for axial fluorine atoms in R_2PF_3.

Table 9. Chemical shifts in the ^{19}F-NMR spectra of fluorophosphoranes [a].

Compound	δCF_3 [p.p.m.]	δF (mono) [p.p.m.]	δF_e [p.p.m.]	δF_a [p.p.m.]	Ref.
CF_3PF_4	− 3.4	−10	—	—	[60]
$(CF_3)_2PF_3$	− 3.8	—	− 7.5	—	[60]
$(CF_3)_3PF_2$	−12	—	—	−16.8	[60]
CH_3PF_4	—	−31	—	—	[60]
$(CH_3)_2PF_3$	—	—	+ 9.8	−74	[60]
$(CH_3)_3PF_2$	—	—	—	−73	[60]
$(CH_2)_4PF_3$ (25 °C)	—	−34.9 [b]	—	—	[63]
$(CH_2)_5PF_3$	—	—	+ 6	−58	[60]
$C_2H_5PF_4$	—	− 25	—	—	[60]
$(C_2H_5)_2PF_3$	—	—	+ 16	−52	[60]
$(C_2H_5)_3PF_2$	—	—	—	−44	[60]
$C_2F_5PF_4$	—	−15.8	—	—	[61]
$(C_2F_5)_2PF_3$	—	—	−21	—	[61]
$n\text{-}C_3F_7PF_4$	—	−20.9	—	—	[29]
$(n\text{-}C_3F_7)_2PF_3$	—	—	−26.5	—	[29]
$n\text{-}C_4H_9PF_4$	—	−27	—	—	[60]
$(n\text{-}C_4H_9)_2PF_3$	—	—	+13	−56	[60]
$(n\text{-}C_4H_9)_3PF_2$	—	—	—	−44	[60]
$C_6H_5PF_4$	—	−23	—	—	[60]
$(C_6H_5)_2PF_3$	—	—	+ 1.2	−44	[60]
$(C_6H_5)_3PF_2$	—	—	—	−39	[60]
$C_6H_5(CH_3)PF_3$	—	—	+ 5.4	−60	[60]
$ClCH_2PF_4$	—	−24	—	—	[60]
CCl_3PF_4	—	−10.4 [b]	—	—	[29]
$i\text{-}C_8H_{15}PF_4$	—	−31	—	—	[60]
$C_6H_5CH=CHPF_4$	—	−32	—	—	[60]
m- and *p*-$CH_3C_6H_4PF_4$	—	−23; −23.9 [b,c]	—	—	[63]
$(C_2H_5)_2NPF_4$	—	−10 (25 °C)	− 5.2 (−85 °C)	−17.3 (−85 °C)	[61]
$[(C_2H_5)_2N]_2PF_3$	—	—	− 9	−17.0	[44,61]
$CH_3PF_3N(CH_3)_2$	—	—	− 8.5 [b]	−49.0	[29]
$C_2H_5PF_3N(C_2H_5)_2$	—	—	− 8.0	−37.0	[38,61]
$C_6H_5PF_3NHCH_3$	—	—	− 5.8 [b]	−37.8	[38]
$C_6H_5PF_3N(CH_3)_2$	—	—	− 9.0	−36.0	[38,61]
$C_6H_5PF_3N(C_2H_5)_2$	—	—	−11.0	−35.0	[38,61]
$C_6H_5PF_3$-Piperidino	—	—	− 0.5 [b]	−33.9	[38]
$C_6H_5PF_3$-*N*-Pyrrolyl	—	—	− 8.5 [b]	−38.3	[40]
$C_6H_5PF_3H$	—	—	+ 9.7	− 46.0	[61]
$C_6H_5PF_3Cl$	—	—	−23.0	− 89.0	[61]
$CCl_3PCl_2F_2$	—	—	—	− 79.9 [b]	[18,19]
$CCl_3PBr_2F_2$	—	—	—	−110.3 [b]	[18,29]
$n\text{-}C_3F_7PCl_2F_2$	—	—	—	−115.7 [b]	[29]

[a] Relative to CF_3COOH (external standard) [60,61].

[b] Calculated from values measured relative to CCl_3F as internal standard according to $\delta F(CF_3COOH) = \delta F(CCl_3F) - 77.5$ p.p.m.

[c] Two isomers present.

4. ^{19}F Chemical Shifts of Fluorophosphoranes

Important conclusions as to the stereochemistry of fluorophosphoranes may be drawn from the ^{19}F chemical shifts δ_F [29,38–40,60,61,63]. With the exception of CF_3PF_4, CCl_3PF_4, and $(C_2H_5)_2NPF_4$ (ca. −10 p.p.m.), all values for δ_F of tetrafluorophosphoranes fall in the narrow range −23 to −31 p.p.m. (relative to CF_3COOH).

Especially revealing is a comparison of δ_F for axial fluorine atoms in R_2PF_3 and R'_3PF_2, where R = R'. There usually is very good agreement, the greatest deviation (12 p.p.m.) being found in the butyl series [60].

The differences in δ_F for equatorial and axial fluorine atoms in R_2PF_3 and R_3PF_2 usually are substantial. Therefore, it seemed justified to use these data to calculate approximate values for δ_F of the corresponding tetrafluorophosphoranes in which fast positional exchange of fluorine atoms takes place. Assuming equatorial substitution, excellent agreement was found for alkyl and aryl derivatives [60].

Table 10. ^{19}F-NMR data for trifluorophosphoranes.

Compound	J_{P-F_a} [c.p.s.]	J_{P-F_e} [c.p.s.]	$\delta F_e - \delta F_a$ [p.p.m.]	$J_{F_a-F_e}$ [c.p.s.]	J_{H-F_e} [c.p.s.]	J_{H-F_a} [c.p.s.]	Ref.
$(CH_3)_2PF_3$	772	960	83.8	26	≈ 2	–	[60]
$(CF_3)_2PF_3$	1260		–	–	175 ($P-CF$)	16 ($CF-PF$)	[60]
$(C_2H_5)_2PF_3$	815	980	68.0	29	–	12	[60]
$(n\text{-}C_4H_9)_2PF_3$	810	985	69.0	28	≈ 2	14	[60]
$(CH_3)(C_6H_5)PF_3$	785	935	65.4	33	–	14	[60]
$(C_6H_5)_2PF_3$	838	970	45.2	37	–	–	[60]
$(CH_2)_4PF_3$ (−100 °C)	865	990	–	50	–	–	[60]
$(CH_2)_4PF_3$ (25 °C)	915		–	–	–	–	[60]
$(CH_2)_5PF_3$	800	1005	64	42	–	–	[60]
$CH_3PF_3N(CH_3)_2$	808	965	41.4	54	–	–	[39]
$C_2H_5PF_3N(C_2H_5)_2$	825	985	29.0	51	–	11	[61]
$C_6H_5PF_3N(CH_3)_2$	820	955	27.0	55	–	–	[61]
$C_6H_5PF_3NHCH_3$	770	953	32.1	–	–	–	[63]
$C_6H_5PF_3N(C_2H_5)_2$	815	955	24.0	55	–	–	[61]
$C_6H_5PF_3$-Piperidino	820	964	24.4	56	–	–	[38]
$C_6H_5PF_3$-*N*-Pyrrolyl	860	979	29.8	58	–	–	[40]
$[(CH_3)_2N]_2PF_3$	752	871	–	42	1.3	2.7	[34]
$[(C_2H_5)_2N]_2PF_3$	751	875	8.0	46	–	–	[61]
$C_6H_5PF_3H$	831	969	55.7	31.5	31.5	124	[61]
$C_6H_5PF_3Cl$	956	1035	80	66	–	–	[61]

5. ^{31}P-NMR Spectra of Fluorophosphoranes

Most of the ^{31}P-NMR data for various types of pentacoordinate P–F compounds are summarized in [62]. Difluorophosphoranes show a 1–2–1 triplet in the ^{31}P-NMR spectrum. The spectra of the trifluorophosphoranes consist of a doublet (J_{P-F_e}), each component being split into a triplet (J_{P-F_a} – cf. formula *(2)*). A quintet is observed for RPF_4, in accord with the equivalence of the four fluorine atoms due to fast positional exchange which is also noted in the ^{19}F spectra (cf. above). For the same reason, the ^{31}P-NMR spectrum of the ring compound, $(CH_2)_4PF_3$, shows a quartet at room temperature.

Almost without exception, the ^{31}P chemical shifts of fluorophosphoranes are positive, as high as +71.6 p.p.m., characteristic of phosphorus in coordination number 5. The very low value of δ_P for $(CH_2)_4PF_3$ is due to phosphorus being part of a strained ring system. The perfluoroalkyl compounds, $(R_F)_nPF_{5-n}$, are distinguished by particularly high positive values of δ_P. P–F coupling constants for pentacoordinate P–F compounds are usually below 1000 c.p.s.

6. Conclusions

In summarizing the ^{19}F- and ^{31}P-NMR data, the conclusion may be drawn that alkyl and aryl groups in R_3PF_2 and R_2PF_3 normally occupy equatorial positions of a trigonal bipyramid. In RPF_4, R is located either in the axial position of a square pyramid, or, more likely, in the equatorial position of a trigonal bipyramid in which fast positional exchange takes place. Similar exchange processes are known for other pentacoordinate molecules, *e.g.* $Fe(CO)_5$, AsF_5, SOF_4, *etc.* [60].

7. Stereochemistry of Fluoro-1,3,2,4-diazadiphosphetidines

The NMR data on this class of compounds available to date do not permit definite conclusions with regard to their stereochemistry. Especially complicated a situ-

Table 11. ^{31}P-NMR data for fluorophosphoranes.

Compound	δ_P [a] [p.p.m]	J_{P-F} [c.p.s.]	Ref.
CH_3PF_4	+29.9	965	[53, 62]
$ClCH_2PF_4$	+43.7	1008	[53, 62]
CCl_3PF_4	+66.9	1120	[62]
CF_3PF_4 [b]	+66.4	1103	[62]
$C_2H_5PF_4$	+30.2	995	[53, 62]
$C_6H_5PF_4$	+51.7	973	[53, 62]
$CH_3C_6H_4PF_4$	+49.7	950	[62]
$m\text{-}CF_3C_6H_4PF_4$	+52.9	965	[63]
$(C_2H_5)_2NPF_4$	+70.2	875	[40]
$(CH_3)_2PF_3$	− 8.0	975 (eq) 787 (ax)	[53, 62]
$(CF_3)_2PF_3$ [c]	+50.9	1260	[62]
$(C_2H_5)_2PF_3$	− 6.3	975 (eq) 827 (ax)	[53, 62]
$C_6H_5(CH_3)PF_3$	+13.4	955 (eq) 813 (ax)	[53, 62]
$(C_6H_5)_2PF_3$	+34.8	966 (eq) 837 (ax)	[53, 62]
$(CH_2)_4PF_3$ (25 °C)	−29.8	915	[53, 62]
$CH_3PF_3N(CH_3)_2$	+37.2	964 (eq) 803 (ax)	[63]
$C_2H_5PF_3N(C_2H_5)_2$	+35.5	976 (eq) 825 (ax)	[38]
$C_6H_5PF_3N(CH_3)_2$	+53.6	963 (eq) 821 (ax)	[38, 40]
$C_6H_5PF_3N(C_2H_5)_2$	+52.5	962 (eq) 823 (ax)	[38, 40]
$C_6H_5PF_3$-*N*-Pyrrolyl	+60.0	978 (eq) 860 (ax)	[40]
$[(C_2H_5)_2N]_2PF_3$	+63.7	890 (eq) 758 (ax)	[38]
$[F_3PNCH_3]_2$	+71.6	–	[42]
$(n\text{-}C_4H_9)_3PF_2$	+15.4	553	[53, 62]
$(CF_3)_3PF_2$ [d]	+59.8	988	[62]
$CCl_3PCl_2F_2$	+ 7.4	1106	[62]
$CCl_3PBr_2F_2$	+27.0	1109	[62]
$n\text{-}C_3F_7PCl_2F_2$ [e]	+14.2	1095	[62]
$[C_2H_5PF_2NCH_3]_2$	+45.6	911	[42]
$[ClCH_2PF_2NCH_3]_2$	+56.3	910	[42]
PF_5	+35.1	1010	[67]

[a] Relative to 85 % H_3PO_4 as external standard.

[b] J_{P-CF_3} = 172 c.p.s.

[c] J_{P-CF_3} = 174 c.p.s.

[d] J_{P-CF_3} = 167 c.p.s.

[e] $J_{P-CF(\alpha)}$ = 129 c.p.s.

ation is encountered in the case of the "parent" compound $[F_3PNCH_3]_2$, whose ^{19}F-NMR spectrum exhibits a mirror image (doublet) of four groups of resonances. The two strongest signals are separated by 880 c.p.s. [63].

The P–F coupling constant in compounds of the type $[RPF_2NCH_3]_2$ is also around 880–900 c.p.s., a 1–1 doublet being observed in the ^{19}F-, and a 1–2–1 triplet in the ^{31}P resonance. For the compound $[F_3PNC_6H_5]_2$, the ^{19}F-NMR spectrum has been reported to indicate two different fluorine atom environments in a 2:1 ratio. Accordingly, one of the P–N bonds has been suggested to be axial and the other equatorial; thus the P–N–P bond angle would be 90° [44].

Aside from molecular-weight data, an important argument in favour of a P–N–P–N ring structure may be drawn from the ^1H-NMR spectra of the compounds $[R_nPF_{3-n}NCH_3]_2$. In every instance, a 1–2–1 triplet is observed which is due to coupling between NCH_3 protons and the two adjacent ^{31}P nuclei. There is no evidence for interaction between ^1H and ^{19}F in the compounds investigated thus far.

According to the infrared spectra, delocalization of nonbonding electrons on the NCH_3 groups into the four-membered ring does not occur to a significant extent. C–H stretching frequencies characteristic of $\rangle\ddot{N}-CH_3$ groups, where the lone pair of electrons is retained, are known to disappear when the lone pair becomes involved in bonding. Distinct absorptions due to $\rangle\ddot{N}-CH_3$ are observed in all the compounds investigated. It may be noted that a zero dipole moment has been found for $[F_3PNCH_3]_2$ [42].

Table 12. ^{19}F- and ^1H-NMR and infrared data for fluoro-1,3,2,4-diazadiphosphetidines [42,63].

Compound	^{19}F-NMR		^1H-NMR		Infrared
	J_{P-F} [c.p.s.]	δ_F [p.p.m.] [a]	J_{P-H} [c.p.s.]	δ_H [p.p.m.] [b]	ν_{NCH_3} [cm^{-1}]
$[F_3PNCH_3]_2$	cf. text		14.5	−2.48	2840
$[C_6H_5PF_2NCH_3]_2$	885	−14.5	12.5	−2.46	2816
$[ClCH_2PF_2NCH_3]_2$	921	−14.6	12.7	−2.32	2810
$[C_2H_5PF_3NCH_3]_2$	903	−12.1	12.5	−2.47	2819

[a] Trifluoroacetic acid as external standard.

[b] Tetramethylsilane as external standard.

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Automation of X-Ray Structural Analysis [1]

Part I. Automation of the Measuring Process [2]

BY PROF. DR. W. HOPPE

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The present paper is the first of two reports describing the principles which can be applied to the construction of automatic counter-tube diffractometers for the X-ray analysis of crystals. These instruments can reduce the time required for the analysis of an organic crystal (measurement of a few thousand intensities) from several months (by the photographic method) to a few days.

Introduction

X-Ray structural analysis of a crystal of a medium-sized organic molecule (20 to 40 atoms, excluding hydrogen) involves the measurement of several thousand intensities. Since each of these intensities must be measured several times to minimize uncertainty, it is by no means unusual to carry out about 10 000 measurements in a single analysis. It is therefore not surprising that automatic instruments have now been developed to collect these data. This development has its counterparts in other fields of physics and physical chemistry. However, the automatic recording of infrared spectra or of electron and nuclear resonance signals supplies only the "raw material" from which the scientist then has to

[1] Extension of a lecture given during the Symposium on Modern Methods in the Analysis of Organic Compounds at the invitation of the Analytical Chemistry Division of the Gesellschaft Deutscher Chemiker and the Sectie voor Analytische Chemie van de Koninklijke Nederlandse Chemische Vereniging, Eindhoven (Holland), in May, 1964.

[2] X-Ray structural analysis has long been known as a method of determining the structure or (knowing only the overall formula) the constitution of organic molecules, and has been the subject of articles in this journal [cf. *W. Hoppe*, Angew. Chem. 69, 639 (1957); *G. Habermehl*, ibid. 75, 78 (1963); *M. F. Perutz*, ibid. 75, 589 (1963); *J. C. Kendrew*, ibid. 75, 595 (1963)]. Advances have recently been made both in experimental methods and in evaluation with the aid of large electronic computers, as a result of which it may become possible to solve at least some of the structural problems "automatically".

extract the physical or chemical information required. In X-ray structural analysis, on the other hand, an attempt is being made for the first time to entrust the calculation of the structure of the unit cell to machines, too. Since the beginning of crystal structure analysis, many thousands of structures have been elucidated by an extraordinary display of mental brilliance and intuition, so that it might justifiably be asked whether it is in fact possible to introduce automation into investigations of this type. This point will be examined in greater detail in the second paper of the present series. The first part will deal with the simpler question of how to design automatic devices for the measurement of data required for the evaluation of a structure.

Survey of Automatic Devices

Various classifications are possible (Table 1).

Table 1. Automatic single-crystal diffractometers.

Number of adjustable angular coordinates	Input control	Checking of results
One-circle instruments (powder diffractometer)	Built-in analog computer	Inspection of data by the experimenter
Two-circle instruments (Weissenberg type) (Linear diffractometer)	Punched paper tape or similar program control	Partial automatic checking in the computer (reference reflections and equivalent reflections)
Three- and four-circle instruments (Eulerian-cradle diffractometer)	Digital computer connected to instrument	Self-checking diffractometer

According to *Bragg*, the diffraction of X-rays can be formally regarded as selective reflection at crystal lattice planes running through the crystal in a strictly regular pattern and oriented in various ways with respect to the axes. From the intensities of the selective reflections at the glancing angles of incidence, it is possible to determine a quantity known to the crystallographer as the structure amplitude (the absolute value of the structure factor). The more strongly the primary beam is "reflected" at the lattice plane, the greater is the structure amplitude. In order to measure this quantity, therefore, it is necessary to direct a finely focussed beam of X-rays (the primary beam) onto the lattice plane at the glancing angle of incidence, and measure the intensity of the reflected beam. This measurement may be carried out either directly by counting the X-ray quanta, or indirectly by means of a photograph. The latter method was normally used in non-automated structural analysis. In the automatic measuring devices, however, direct electrical measurement with scintillation counters or proportional counters is used for the sake of accuracy and speed.

A crystallographic diffractometer must obviously contain angle adjusters to bring the lattice plane of the crystal into the correct orientation with respect to the primary beam for selective reflection, and to align the radiation detector so that it can measure the intensity of the reflected beam. In an automatic diffractometer, this angle adjustment must be automatic, and the same holds for the measuring process.

In principle, therefore, an automatic measuring instrument consists of (1) the diffractometer proper, *i.e.* the instrument in which the primary beam, the lattice plane, and the counter tube are brought into the correct geometrical position with respect to one another, (2) the electronic measuring equipment, *i.e.* a system of supply units, an amplifier, a discriminator, an electric clock, and a counter which permits the determination of the number of X-ray quanta in the scattered beam at preset times, and (3) the electronic control equipment, responsible for the correct setting of the angles in the diffractometer and for the correct running of the measurement program.

A universal feature is that the measured data are given out on an information carrier such as punched cards or paper tape. This arrangement is essential in view of the quantity of information to be processed. It would be a waste of time if these data were simply printed out, since the punched-code output can be fed directly into a computer. A greater variety is found in the input control electronics. The need for a control which must be adjusted to suit the crystal under investigation can be avoided by allowing the crystal and the counter tube to assume all possible angle settings and carrying out a measurement in each position. The results will then necessarily include the reflections from lattice planes. This principle of searching for reflections makes the measurements very time-consuming, since a large number of unwanted settings and measurements go with those yielding useful results. Therefore, this principle has only been utilized in a variant for single crystals. On the other hand, controls which pick out the reflections selectively are quite common.

In these systems the angles for all reflections are calculated from the lattice constants by a computer which works together with the automatic measuring instrument. The angle adjustment of the instrument is set to each of these angles in turn, and the measurements are carried out. The calculations may be done by an electrical or mechanical analog computer, or by a digital computer connected to the automat. Finally, it is also possible to calculate the angles for the individual reflections in advance, using a digital computer, and to feed the information to the automatic device on paper tape or on punched cards, which are then referred to in the course of the measurements. This is the most usual method. It is very accurate, since the digital computer can calculate the angles as accurately as is desired. It is however also very economical since the automatic device does not require its own computer. Built-in analog computers are

also used, but apart from the higher outlay, these frequently lead to limitations in the measurements as a result of constructional factors. The most elegant method, although admittedly the most expensive one, is to connect a digital computer to the automatic measuring instrument.

When an automatic measuring instrument has completed its work, it supplies its results in the form of *e.g.* an extremely long paper tape. It may now be asked how it can be verified that the values are not subject to errors in measurement. The simplest method is to check the results against those obtained by occasional manual measurements, although this is a very laborious process. Some indication of the stability of the apparatus can also be gained by making repeated measurements of selected reflections; if these always give the same value, it may at least be concluded that the intensity of the primary beam has not changed, and that the crystal has not moved out of adjustment. Another criterion is provided by the measurement of symmetrically equivalent reflections. The method which is most in keeping with the idea of automation, however, is to provide an automatic check for errors. This brings us to the self-checking devices. An instrument of this type is programmed to record both actual and check measurements. The check data are then evaluated by a computer, so that the investigator can ascertain whether the results on his output tape are correct.

From the point of view of their function, the automatic devices can be logically classified according to the number of angular coordinates (circles) which are automatically adjusted. As will be shown later, adjustment of at least three circles is essential if the reflections are to be measured for a three-dimensional analysis. A fourth circle is frequently also provided, the essential purpose of which is to permit (in combination with the other angular adjustments) rotation about the normals to the lattice planes. It is not absolutely necessary, however, that all angle adjustments should be automatic. If the geometry of the instrument and the arrangement of the measurements are such that one or two angles remain constant for a group of measurements, these angles can be adjusted manually.

Single-Circle Devices

The best known single-circle device is the powder diffractometer, which has been used in many forms over a long period (Fig. 1). The coordinate adjusted automatically is the glancing angle of incidence ϑ. The counter tube is coupled to the crystal through a 2:1 gear, so that the beam reflected from the powder always enters the counter tube. A necessary condition for reflection is that the lattice planes lie in the plane of the powder layer, but since all lattice planes are present in all orientations in a powder, this condition is satisfied for every lattice plane.

The corresponding single-crystal instrument is the Bragg spectrometer. The orientation of the lattice plane is indicated in Fig. 1 by the line N. In contrast to the powder diffractometer, this instrument can record only the various-order reflections of the correctly oriented lattice plane, and if it is desired to measure a number of different lattice planes, the crystal must be rotated by hand through an angle φ. Since only a few reflections, namely the individual orders of each lattice plane, can be measured after each adjustment, an apparatus of this type is practically useless as an automatic device and is only mentioned here as a limiting case for the sake of completeness.

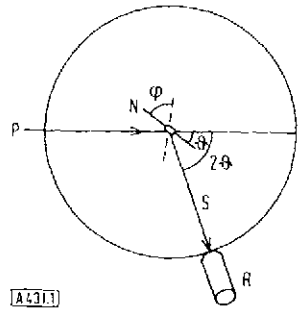

Fig. 1. Powder diffractometer. The glancing angle of incidence ϑ between the lattice plane N and the primary beam P, and the scattering angle ϑ of the scattered beam S, are adjusted together (mechanically coupled in a gear ratio of 1:2). For a single crystal (Bragg spectrometer) only the individual orders of a single lattice plane can be measured. To measure another lattice plane (*e.g.* that indicated by the broken line) it is necessary to turn the crystal through an angle φ. — R = Counter tube.

Two-Circle Devices

The situation becomes different when the adjustment of the angle φ is also carried out automatically. We then have the simplest form of a two-circle device, in which the coordinates are ϑ (and hence 2ϑ) and φ. A device of this type permits the measurement of the reflections of only one zone, *i.e.* the zone which lies parallel to the axis of rotation of the diffractometer. It is not difficult, however, to equip such an instrument for three-dimensional measurement (Fig. 2). As is known from the principle of

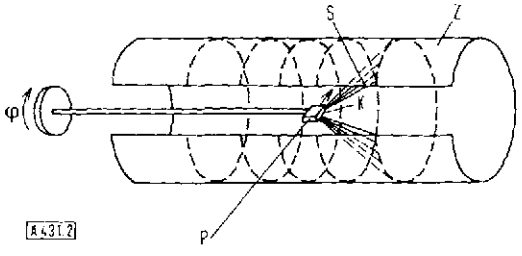

Fig. 2. Principle of the rotating-crystal camera. If a crystal K is oriented along a zone axis, the scattered beams S form cones. The intersections of these with the encircling cylindrical film Z are shown as broken lines in the diagram. — P = Primary beam.

the rotating-crystal camera, if a crystal is rotated about a zone axis, the scattered beams form concentric cones, which contain the reflections with the indices (hk0), (hk1), (hk2), *etc.* The reflections of the zone with the index (hk0) lie on a cone with an apical angle of 180°, *i.e.* on a circular disk. We have already considered the measurement of these reflections in the course of the discussion of the generalized Bragg spectrometer with the aid of Figure 1. It is easy to see that the reflections of the higher layer lines can be measured if the counter tube is directed along the directrices of the cone. Thus the measurement with a two-coordinate automatic device of

this type is carried out in several steps. The axis of the counter tube is first oriented in the equator and all (hk0) reflections are measured automatically. The counter tube is then inclined into the next cone, and all the (hk1) reflections are measured automatically, and so on, until all obtainable reflection cones have been accounted for.

It is recommended, however, that not only the axis of the counter tube, but also the primary beam should be inclined with respect to the axis of rotation of the diffractometer (Fig. 3). Both are inclined through the same angle, and the

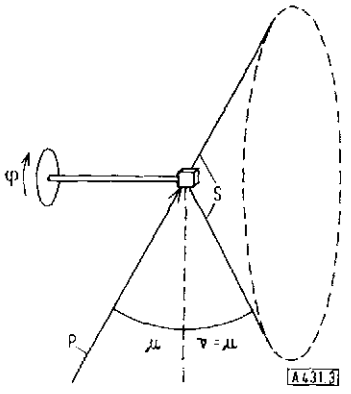

Fig. 3. Equi-inclination adjustment. The angle of incidence μ and the angle of the scatter cone ν are equal.

corresponding layer-line adjustment is consequently also named the equi-inclination adjustment. This procedure has been in use for some time in making photographic diagrams with the Weissenberg goniometer. It has the advantage that it permits the measurement of more layer lines than if the primary beam were kept perpendicular to the angle of rotation. Moreover, all reflections with an equator-like geometry are measured, and all reflections which can possibly be measured with radiation of the wavelength used can be collected on a single layer plane (elimination of the "blind spot".)

Two-circle devices of this type are relatively simple mechanically. Only two high-precision coaxial bearings are required for the adjustment of the angles φ and χ [χ corresponds to the φ of (hk0)]. The electronics of the apparatus are also relatively simple, since automatic adjustment is necessary for only two angular coordinates. It is, however, unfortunate that the diffractometer must be reset by hand after a relatively short period of operation, so that operation during the night, for example, is difficult. It must be remembered that even an automatic diffractometer requires several days for the three-dimensional measurement of a complicated single crystal. The situation is not quite the same as in the case of computers, which can reduce the time required for calculation from a matter of years to a few seconds. The main difference is that the measuring time in the case of the diffractometer is governed by the intensity of the source of X-rays and the size of the crystal, and so cannot be made as short as we wish [3]. It can be reckoned that an automatic measuring instrument is about three times as fast as a well-trained operator. Taking into account the 24-hour day for the device as opposed to the 8-hour day for the human operator, we find that the time required for measurements is shortened by a factor of about 10.

The device described above does not however permit complete three-dimensional measurement of the crystal with a single adjustment, since very high layer lines cannot be measured owing to spatial factors. Finally, a diffractometer based on the rotating-crystal principle requires accurate orientation of the crystal with respect to one of its axes. It must therefore be carefully adjusted before the measurement is carried out. We shall subsequently see that the crystal can be measured in any orientation with the aid of three- and four-circle devices. It is then possible to leave the adjustment, and even the determination of the unit cell and the space group, to the automatic device.

The angles φ and χ in the two-circle diffractometer can be set automatically in various ways. The simplest method is to scan the entire φ,χ field and record all reflections encountered. This is the principle of one of the earliest two-circle devices, *i.e. Bond*'s "hunting goniometer" [4]. ϑ and φ are coupled in such a way that a rotation of the crystal through $\varphi = 360°$ is associated with a rotation of the counter tube through $\chi = 2°$. The diffractometer scans rapidly until the flash of a reflection is recorded. The control electronics then ensure a slow, careful measurement of the reflection. As we have already pointed out, however, this simple principle is very time-consuming, since the diffractometer must pass through all possible settings of φ and χ in succession. Consequently, wide use is now made in two-circle devices of the system used in three-circle instruments, namely the direct automatic setting of the angle according to instructions from a paper tape or punched card, *i.e.* indirect program control as used in digital computers.

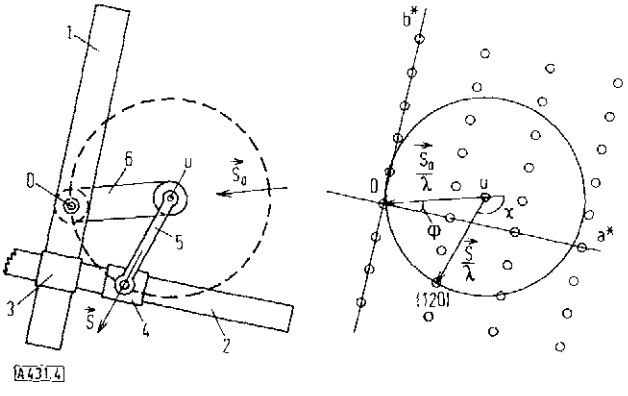

Fig. 4. Principle of the linear diffractometer. The right-hand half of the figure shows the geometrical relationships, and the left-hand half their mechanical counterparts. The reflection condition for the (120) reflection is satisfied in the position shown.
φ - Angle of rotation of the crystal.
χ - Complementary angle of the scattered beam.
The numbers are explained in the text.

An interesting method of setting is used in a variant of the two-circle device, the linear diffractometer [5,6] (Fig. 4). This method is based on a graphical construction of the scatter directions in a layer line of a crystal, which was first proposed some time ago by *P. P. Ewald* (Ewald's sphere). The principle of this construction is shown on the right of Figure 4. The diffraction reflec-

[3] Further reduction of the measuring time is possible only if the geometry of the diffractometer is such that several reflections can be measured simultaneously. Owing to the danger of "umweganregung", such a procedure is not really permissible. However such "multichannel diffractometers" are being discussed for crystals with very large numbers of reflections (large proteins, virus crystals).

[4] *W. L. Bond*, Acta crystallogr. *8*, 741 (1955).

[5] *U. W. Arndt* and *D. C. Phillips*, Acta crystallogr. *14*, 807 (1961).

[6] *J. Ladell, N. Spielberg*, and *K. Lowitzsch*, Acta crystallogr. *13*, 205 (1960).

otins corresponding to the individual lattice planes can be arranged in a manner which cannot be discussed in detail in the present paper, to form what is known as a reciprocal lattice [7]. The lattice constants of the reciprocal lattice bear a very simple relationship to the parameters of the crystal in question. The reflections of a layer line lie on a plane of the reciprocal lattice. A reciprocal lattice plane can be easily drawn if we know the unit cell of the crystal and the axis of rotation [8]. The small circles in Fig. 4 represent the reciprocal lattice points of such a plane. The arrow marked $\vec{s}_o/\lambda$ indicates the direction of the primary beam. To carry out *Ewald*'s construction, we draw a circle with a radius $1/\lambda$. We imagine the representation of the reciprocal lattice plane to be pivoted at the other end of the primary beam vector $\vec{s}_o/\lambda$, *i.e.* at a point on the circumference of the circle. Scattering is then always encountered whenever one of the reciprocal lattice points touches the circumference of the circle during the rotation of the reciprocal lattice plane about 0. The required angle of rotation φ of the lattice plane is the angle through which the crystal must be rotated to bring it into the reflecting position. The direction of the scattered beam is given hy the line joining the center of the circle to the reciprocal lattice point lying on the circumference. The corresponding vector is marked $\vec{s}/\lambda$ in Fig. 4.

This geometrical construction can be mechanized in a very obvious manner. The two principal coordinates of the reciprocal lattice plane are represented by two rails. Rail 1 can pivot about the fixed point 0, while rail 2 is mounted on rail 1 by means of a slide 3, so that it can be moved. A slide 4 on this second rail carries a lever 5 of length $1/\lambda$, which is connected *via* a ball-bearing to the axis of rotation of the crystal. The rotation of the crystal axis is synchronized with that of the first rail. The rotation is transmitted through a system 6 of gears, steel band transmissions, *etc.* The slide 3 is now moved together with the second rail until it coincides with a reciprocal lattice line. If the slide 4 is slowly moved from left to right along the rail 2, this parallelogram-lever combination turns the crystal so as to present the successive reflections of the lattice planes arranged on this lattice line. Thus a comparison of the left-hand and right-hand halves of the photograph shows that this movement satisfies *Ewald*'s condition for these lattice planes in turn. Since the lever 5 always points in the direction of the scattered beam, it is only necessary to fix a counter tube to the lever to ensure that the recording meter is also held in the correct orientation for the measurement. The movement of the slide 3 with rail 2 (setting to the lattice line) and the movement of slide 4 with the lever 5 (scanning of the lattice points) can both be carried out by servomotors. The scan of a reciprocal lattice line in the reciprocal lattice of a protein crystal is shown in Figure 5. It can be seen that, since the distances between the reciprocal lattice points on the lattice line are equal, the individual reflections are also equally spaced.

[7] Cf. *e.g. P. P. Ewald*, Z. Kristallogr., Mineralog. Petrogr., Abt. A *90*, 493 (1935).

[8] The dimensions of the reciprocal lattice constant and the reciprocal wavelength $1/\lambda$ are those of reciprocal length. We must therefore define a conversion constant (*e.g.* 1 $Å^{-1}$ = 20 cm) for the diagram.

The arrangement described above is basically a mechanical analog computer for calculating the positions of reflections from the unit cells of the crystal. Linear diffractometers have been built with the aim of considerably simplifying the control electronics. This end is also achieved if the instrument records the lattice lines as it scans, as in a powder diffractometer, although automation of the shift from one lattice line to another requires a certain outlay.

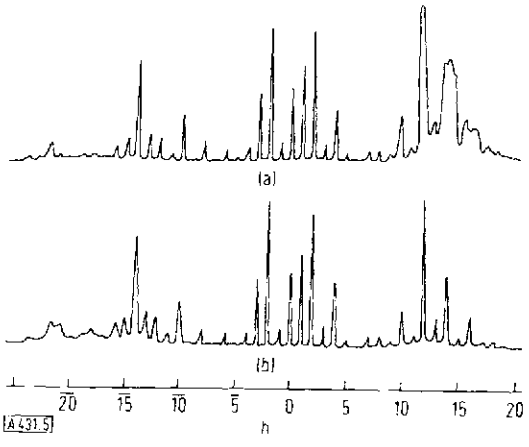

Fig. 5. Scanning a reciprocal lattice line (myoglobin) in the Arndt linear diffractometer (cf. [5]).

Even in these cases, however, further development has led to the digital punching of reflection and background intensities with scanning over narrow angular fields. The simplification in the electronics simply consists in the fact that the setting of the angles in accordance with instructions from a punched paper tape is replaced by the setting of lattice constants by the operator. This is offset to some extent by the complication introduced by the mechanical analog computer, and by the fact that the instrument is restricted to the rigid program of measurement in successive lattice lines. Furthermore, in some instruments (cf. [5]) the range of reflections which can be recorded is considerably reduced owing to the analog computer.

Three- and Four-Circle Devices

In principle, any two-circle device can be converted into a three-circle one by introducing automatic control of the inclination of the primary beam and counter tube with respect to the axis of rotation of the diffractometer. This principle is used in a French instrument [9]. Generally, however, use is made of a geometry derived from the powder diffractometer and first applied by *Furnas* and *Harker* in a hand-operated diffractometer [10]. In the powder diffractometer (cf. Fig. 1), lattice planes are measured which are oriented parallel to the plane of the powder layer. If it is desired to measure a crystal using a geometry similar to that of the powder diffractometer, all that is required is to rotate each of the lattice planes of the crystal into this plane in turn. It follows from geometrical considerations that this can be done by turning the crystal in such a manner as to change two angular coordinates. The principle of the instrument is shown in Figure 6. The two lower circles characterize the ϑ- and 2ϑ-circles of the powder diffractometer. The crystal rotates in a sort of gimbals consisting of the vertical χ circle and

[9] *J. Clastre*, Acta crystallogr. *13*, 986 (1960).

[10] *T. C. Furnas* and *D. Harker*, Rev. sci. Instr. *26*, 446 (1955).

the φ circle, which is perpendicular to the latter. This device is known in crystallography as a Eulerian cradle. The three-circle device requires three servomotors, two of which control φ and χ, and so bring the lattice plane of the crystal into the axis of rotation of the powder diffractometer, while the third motor operates the ϑ–2ϑ shaft of the powder diffractometer (symmetric setting).

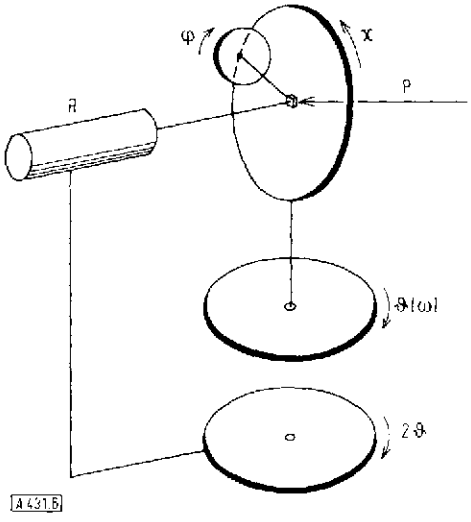

Fig. 6. Principle of the Eulerian cradle diffractometer. A "gimbals" arrangement with the angle circles φ and χ brings the crystal into various spatial orientations. The crystal can also be rotated with respect to the primary beam P in the equatorial plane of the instrument, using the ϑ (ω) circle (equatorial circle). The coaxial ϑ circle, which carries the counter tube R, is also situated in the equatorial plane. In measurements in the symmetrical setting (three-circle operation), the normals to the lattice planes are turned into the equatorial plane and into the plane of the χ circle by means of the φ and χ circles. The lattice plane thus has the same orientation as the reflecting lattice planes in a powder diffractometer. As in the powder diffractometer, therefore, the ϑ and 2ϑ circles can be coupled in a gear ratio of 1:2 (cf. Fig. 1). In the unsymmetrical setting (four-circle operation), the lattice plane is turned into the equatorial plane, but not into the χ plane. The angle (ω) of the ϑ circle is therefore different from that of the scatter angle ϑ.

For less fundamental reasons, it has become usual to design the ϑ and 2ϑ circles so that they can be operated independently, or even to provide a fourth circle (the ω circle), concentric with the coupled ϑ–2ϑ circles (four-circle instrument).

In instruments with Eulerian cradles, in which the mechanics can be simplified if the χ circle is in the form of a closed, eccentrically mounted ring [11, 12], the uncoupling of ω and ϑ is essential to avoid serious restriction, owing to shadowing, of the number of reflections which can be measured. Where the χ circle is in the form of an open segment, the independent adjustment would be superfluous, since shadowing cannot occur in the coupled position. However, it may be an advantage in many problems [Reminger effect ("Umweganregung"), absorption], since the four-circle adjustment corresponds to an additional rotation about the normal to the lattice plane. The setting of three- and four-circle devices is done by program control. With the aid of suitable programs, it is possible to carry out any measurement of crystal reflections or of the background scatter. The automatic instruments can be directly coupled with digital computers, and this coupling appears logical in view of the extreme flexibility of the Eulerian-cradle diffractometer.

As already pointed out, it is possible, for example, to place an unoriented crystal in the diffractometer. All the crystal reflections occurring in a small region of the reciprocal space are recorded. The computer which is attached to the instrument determines the unit cell and the orientation of the crystal from the angular coordinates of the recorded reflections. It also works out a program which allows determination of the reflections of the principal axes up to high angles of diffraction. This measurement provides the basis for the accurate calculation of lattice constants. With the aid of these data, the computer sets up a program permitting the measurement of reflections which could exhibit extinctions. The presence or absence of such reflections provides the computer with the information required for the determination of the possible space groups. The computer finally produces a punched paper tape which contains the angle settings of all reflections for the unoriented crystal. The computer can now be uncoupled from the instrument. In the normal "off-line operation", the automatic device determines the intensities of all X-ray reflections of the crystal in accordance with the instructions on the paper tape. However, the scheme which has just been described has never yet been put into practice, although there is no reason why it should not work. Owing to the high cost of a special computer, however, it will still be preferable in future to use crystals of known geometry and in known orientations, for which the measuring programs can be worked out in advance on an external computer.

The mechanical construction of three- and four-circle devices is more difficult than that of the two-circle instruments, since up to four automatically adjustable circles are required, all of which must intersect accurately at one point. High standards of precision and stability of the mechanics are required in automatic instruments, which must operate continuously, day and night. All play in the motor parts must be avoided by special construction of the bearings and by spring-loading of the worm drives. It is advisable to install the diffractometer in a thermostatically controlled room to eliminate the effect of temperature on the lattice constants, as well as the influence of temperature gradients on the mechanism. Two- to four-circle devices have been developed in various laboratories (cf. *e.g.* [13]), and instruments of this type have recently been even offered on the market.

The construction of automatic three- and four-circle devices was started a few years ago in our Institute. Our first instrument [14, 15] incorporates a complete, centrally arranged χ circle and is controlled by a tube-relay circuit. The number of servomotors is reduced to two by a mechanical artifice: the φ ajustment is carried out *via* a drive of the (2:1 coupled) ϑ–2ϑ circles. To make this adjustment, the φ circle is connected to the ϑ circle by a magnetic coupling which can be switched on by the program. The angles are adjusted by one of the most suitable methods for this purpose, *i.e.* the "impulse counting method". A perforated disk coupled to the drive motor transmits light impulses every hundredth of a degree, and these impulses are counted in an electric counter. Thus, for example, an angle of 14.56° corresponds to 1456 impulses. When this number is reached, the counter emits a "stop" impulse, which switches off the drive motor.

[11] *U. W. Arndt* and *B. T. M. Willis*, Rev. sci. Instr. *34*, 224 (1963).

[12] *W. A. Wooster* and *A. M. Wooster*, J. sci. Instruments *39*, 103 (1962).

[13] *S. C. Abrahams*, Chem. Engng. News *41*, no. 22, 108 (1963).

[14] *W. Hoppe* and *E. Berkl*, Acta crystallogr. *13*, 989 (1960).

[15] *W. Hoppe* and *E. Berkl*, Z. angew. Physik *14*, 434 (1962).

On the basis of the experience gained with this instrument, a new, greatly improved mechanical diffractometer was designed (cf. Fig. 7). The electronics were subsequently developed further and transferred to transistorized printed circuits. Finally, an automatic checking

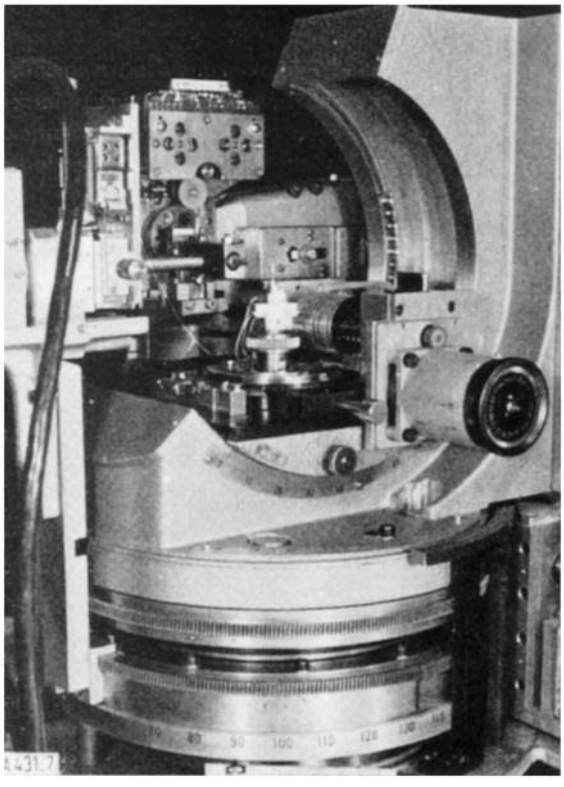

Fig. 7. The new Munich single-crystal diffractometer.

device was incorporated, which kept a constant check on the recorded data for errors in adjustment or in the lattice constants (cf. also Table 1). The device is described in detail below to show the points which require particular attention in the design and use of such instruments.

We have already referred to the importance of mechanical stability and precision. Accuracy can be maintained only if there is no possibility of plastic or elastic deformations. Figure 8 shows how this point was taken into account in the design of the ϑ and 2ϑ bearings. The diffractometer is supported on a cylinder 1 with an accurately ground surface, on which is mounted a large-diameter roller-thrust bearing 2 (needle roller bearing). The ϑ circle takes the form of a flat disk 3 which runs on this bearing, centered by a radial bush bearing. The play in the thrust bearing is very slight, since the rollers and bearing surfaces can be accurately ground. On the other hand, the weight of the ϑ disk superstructure (Eulerian cradle and accessories) is transferred directly to the cylindrical support 1 by the wide-based thrust bearing, and an additional flexible roller-relief bearing (not shown in the illustration) ensures that the forces are distributed symmetrically with respect to the ϑ axis. The 2ϑ bearing (which is subject to less stringent requirements, since it carries no other circle which must be centered) is a collar bearing 4. The vertical χ circle (cf. Fig. 6) was no longer designed as a complete circle, again for the sake of stability and accuracy. An open circle 5 can be made very rigid without cutting out reflections. This also allows symmetrical measurement (cf. Fig. 6) of all reflections, which not only presents the advantage of uniform organization of the preliminary calculations, but also leads to a reduction in the absorption for reflections of needle-shaped crystals set parallel to the φ axis. The ϑ circle and the 2ϑ circle are magnetically coupled in a gear ratio of 1:2. Separate automatic adjustment of the ϑ disk (angle ω) is possible if the two circles are uncoupled (four-circle operation, cf. Fig. 6); the uncoupling can be controlled by the program. The φ disk 7, which is also adjusted by means of a worm gear, is fixed to the slide 6 of the χ circle. The goniometer head 8 and the crystal 9 are mounted on the φ disk. Three drive motors are provided [φ, χ, ϑ–2ϑ (ω)]. To obtain short adjustment times without endangering the worm drives of the individual circles, the motors are run simultaneously. The angles are electrically checked and small errors are automatically corrected, if necessary (accuracy of angle setting is 0.01°, and hence 0.02° in the case of 2ϑ).

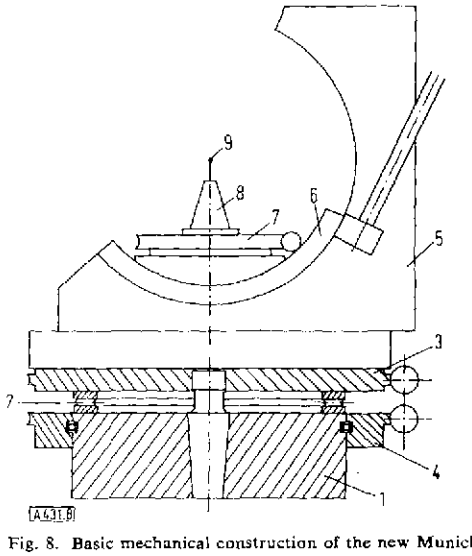

Fig. 8. Basic mechanical construction of the new Munich single-crystal diffractometer.
The numbers are explained in the text.

An important factor in the use of a "measuring robot" is the logic of the measuring program. We differentiate here between "internal measuring programs", which are built into the instrument, and "external measuring programs" fed in on paper tapes. After characteristic data have been supplied to the instrument by paper tapes, the internal program carries out the automatic measurement of a reflection. Internal programs can be avoided by breaking down each measurement into its elementary steps, and making each step an instruction in the external program. This procedure seems at first sight to be very flexible. However, it can lead to disadvantages if used to excess: the new program becomes long and involved, owing to the constant repetition of operations. Moreover, internal programs can often make decisions which are difficult to introduce with an external program, since they are undetermined before the measurement is carried out. A typical example is the measuring time for a reflection. The intensities of the X-ray reflections vary over a wide range. It is therefore desirable to match the measuring time (which governs the error of the measurement)

to the expected intensity. A suitable measuring time can be incorporated into an external program only if the intensities are already known. Since, however, the number of reflections is very large, even a very rough estimation (*e.g.* from photographs) would be extremely laborious and time-consuming. An internal program, on the other hand, can be so designed that an approximate intensity measurement is first carried out; the internal program then fixes the measuring time in accordance with the desired statistical accuracy, and taking into account a maximum measuring time which can be adjusted externally. Our instruments were the first to use internal programs for fixing the measuring times.

An internal program will always include a fixed sequence of "measuring steps". *It is therefore essential to measure not* only the reflections, but also the adjacent background (cf. Fig. 9), which results from non-monochromatic radiation

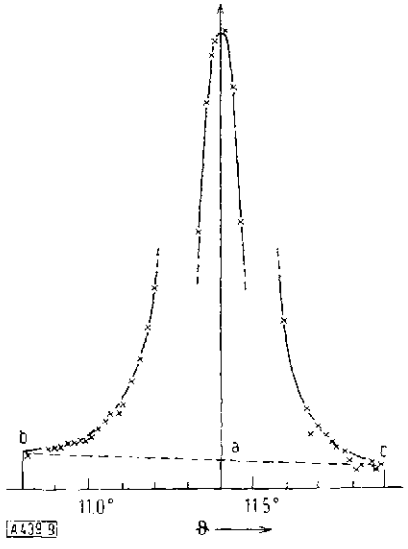

Fig. 9. Differential reflection curve of basic beryllium acetate, (004) plane, $\vartheta = 11.4°$.

ϑ–2ϑ coupled; step width 0.02°; a = maximum of the reflection curve. The ordinates correspond to numbers of impulses, measured over a constant time Δt, integrated over the angle increment of 0.02°. These ordinates are punched out in digital code.

"Five-point measurement":

1. Integral over the reflection curve from a to b.
2. Background measurement at the point on the reflection curve.
3. Integral of the reflection curve from b to c.
4. Background measurement at the point c.
5. Integral of the reflection curve from c to a.

The ratio of measurements 1 and 5 gives a measure of the centering of the reflection curve.

and from incoherent radiation (Compton scattering, thermal scattering). Since the background is not the same on both sides of a reflection, at least two background measurements are required. The radiation can be made more monochromatic by discrimination of the impulses according to magnitude and by filters and Ross filters. Strictly monochromatic radiation can be obtained by the use of crystal monochromators in conjunction with a discriminator (to cut out the $\lambda/2$ reflection). Unfortunately, however, flat monochromators form an image of the most non-homogeneous focus of the tubes in the cross-section of the beam; they therefore produce a non-uniform primary-ray plateau at the position of the crystal. This may give rise to systematic errors in the intensity measurements. The scanning method using a filtered primary beam or with a curved monochromator crystal makes no demands on uniformity of the focus. A primary beam with a slight angular divergence is masked off. During the measurement, the crystal is slowly rotated through its reflection field. The internal or external program must therefore also control the angle through which the crystal is to turn during the measurement (cf. Fig. 6).

This brief excursion into a few physical problems of the measurement shows that the internal organization of an automatic measuring device must be given careful consideration if it is to take into account the wide range of possible measuring procedures. In our device, an external program which could be broken down into elementary steps was used in conjugation with a number of internal programs which could be combined with one another. This arrangement permits the use of all the procedures described. It would take too long to describe the structure of the program system in detail; we shall simply explain the automatic check on errors in measurement, in view of its general interest.

A measurement is free from error when:

(1) the crystal is suitable for measurement and the measuring procedure is used correctly;

(2) the intensity of the primary beam is constant and the electronic equipment is stable;

(3a) the reflection is situated in the center of the counter-tube aperture;

(3b) in the case of the scanning method, the maximum of the reflection curve falls in the correct position between the two background measurements.

The experimenter himself must ensure that point (1) is satisfied (by carefully taking photographs before the measurement in the diffractometer, by the choice of apertures to suit the size of the crystal, *etc.*). Point (2) requires a stable source of X-rays and stable electronic equipment; long-term fluctuations, which are troublesome and particularly difficult to eliminate, can be checked by regularly repeated measurements of reference reflections, and prevented from interfering by interpolation. Point (3a) is checked in our diffractometer by measuring each reflection three times; in the second measurement the right-hand half of the counter-tube aperture is masked, and in the third measurement the lower half is masked, by screens which are controlled by the program. If the reflection is centered in the aperture of the counter tube, the difference between the first and second readings must be equal to the second reading, and the difference between the first and third readings equal to the third reading ("automatic cross-wires"). The computer which carries out the evaluation can assess the extent of decentering from the deviations. Since this check triples the measuring time, it is controlled by the external program in such a way that it is carried out on only a certain proportion of the reflections.

Point (3b) can be checked from the shape of the reflection curve. In the differential measuring program of our instrument, the ordinates of the reflection curves at arbitrary angular increments are recorded in digital code. The resulting reflection profile is fed in punched paper tapes to the computer, which can then calculate the position of the maximum. This check can be carried out on shorter punched paper tapes using our "five-point method". In addition to three values for the intensity of the reflection and the background on the left and right of the reflection, the reflection intensities to the left and right of

the glancing angle of incidence are also measured (cf. Fig. 9) and punched out. The computer can determine any displacement of the reflection curve from the ratio of these two values. This method involves no additional measuring time, since the three measurements of the reflections for the evaluation can be added together; the sum determines the statistical error for the overall measurement.

Concluding Remarks

It was mentioned in the Introduction that the experimental automation which is now being introduced into the analysis of crystal structures has its parallel in the automation of other physicochemical measurements (infrared analysis, gas chromatography, analysis of amino acids). The detailed discussion has however shown a number of differences. One of these is the digital coding of the problem, and another is the relatively complex logical structure of the program. We are therefore inclined to look for parallels in the complicated control and regulation problems of an automated factory, rather than in the known measuring procedures of physics and chemistry. This relationship becomes even more pronounced when we consider the automatic X-ray diffractometers controlled by computers; we may regard this as being possibly the first "process-calculation procedure" in measuring technology. This development has been necessitated by the large volume of information to be measured, and by the dependence of the results on several coordinates.

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A Code for the Classification of the Ultraviolet Spectra of Organic Compounds

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The ultraviolet spectra of all organic compounds can be classified according to the chemical constitution with the aid of a simple code based on a ten-digit decimal system, each digit indicating the "spectroscopic weight" of the encoded information. The code discussed here will shortly be used in the Atlas of Ultraviolet Spectra which appears in the Documentation of Molecular Spectroscopy Series.

Owing to the large and ever increasing number of published ultraviolet absorption spectra, there is a need for their systematic classification. The chemist's interest in this respect is focussed on the connection between chemical constitution and ultraviolet absorption spectrum.

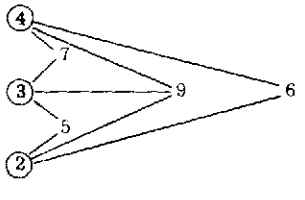
Classification according to the molecular formula would be futile, because the ultraviolet spectra are mainly determined by the system of double bonds (π-electrons) and non-bonding electrons (n-electrons) present in the molecule. This may be illustrated by the fact that all compounds of a homologous series can exhibit identical spectra. It is therefore better to devise a key, using as the principle of classification the structural elements containing π- and n-electrons and taking into account their positions with respect to each other. Rapid classification and retrieval of the spectra, as well as maintenance of the system in the event of any future expansion of the material are desirable.

It is hoped that these requirements have been met by the following "one-dimensional" system, which can be used both for the classification of spectra and for setting up a peephole or edge-punched card index [1].

Explanation of the Code

Each compound is described by a ten-digit code number characterizing – from left to right – 10 groups of chromophoric and structural features (criteria) arranged in decreasing order of "spectroscopic weight".

Each of these 10 sets of criteria comprises three subcriteria, which – again in decreasing order of spectroscopic weight – define more closely each criterion by code numbers 4, 3, and 2, as shown in Table 1. If, in the case



[1] The authors of the Varian NMR Spectra Catalog (*N. S. Bhacca, L. F. Johnson*, and *J. N. Shoolery*: NMR Spectra Catalog, Varian Assoc., Palo Alto, California, 1962) have apparently been governed by similar considerations. They devised an index for functional groups, in which the vicinity of a proton is characterized by a code word consisting of numbers and upper-case and lower-case letters.

of more complicated compounds, these subcriteria occur in combinations, then each combination is characterized by the sum of the code numbers.

Thus the code number 6 denotes the presence of subcriteria 4 and 2, and the code number 9 the simultaneous occurrence of subcriteria 2, 3, and 4. The multiplicity of identical criteria is indicated by a separate code number, and it is therefore possible to characterize both the subcriteria and their combinations by a single number, so that only one position in the total code number is needed for one set of subcriteria. The absence of a criterion is denoted by "0". Numbers 8 and 1 are not used here. It is only in position (3) that "8" is employed for free radicals; this number must not however be combined with the code numbers of other subcriteria in the same group.

The ten code digits are arranged, according to the spectroscopic properties encoded by them, in groups of two or three, in such a way that each of the two principal groups contains five decimal positions, for example

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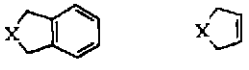
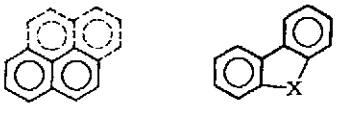
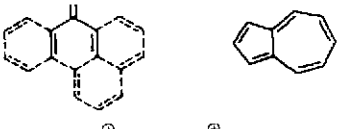
The subcriteria of the first decimal position (1) subdivide the unsaturated compounds containing ultraviolet-active chromophores into heterocyclic and homocyclic systems as well as unsaturated chains, and emphasize the aromatic compounds among the homocyclic systems (see Table 1).

Table 1. The coding of the spectroscopically active structural elements of organic compounds.

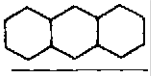
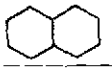
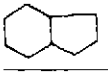
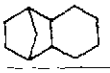
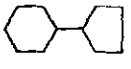
Decimal position	Code-number	Criterion	Examples
(1)		*Unsaturated rings and multiple CC-bonds*	
	4	unsaturated heterocycles	
	3	aromatics	
	2	homocycles or chains with C–C bonds	
(2)		*Fused unsaturated heterocyclic and aromatic systems, and conjugated unsaturated homocyclic systems*	
	4	angularly or peri-fused systems with three or more rings	
	3	three or more rings fused linearly	
	2	two rings	
(3)		*Conjugation and cumulation*	
	8	free radicals	
	4	cumulation	
	3	cross conjugation or peri-fusion	
	2	conjugation in molecular ions with charge-resonance	
(4)		*Conjugation of*	
	4	aromatic rings (homo- or heterocycles)	
	3	triple bonds (including those with hetero-atoms)	
	2	double bonds (in non-aromatic rings and in chains), and three-membered rings (including heterocycles)	
(5)		*Conjugation with*	
	4	doubly bonded hetero-atoms in a conjugated system	–N=N–, –C=N–
	3	doubly bonded hetero-atoms in the terminal position of a conjugated system	–C=O, –C=NR, >C=S
	2	singly bonded hetero-atoms in the terminal position of a conjugated system	–C=C–X, where X = NR_2, OR, Halogen
(6)		*Saturated heterocycles containing* (only the hetero-atoms in the ring are considered)	
	4	N (and other trivalent atoms)	
	3	S, Se, Te	
	2	O	
(7)		*Number of the hetero-atoms in the ring*	
	4	two or more different hetero-atoms in one ring	
	3	two or more identical hetero-atoms in one ring	
	2	one hetero-atom common to two rings	
(8)		*Ring size* (counting each formal ring including the perimeter in the case of fused ring systems [2])	
	4	three, four, seven, or more atoms in one ring	
	3	five atoms in one ring	
	2	six atoms in one ring	
(9)		*Substituents*	
	4	multiply bonded and containing multiple bonds	>C=O, >C=N–, –N=N–, $>SO_2$
	3	singly bonded and containing multiple bonds	$-NO_2$, –N=O, –C≡N
	2	containing single bonds only	$-NH_2$, -OH, -Halogen, -OR, >Si<, -B<
(10)		*Multiple occurrence of one of the above criteria*	
	4	four times or more	
	3	three times	
	2	twice	

The second decimal position (2) characterizes the type of ring fusion in the unsaturated systems entered under (1). The appearance of "0" in the second position would mean that the characteristics of set (1) are not present as a fused system, so that a subdivision into mononuclear and polynuclear ring systems is thereby achieved. The first two code digits therefore characterize the skeleton of the chromophoric system.

The subsequent three positions, (3), (4), and (5), determine the conjugation within the skeleton. The absence of conjugation is indicated by three zeros. Thus the combination 20000/ would mean the presence of unconjugated double bonds; 30000/ would denote an isolated benzene ring, which can be further characterized by the code numbers in positions (5), (9), and (10). The sequence 40000/ denotes pyridine or other mononuclear heterocycles.

Heterocyclic systems are further defined by code numbers in positions (6) and (7). Position (6) is the "latest position" for heterocycles, *i.e.* here the saturated heterocycles appear. The combination 00000/40220 would denote singly substituted piperidines, *e.g.* chloropiperidine. The corresponding five-membered heterocycle, for example a chloropyrrolidine, is designated by the combination 00000/40320.

[2] Examples for determining the code number for position (8):

Compound	Criteria	Code number
	6- plus 14-membered rings	2 + 4 = 6
	6- plus 10-membered rings	2 + 4 = 6
	6- plus 5- plus 9-membered rings	2 + 3 + 4 = 9
	6- plus 5- plus 10-membered rings	2 + 3 + 4 + = 9
	6- plus 5-membered rings	2 + 3 = 5

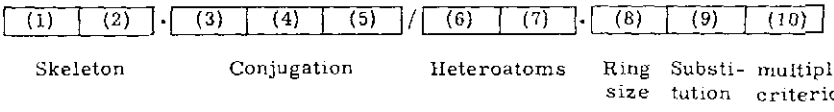
[3] Examples illustrating the use of this code, and a summary of the systematic classification of chromophoric systems, are obtainable from Prof. *H.-H. Perkampus*, 33 Braunschweig (Germany), Institut für Organische Chemie, Abteilung für Molekülspektroskopie, Technische Hochschule, Schleinitzstrasse.

The last three digits describe the ring size (8), the substitution (9), and the multiple occurrence of some particularly typical characteristic (10).

A zero in the first position indicates that all criteria of groups (1) -(3) are absent, since the criteria in groups (2) and (3) require the presence of a criterion of group (1). Saturated compounds containing no heteroatoms are denoted only by the last triad, and it can be immediately seen whether a chain or a ring is present. For example, numbers in positions (8) and (9) characterize dichlorohexane by 00000/00022 and dichlorocyclohexane by

00000/00222.

The code can be summarized in the following manner [3]:



The code can be extended by using additional decimal positions.

For example, the total number (up to 97) of carbon atoms present in a compound can be indicated by combining positions (11) and (12). Code number "98" in these positions would then designate monomeric compounds having 98 and more carbon atoms, whereas oligo(poly)-mers, oligo(poly)adducts, and oligo(poly)condensates containing 98 and more carbon atoms would be described by "99".

Complexes containing organic components are coded according to the latter, even if there is strong interaction within the complex. The sum of the organic components is coded as if the latter were bonded by CH_2-bridges without conjugation.

An additional decimal position (13) may be used to describe the nature of the inorganic components of such complexes. Here the code number 4 would be used to denote groups containing elements with atomic numbers up to 18 ($AlCl_3$, BF_3), 3 coding groups with elements above 18 (UO_2), and 2 indicating single atoms (Fe^{II}, N^{III}). Complexes with inorganic components always follow their organic components.

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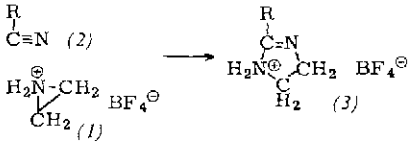
COMMUNICATIONS

Synthesis of Imidazolines and Imidazolidines by the Reaction of Aziridinium Tetrafluoroborate with Nitriles and Benzylideneaniline

By Prof. Dr. E. Pfeil and Dipl.-Chem. U. Harder

Chemisches Institut der Universität Marburg/Lahn (Germany)

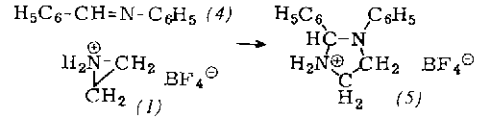
Aziridinium tetrafluoroborate *(1)*, which can be prepared from aziridine and fluoroboric acid in ether [1] adds onto nitriles *(2)* to form 2-imidazolinium fluoroborates *(3)*.



(3), R	M.p. [°C]	Yield [%]
CH_3	107	53
C_6H_5	102–103	49
$C_6H_5CH_2$	68	43

The salt *(1)* is heated with two to three times its molar amount of *(2)* for 24–48 h at 100 °C. After removal of excess *(2)* by vacuum distillation, sodium methoxide is added to liberate the imidazoline from the salt *(3)*. The free base is then purified by distillation.

Benzylideneaniline *(4)* reacts with *(1)* in diglyme [2] [molar ratio of *(4)*:*(1)* = 1:1] at 130 °C to yield 1,2-diphenylimidazolidinium fluoroborate *(5)*. The free base obtained from *(5)* in a crude yield of 62 % by treating it with potassium hydroxide is a very labile substance which is decomposed by all acids, even carbonic acid. 1,2-Diphenylimidazolidine is extremely difficult to crystallize. A finely crystalline yellow-white product obtained by recrystallization from decalin sinters at 110–120 °C.



Received: January 17th, 1964 [Z 935/761 IE]
German version: Angew. Chem. 77, 505 (1965)
Publication deferred until now at the authors' request

[1] *U. Harder, E. Pfeil*, and *K. F. Zenner*, Chem. Ber. *97*, 510 (1964).

[2] Diethylene glycol dimethyl ether.

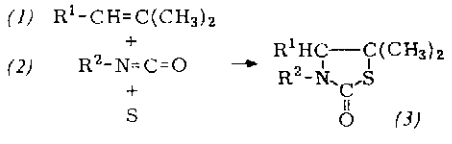
Synthesis of 1,3-Thiazolidin-2-ones from Aminoalkenes, Isocyanates, and Sulfur [1]

By Dr. habil. K. Ley and Dr. R. Nast

Wissenschaftliches Hauptlaboratorium der Farbenfabriken Bayer AG., Leverkusen (Germany)

Dedicated to Professor Eugen Müller on the occasion of his 60th birthday

α-Aminoalkenes *(1)*, sulfur, and isocyanates *(2)* condense together in an exothermal reaction to give 1,3-thiazolidin-2-ones *(3)*. The best yields (up to 90 %) of *(3)* are obtained if



the sulfur is first condensed with the amino-olefin *(1)* in a solvent containing carhonyl groups, preferably dimethylformamide, and the adduct is then treated with the isocyanate *(2)*.

3,5,5-Trimethyl-4-piperidino-1,3-thiazolidin-2-one:

N-Isobutenylpiperidine (69.5 g) is stirred for 3 h with 16 g of sulfur in 40 ml of dimethylformamide. Methyl isocyanate (38.5 g) is then added dropwise, the temperature rising gradually to 60 °C. The mixture is stirred for 30 min and then cooled to 10 °C, whereupon it solidifies. The crystals are sucked off and dried. The yield is 110 g of the title compound, m.p. 114–116 °C after recrystallization from ethanol.

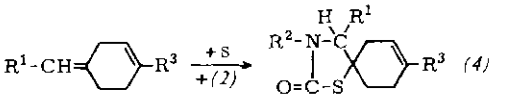
5,5-Dimethyl-3-phenyl-4-pyrrolidino-1,3-thiazolidin-2-one:

A mixture of 60 g of phenyl isocyanate, 16 g of sulfur, and 100 ml of dimethylformamide is stirred, and 62.5 g of *N*-Isobutenylpyrrolidine is added dropwise. The temperature is maintained at 35 °C by cooling. The solution becomes clear as the reaction proceeds. After further stirring (15 min) and cooling to 20 °C, the reaction mixture solidifies. When the product is sucked off and dried, 100 g of the title compound is obtained. After recrystallization from ethanol the m.p. is 117–118 °C.

5,5-Dimethyl-3-(p-toluenesulfonyl)-4-pyrrolidino-1,3-thiazolidin-2-one:

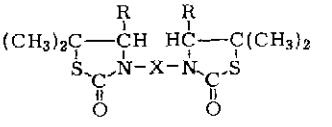
Eight grams of sulfur and 31 g of α-pyrrolidinoisobutene are stirred for 1 h at 65 °C in 60 ml of pyridine. The mixture is cooled to room temperature, and 49 g of *p*-toluenesulfonyl isocyanate is added dropwise. The temperature rises rapidly and is kept at 40 °C by cooling. The mixture is stirred for 30 min, and the solvent is then distilled off *in vacuo*. The crystalline residue is washed with methanol and sucked dry, leaving 61 g of analytically pure title compound, m.p. 144 °C (decomp.).

Condensation of derivatives of aminomethylenecyclohexane (or aminomethylenecyclohexene) with sulfur and *(2)* yields the spiro compounds *(4)*.

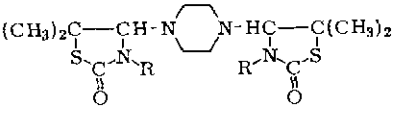


(4), R^1 = *N*-Morpholino, R^2 = C_6H_5, R^3 = CH_3, m.p. 200–203 °C
R^1 = *N*-Morpholino, R^2 = C_6H_5, R^3 = H, m.p. 168–170 °C

If the reaction is carried out with di-isocyanates or diaminodienes, the corresponding bicyclic compounds *(5)* and *(6)* are formed.



(5), R = *N*-Piperidinyl, X = $(CH_2)_6$, m.p. 164 °C (decomp.)
R = *N*-Piperidinyl, X = C_6H_4, m.p. 247 °C (decomp.)



(6), R = C_6H_5, m.p. 268 °C (decomp.)

Received: February 4 th, 1965 [Z 941/767 IE]
Publication deferred until now at the authors' request
German version: Angew. Chem. 77, 544 (1965)

[1] Multicomponent Reactions, Part 1.

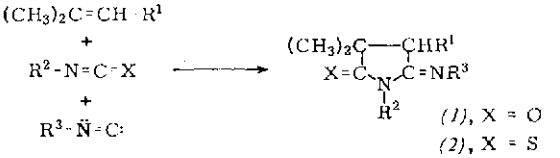
Synthesis of Iminopyrrolidones and Iminothiopyrrolidones from Aminoalkenes and Isonitriles plus Isocyanates or Isothiocyanates [1]

By Dr. habil. K. Ley, Dr. U. Eholzer, and Dr. R. Nast

Wissenschaftliches Hauptlaboratorium der Farbenfabriken Bayer AG., Leverkusen (Germany)

Dedicated to Professor Eugen Müller on the occasion of his 60th birthday

α-Aminoalkenes react with isonitriles and either isocyanates or isothiocyanates in polar solvents to give high yields of *N*-substituted 2-imino-5-pyrrolidones *(1)* and 2-imino-5-thiopyrrolidones *(2)*, respectively.



(1), X = O
(2), X = S

2-Cyclohexylimino-4,4-dimethyl-1-phenyl-3-piperidino-5-pyrrolidone:

Phenyl isocyanate (11.9 g) is added dropwise to a stirred solution of 13.8 g of *N*-isobutenylpiperidine and 10.8 g of cyclohexyl isonitrile in 25 ml of dimethylformamide. The temperature rises to 33 °C. The mixture is then heated to 50 °C for 30 min. On cooling, 33 g of the title compound crystallizes out; after recrystallization from acetonitrile it melts at 95–97 °C.

2-(t-Butylimino)-1-(p-chlorophenyl)-4,4-dimethyl-3-pyrrolidino-5-pyrrolidone:

When 12.5 g of *N*-isobutenylpyrrolidine, 8.3 g of t-butyl isonitrile, and 15.4 g of *p*-chlorophenyl isocyanate are dissolved in 40 ml of dimethylformamide, the temperature rises to 62 °C. On cooling, 30 g of the title compound crystallizes out; after recrystallization from acetonitrile, the m.p. is 84–85 °C.

2-Cyclohexylimino-4,4-dimethyl-3-pyrrolidino-1-(p-toluenesulfonyl)-5-pyrrolidone:

p-Toluenesulfonyl isocyanate (19.7 g) is added dropwise to a solution of 12.5 g of *N*-isobutenylpyrrolidine and 10.8 g of cyclohexyl isonitrile in 60 ml of acetonitrile, the temperature rising to 65 °C. On cooling, 40 g of title compound is deposited; after recrystallization from acetonitrile, the m.p. is 110–113 °C.

4,4-Dimethyl-2-(2-methyl-3-nitrophenylimino)-1-phenyl-3-pyrrolidino-5-pyrrolidone:

Phenyl isocyanate (23.8 g) is added dropwise to 25.0 g of *N*-isobutenylpyrrolidine and 32.4 g of 6-methyl-3-nitrophenyl isonitrile in 100 ml of acetonitrile, the solution being cooled to keep the temperature below 60 °C. On cooling, 65 g of the title compound precipitates as orange-yellow crystals, which after recrystallization from acetonitrile melt at 164–165 °C.

1-Cyclohexyl-2-cyclohexylimino-4,4-dimethyl-3-pyrrolidino-5-thiopyrrolidone:

Twenty-five grams of *N*-isobutenylpyrrolidine, 28.2 g of cyclohexyl isothiocyanate, and 20.6 g of cyclohexyl isonitrile are heated together in 100 ml of dimethylformamide for 3 h at 120 °C. On cooling, 68 g of colorless crystals separate out, m.p. 76–77 °C from ethanol.

2-Cyclohexylimino-4,4-dimethyl-1-(p-nitrophenyl)-3-piperidino-5-thiopyrrolidone:

A solution of 36 g of *p*-nitrophenyl isothiocyanate, 20.6 g of cyclohexyl isonitrile, and 28.0 g of *N*-isobutenylpiperidine in 100 ml of acetonitrile is refluxed for 1 h. On cooling, 77 g of bright yellow crystals are deposited, m.p. 119–120 °C from ethanol.

2-Cyclohexylimino-3-pyrrolidino-1,4,4-trimethyl-5-thiopyrrolidine:

A solution of 25 g of *N*-isobutenylpyrrolidine, 14.6 g of methyl isothiocyanate, and 20.6 g of cyclohexyl isonitrile in 50 ml of acetonitrile is refluxed for 6 h. On cooling, 42 g of title compound is deposited, m.p. 97–98 °C from ethanol.

4,4-Dimethyl-2-(3,3'-dimethyl-4-azophenylimino)-1-(p-nitrophenyl)-3-piperidino-5-thiopyrrolidone:

A solution of 47 g of 3,3'-dimethyl-4-isocyanoazobenzene, 36 g of *p*-nitrophenyl isothiocyanate, and 28 g of *N*-isobutenylpiperidine in 300 ml of acetonitrile is refluxed for 3 h. On cooling, 85 g of orange-yellow crystals are obtained, m.p. 141–142 °C from ethanol.

If diaminodienes, di-isocyanates, or di-isothiocyanates are used as starting materials, the corresponding bicyclic heterocycles are obtained. The reaction has great scope.

Received: February 4th, 1965 [Z 942/768 IE]
Publication deferred until now at the authors' request
German version: Angew. Chem. 77, 544 (1965)

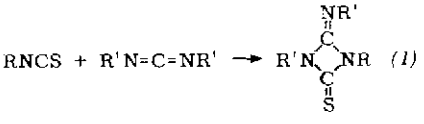
[1] Multicomponent Reactions, Part 2. Part 1: *K. Ley* and *R. Nast*, Angew. Chem. 77, 544 (1965); Angew. Chem. internat. Edit. 4, 519 (1965).

Synthesis of 2-Imino-4-thioxo-1,3-diazetidine Derivatives by Cycloaddition of Isothiocyanates onto Carbodiimides

By Dr. H. Ulrich and Dr. A. A. R. Sayigh

The Upjohn Company, Carwin Research Laboratories, North Haven, Connecticut (U.S.A.)

The addition of isothiocyanates onto carbodiimides has not yet been observed. We found that 2-imino-4-thioxo-1,3-diazetidines *(1)* are formed in quantitative yields when isothiocyanates activated by an electron withdrawing substituent (such as p-nitrophenyl or alkyl- and arylsulfonyl) and carbodiimides are mixed at room temperature in a molar ratio of 1:1 with or without solvent. The reaction can be followed by infrared spectroscopy by the disappearance of the absorptions in the cumulative double bond region (4.7–4.9 μ) and by the appearance of a new C=N absorption at 6.05 μ in the case of *(1a)* and *(1b)*, at 6.19 μ in the case of *(1c)*, and at 6.25 μ in the case of *(1d)*.



RNCS + R'N=C=NR' → (*1*)

(a), R = *p*-Nitrophenyl,	R' = Isopropyl,	m.p. 51–52 °C
(b), R = *p*-Nitrophenyl,	R' = Cyclohexyl,	m.p. 73–75 °C
(c), R = Methylsulfonyl,	R' = Phenyl,	m.p. 173–174 °C
(d), R = *p*-Tolylsulfonyl,	R' = Tolyl,	m.p. 128–129 °C

The structure of the compounds *(1)* was determined by elemental analysis, molecular weight determination and cleavage into the starting components on heating in an inert solvent (*o*-dichlorobenzene, 180 °C). In no instance was cleavage with formation of the unsymmetrically substituted carbodiimide observed. With compounds *(1c)* and *(1d)*, especially, such a reaction would have been detected easily since sulfonyl isothiocyanates absorb at 5.25 μ, while other isothiocyanates absorb at 4.9 μ.

Received: March 26th, 1965 [Z 951/774 IE]
German version: Angew. Chem. 77, 545 (1965)

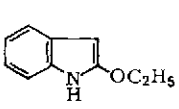
Formation of Indirubin and 2-Ethoxy-3-(indol-2-yl)indole from 2-Ethoxyindole

By Prof. Dr. H. Plieninger, Dr. U. Lerch, and Dipl.-Chem. D. Wild

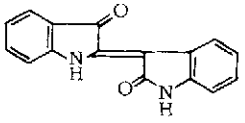
Organisch-Chemisches Institut der Universität Heidelberg (Germany)

2-Ethoxyindole *(1)* [1] in solution or in the solid state turns red-violet on admission of oxygen. After a crystalline sample of *(1)* has stood for several weeks in air, unchanged starting material can be extracted with ether or ethanol, and the undissolved residue of pigment can be recrystallized from acetic acid/ethanol. The melting point, infrared spectrum,

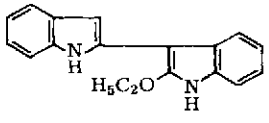
and behavior on thin-layer chromatograms of the colored product are those of indirubin *(2)*



(1)



(2)



(3)

A similar "dimerization" is observed on treating 2-ethoxyindole in dioxane at 20 °C with boron trifluoride etherate. A BF_3 complex is deposited from which colorless 2-ethoxy-3-(indol-2-yl)indole *(3)* is formed on adding aqueous ammonia. The structure of *(3)* was proved by its elemental analysis, infrared spectrum (two NH absorptions at 3440 and 3380 cm^{-1}), and NMR spectrum [signals at 1.16 τ (NH), 2.1–2.9 τ (multiplet; aromatic protons and 1 NH), 3.16 τ (singlet; β-proton), 5.86 τ (quartet), and 8.62 τ (triplet) in area ratios of 1:9:1:2:3]. Compound *(3)* gives a deep blue color in the Ehrlich reaction and is oxidized in air. Indirubin *(2)* could be isolated from the oxidation products.

The introductory step in both reactions is possibly an electrophilic attack [by oxygen in the autoxidation to *(2)* and by BF_3 during the formation of *(3)*] at C-3 of the ethoxyindole skeleton.

[Z 950/776 IE]
Received: February 25th, 1965; supplemented: March 30th, 1965
German version: Angew. Chem. 77, 505 (1965)

[1] *H. Plieninger* and *H. Bauer*, Angew. Chem. *73*, 433 (1961).

Synthesis of Tetrakis(trifluorophosphine)-platinum(0) and Tetrakis(trifluorophosphine)-palladium(0) [1]

By Priv.-Doz. Dr. Th. Kruck and Dipl.-Chem. K. Baur

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Technischen Hochschule München (Germany)

The reductive fluorophosphination of simple transition metal salts has proved to be a generally applicable method of preparing metal trifluorophosphines, which are largely analogous to the metal carbonyls [1, 2].

On treating anhydrous platinum(II) chloride and palladium(II) chloride with trifluorophosphine in the presence of copper powder as halogen acceptor at 100 °C and initial PF_3 pressures of 300 atm (with $PdCl_2$) or 100 atm (for $PtCl_2$), the tetrakis-(trifluorophosphine) derivatives of the two platinum metals are formed. The yields are 70–80 % and 80 %, respectively.

These volatile, hydrophobic compounds deserve attention, since volatile, four-coordinate complexes, including carbonyls, of these metals in the zerovalent state had previously not been known. In appearance and other properties the new compounds resemble nickel trifluorophosphine and nickel carbonyl.

$Pt(PF_3)_4$ is a colorless, mobile liquid with m.p. −15 °C, b.p. 86 °C/730 mm, which decomposes above 90 °C with deposition of the metal. In a nitrogen atmosphere the liquid can be distilled at normal pressure with only little decomposition. The pale yellow distillate must however be recondensed in vacuum at 20 °C to render it colorless and analytically pure. In the infrared spectrum [3] of the diamagnetic compound, only two P–F valence vibration bands are observed, as with $Ni(PF_3)_4$, namely at 906 (vs) and 867 cm^{-1} (vs) (gas-phase measurement), which indicate a tetrahedral structure (T_d). $Pd(PF_3)_4$ is thermally less stable than $Pt(PF_3)_4$. It is also a colorless, mobile liquid and melts at −41 °C. Decomposition occurs above −20 °C with deposition of a palladium mirror. Rapid decomposition with PF_3 literally boiling off occurs at room temperature. The infrared spectrum of the compound was therefore measured at −25 °C between KCl plates [4]; the two P–F valence vibration frequencies expected for a tetrahedral structure were found at 910 (vs, b) and 860 (s) cm^{-1}.

Received: April 5th, 1965 [Z 956/783 IE]
German version: Angew. Chem. 77, 505 (1965)

[1] IXth communication on metal trifluorophosphine complexes. VIIIth communication: *Th. Kruck* and *K. Baur*, Chem. Ber. *98* (1965), in the press.

[2] *Th. Kruck*, *W. Lang*, and *A. Engelmann*, Angew. Chem. *77*, 132 (1965); Angew. Chem. internat. Edit. *4*, 148 (1965), and literature cited there.

[3] The infrared spectra were obtained using a Perkin-Elmer Model 21 spectrophotometer with NaCl optics. s = strong, vs = very strong, b = broad.

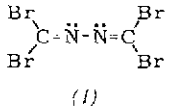
[4] Gas-phase measurements at room temperature reveal only the ν_{P-F} vibration bands at 892 and 853 cm^{-1} of the liberated PF_3, together with an intense broad band at 865 cm^{-1}, which is ascribed to an as yet unidentified decomposition product.

Synthesis of Bis(diaziridin-1-ylmethylene)-hydrazine

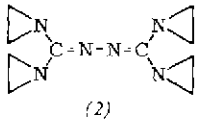
By Doz. Dr. R. Neidlein and W. Haussmann

Institut für Pharmazeutische Chemie und Lebensmittelchemie
der Universität Marburg (Germany)

Starting from isocyanogen tetrabromide *(1)* [1, 2], which can be regarded as a derivative of the (as yet unknown) isocyanogen, we have synthesized various tetra-amino derivatives of isocyanogen.



(1)



(2)

Bis(diaziridin-1-ylmethylene)hydrazine *(2)* is prepared by dissolving 3.71 g (0.01 mole) of isocyanogen tetrabromide *(1)* in 20 ml of anhydrous tetrahydrofuran, adding 1.6 g (0,04 mole) of finely powdered sodium hydroxide, cooling in ice, and adding 3.44 g (0.08 mole) of ethylenimine dropwise with vigorous stirring. Stirring is continued for 2 h at room temperature. After filtering off the KBr and distilling the tetrahydrofuran from the filtrate, a colorless oil remains, which crystallizes on standing in a refrigerator for several days; yield 1.5 g (68 %), m.p. 134–135 °C.

Bis(dipiperidinomethylene)hydrazine is prepared analogously; yield 2.9 g (76 %), m.p. 148.5 °C.

The compound *(2)* is very sensitive to acids, of which even traces cause an explosion-like polymerization.

Received: April 7th, 1965 [Z 959/785 IE]
German version: Angew. Chem. 77, 506 (1965)

[1] *J. Thiele*, Liebigs Ann. Chem. *303*, 57 (1898).

[2] *J. Diekmann*, J. org. Chemistry *28*, 2933 (1963).

Synthesis of N-(Alkylthiohalogenomethylene) Sulfonamides

By Doz. Dr. R. Neidlein and W. Haussmann

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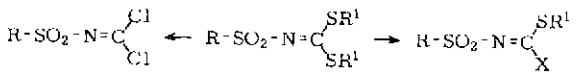
und Lebensmittelchemie der Universität Marburg (Germany)

N-Dichloromethylene sulfonamides *(1)* [1, 2] are obtained by the action of elemental chlorine on *S,S*-dialkyl-*N*-sulfonyldithiocarbonimides *(2)* [3,4] in boiling carbon tetrachloride.

Reaction of *(2)* under analogous conditions with an equimolar amount of bromine, on the other hand, leads to



(1) *(2)* *(3)*

N-(alkylthiobromomethylene) sulfonamides *(3)*, X = Br. Moreover, when *(2)* is cleaved under the same conditions with an equimolar amount of sulfuryl chloride, the product is an alkylthiochloromethylene sulfonamide *(3)*, X = Cl.

(3)

X	R	R^1	M.p. [°C]	Yield [%]
Br	C_6H_5	CH_3	68–69	39
Cl	CH_3	CH_3	52–53	74
Cl	C_6H_5	CH_3	65–66	93
Cl	p-CH_3-C_6H_4	CH_3	89–90	89

The structures of the new compounds have been confirmed by their infrared spectra. The alkylthiobromomethylene sulfonamides have absorption bands at 6.5 and 11.2 μ that are characteristic for the *C*-bromoimide grouping, and the alkylthiochloromethylene sulfonamides have bands between 6.4 and 6.6 μ and between 10.6 and 10.9 μ due to the chloroimido grouping. Satisfactory elemental analyses have been obtained for all of the halogeno compounds *(3)*.

Received: May 5th, 1965 [Z 971/797 IE]
German version: Angew. Chem. *77*, 549 (1965)

[1] *R. Neidlein* and *W. Haussmann*, Tetrahedron Letters, in the press.

[2] *R. Neidlein* and *W. Haussmann*, Südwestdeutsche Chemiedozententagung, Mainz (Germany), April 27th-30th, 1965.

[3] *R. Gompper and W. Hägele*, Angew. Chem. *74*, 753 (1962).

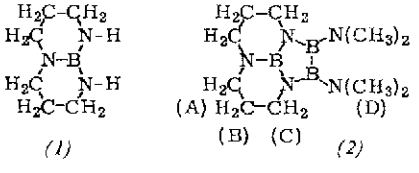
[4] German Published Patent Application 1163802 (Aug. 27th, 1964), Farbenfabriken Bayer AG., inventors: *R. Gompper*, *R. Wegler*, *K. Dickoree*, and *W. Hägele*.

Synthesis of a 2,5-Diaza-1,3,4-triborolidine

By Doz. Dr. H. Nöth and Dipl.-Chem. G. Abeler

Institut für Anorganische Chemie der Universität München (Germany)

N-Metalation of triazaboradecalin *(1)* [1] with methyllithium in ether and subsequent reaction with symmetrical bis(dimethylamino)diboron dichloride gives 1,2-bis(dimethylamino)perhydro-2a,5a,8a-triaza-1,2,8b-triboracenaphthylene *(2)*, b.p. 105 °C/high vacuum, in about 30 % yield. This compound is a derivative of the new B–N ring system 2,5-diaza-1,3,4-triborolidine *(3)*.



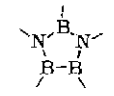
(1)

(A) (B) (C) (D)

(2)

The structure of *(2)* was confirmed by analysis, molecular-weight determination, and by infrared and NMR spectroscopy. The ^{1}H-NMR spectrum of the substance in benzene exhibits a triplet at 3.85 p.p.m. (C), a triplet with a singlet superposed at 4.35 p.p.m. (A+D), and a quintuplet at 5.57 p.p.m. (B), the areas being in the ratio of 1:4:1. The ^{11}B-signal of the B–B group occurs at −35 p.p.m., that of the B atom of the BN_3 group at −28.4 p.p.m. [2].

The compound is being examined with regard to the question of whether the system *(3)* is more stable than 2,3,5-triaza-1,4-



(3)

(4)

diborolidine *(4)* [3]. Calculations using the LCAO-MO method indicate a higher stability for the heterocycle *(3)* [4], are however not free from contradictions [5].

Received: April 7th, 1965 [Z 960/786 IE]
German version: Angew. Chem. *77*, 506 (1965)

[1] *K. Niedenzu*, *P. Fritz*, and *J. W. Dawson*, Inorg. Chem. *3*, 1077 (1964).

[2] Fields higher than that at which the reference signal occurs (internal standard benzene, external standard $BF_3 \cdot O(C_2H_5)_2$) are called positive and *vice versa*.

[3] *H. Nöth* and *W. Regnet*, Z. Naturforsch. *18b*, 1139 (1963); *K. Niedenzu*, *P. Fritz*, and *H. Jenne*, Angew. Chem. *76*, 535 (1964); Angew. Chem. internat. Edit. *3*, 506 (1964).

[4] *T. Balaban* and *A. Simon*, Rev. roum. Chim. *9*, 99 (1964).

[5] *D. A. Bochvar* and *A. A. Bagaturyants*, Izvest. Akad. Nauk. SSSR, Otdel. khim. Nauk *1963*, 785.

Isomer Formation in the Monochlorination of n-Heptane with Phosphorus Pentachloride and with Phosphorus Trichloride/Chlorine

By Dr. B. Fell

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n-Heptane was chlorinated with chlorine or phosphorus pentachloride (98 °C; 2 moles of n-heptane, 0.2 mole of chlorinating agent, 0.1 mole of dibenzoyl peroxide) or with PCl_3/Cl_2 (2 moles of n-heptane, 0.2 mole of PCl_3, 0.1 mole of dibenzoyl peroxide). The isomer composition of the monochloro-n-heptane fraction was determined gas chromatographically:

	x-Chloro-n-heptane [% by weight]			
	1–	2–	3–	4–
Cl_2	15.1	34.6	33.8	16.5
PCl_5	2.5	36.4	41.5	19.5
PCl_3/Cl_2	traces	24.0	52.0	24.0

The results show that the hydrogen atoms of the methyl groups react significantly more slowly with PCl_5 than with gaseous Cl_2. It is particularly surprising that the first methylene group reacts more slowly with PCl_5 than those further along the molecule, whereas no such differences occur with gaseous Cl_2 [1]. The effect found with PCl_5 is even more marked in the chlorination with Cl_2 in the presence of excess PCl_3.

The cause of the different isomer distribution is probably the fact that different chlorine radicals act on the n-heptane. The chlorination employing PCl_5 or PCl_3/Cl_2 does not occur *via* atomic chlorine (as in the reaction using chlorine alone), but rather *via* complex, polarized Cl-containing radicals:

$$Cl\cdot + PCl_3 \rightleftharpoons [Cl_3P^{\delta+}:\rightarrow Cl\cdot^{\delta-}]$$

The analogy with chlorination of an n-alkane in benzene with free chlorine, where the probability of substitution on the first secondary carbon atom is also lower [2], supports this hypothesis. A benzene-chlorine complex is formed [3]:

$$C_6H_6 \rightarrow Cl\cdot^{\delta-}$$

Received: April 8th, 1965 [Z 962/788 IE]
German version: Angew. Chem. *77*, 506 (1965)

[1] *F. Asinger* and *B. Fell*, Erdöl und Kohle *17*, 74 (1964).

[2] *B. Fell* and *L. H. Kung*, Chem. Ber., in press.

[3] *G. A. Russell*, J. Amer. chem. Soc. *80*, 4987 (1958).

The Crystal Structure of Dipotassium Periodate Hydrate

By Prof. Dr. H. Siebert and Dr. H. Wedemeyer [1]

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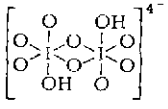
Dipotassium periodate crystallized from aqueous solution was previously assigned the formula $K_4I_2O_9 \cdot 9\,H_2O$ because of its behaviour on dehydration [2]. Its infrared spectrum shows the presence of IOH groups, however, so that the structure $K_2HIO_5 \cdot 4\,H_2O$ containing five-coordinate iodine appears more likely [3]. An X-ray analysis was therefore carried out to settle this question.

The substance crystallizes in the triclinic system with the space group $C_i^1 - P\bar{1}$. The unit cell has the dimensions a = 7.16 Å, b = 10.55 Å, c = 7.08 Å, $\alpha = 98.0°$, $\beta = 116.1°$, $\gamma = 90.1°$, and contains two formula units of $K_2HIO_5 \cdot 4\,H_2O$. *Patterson* and *Fourier* projections in the directions [100], [010], and [001] showed the anion to be dimeric, *i.e.* $H_2I_2O_{10}^{4-}$. Each iodine atom is surrounded almost octahedrally by six oxygen atoms; the octahedra have one edge in common, thus forming an I_2O_2 ring.



Ten of the twelve I–O bonds – including those in the ring – are 2.0 Å long, the remaining two 2.2 Å. The last-named may be the I–OH bonds. The reliability indices of the structure analysis were about 0.2.

This structure does not appear to be unique; the infrared spectra of previously prepared alkali periodates $M_2^IHIO_5$ [3] indicate that these, too, contain the dimeric anion $H_2I_2O_{10}^{4-}$. The same holds for several salts $M^{II}HIO_5$, *e.g.* with M = $[Mg(H_2O)_6]^{2+}$, Ca^{2+}, Sr^{2+}, $[Co(NH_3)_5NO_2]^{2+}$, $[Co(NH_3)_5N_3]^{2+}$, and $[Co(NH_3)_5NCS]^{2+}$. The compounds previously formulated as the double salts $Na_3IO_5 \cdot Na_2HIO_5 \cdot 14H_2O$ and $Li_3IO_5 \cdot Li_2HIO_5 \cdot 11H_2O$ [3] probably contain the ion $HI_2O_{10}^{5-}$; the infrared spectra of the compounds designated $[Co(NH_3)_6]HI_2O_9 \cdot 3H_2O$ and $[Co(en)_3]HI_2O_9 \cdot 4H_2O$ [4] indicate the presence of the anion $H_3I_2O_{10}^{3-}$.

A structure similar to that of the $H_2I_2O_{10}^{4-}$ ion and containing a four-membered As_2O_2 ring was found for the anion of the dimeric tetrafluoroarsenates $M_2^IAs_2O_2F_8$ [5].

Received: April 9th, 1965 [Z 964/791 IE]
German version: Angew. Chem. 77, 507 (1965)

[1] *H. Wedemeyer*, Ph. D. Thesis, Bergakademie Clausthal, 1965.
[2] *A. E. Hill*, J. Amer. chem. Soc. *50*, 2678 (1928).
[3] *H. Siebert*, Z. anorg. allg. Chem. *303*, 162 (1960); *304*, 266 (1960).
[4] *N. I. Lobanov*, Zh. Neorgan. Khim. *5*, 565 (1960); Chem. Abstr. *56*, 3103 (1962).
[5] *H. Dunken* and *W. Haase*, Z. Chem. *3*, 433 (1963); *4*, 156, 193 (1964).

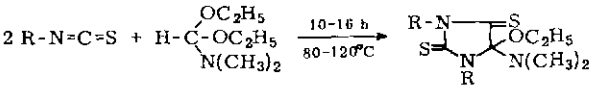
Reactions of Amide Acetals with Isothiocyanates

By Prof. Dr. H. Bredereck, Dr. G. Simchen, and
cand. chem. S. Rebsdat

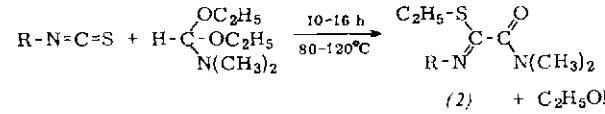
Institut für Organische Chemie der Technischen Hochschule
Stuttgart (Germany)

Recently we reported on reactions of amide acetals with isocyanates which result in *O,N*-acetals of parabanic acid [1].

We have now found that isothiocyanates, which are less electrophilic than isocyanates, also react with dimethylformamide acetals between 80 and 120 °C, directly or in toluene solution. After 10–16 h, probably after primary acylation at the formyl C-atom, 1,3-disubstituted 2,4-dithioxoparabanic *O,N*-acetals *(1)*, which have not previously been described, and/or α-alkyl-(or aryl)-imino-α-(ethylthio)dimethylacetamides *(2)*, are formed, depending on the size of the residue R (see Table below).



(1) + C_2H_5OH



(2) + C_2H_5OH

The ethanol formed together with *(1)* or *(2)* adds only slowly onto the isothiocyanate to give thiourethane.

R	Yield [%] *(1)*	Yield [%] *(2)*	B.p. [°C/mm] *(1)*	M.p. [°C] *(1)*	n_D^{20} *(1)*	Thiourethane yield [%]
CH_3	65	–	85–89/0.001	49	–	7.6
C_2H_5	63	–	88–89/0.001	–	1.5780	8.0
i-C_3H_7	57	–	–	93.5	–	6.2
n-C_4H_9	64	–	104/0.001	–	1.5487	11.7
Cyclohexyl	42		–	119	–	–
		28	94/0.001	–	1.5235	–
$C_6H_5CH_2$	–	34	132–134/0.0017	–	1.5886	–
C_6H_5	–	80	111–115/0.001	–	1.5593	–
Naphthyl	–	43	160/0.0014	98–99	–	–

Received: April 13th, 1965 [Z 965/792 IE]
German version: Angew. Chem. 77, 507 (1965)

[1] *H. Bredereck, G. Simchen*, and *E. Göknel*, Angew. Chem. *76*, 861 (1964); Angew. Chem. internat. Edit. *3*, 704 (1964).

Syntheses of O,N- and N,N-Acetals of α-Ketonitriles

By Prof. Dr. H. Bredereck, Dr. G. Simchen, and
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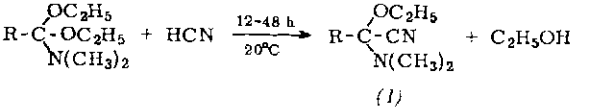
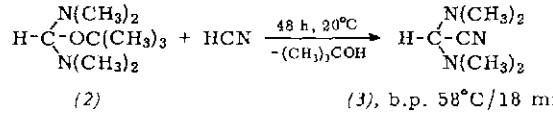
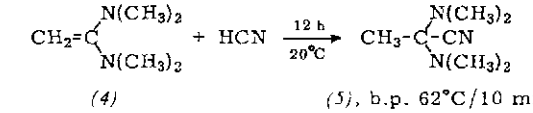
In the course of investigations on the reactions of carboxamide acetals with CH-acidic compounds [1,2], we treated amide acetals with the equivalent amount of hydrocyanic acid at room temperature and obtained *O,N*-acetals *(1)* of α-ketonitriles in good yields.



(1)



(2) *(3)*, b.p. 58°C/18 mm, $n_D^{20} = 1.4282$ yield 92%



(4) *(5)*, b.p. 62°C/10 mm, $n_D^{20} = 1.4359$ yield 51%

R	B.p [°C/mm]	n_D^{20}	Yield [%]
H	64–66/16	1.4143	87
CH_3	57/10	1.4200	73
n-C_3H_7	78–80/10	1.4305	67

N,N-Acetals *(3)* and *(5)* of α-ketonitriles were obtained in the same way from bis(dimethylamino)-t-butoxymethane *(2)* [3] or 1,1-bis(dimethylamino) ethylene *(4)* [4].

Received: January 22nd, 1965; amended April 13th, 1965 [Z 966/790 IE]
German version: Angew. Chem. 77, 508 (1965)

[1] *H. Bredereck, F. Effenberger*, and *H. Botsch*, Chem. Ber. *97*, 3397 (1964).

[2] *P. Horn*, Diploma Thesis, Technische Hochschule Stuttgart, 1965.

[3] Unpublished work.

[4] *H. Bredereck, F. Effenberger*, and *H. P. Beyerlin*, Chem. Ber. *97*, 3081 (1964).

Synthesis of γ-Phenylazopentamethinecyanine Dyes [1]

By Dr. C. Reichardt

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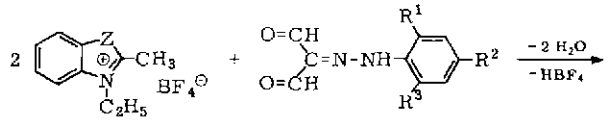
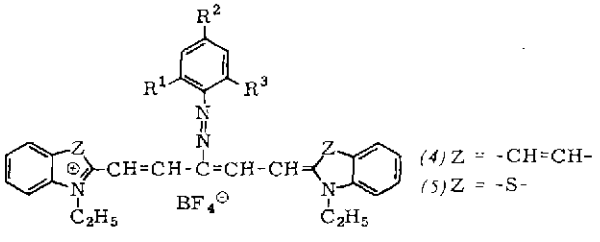
Condensation of phenylazomalondialdehydes with heterocyclic quaternary salts results in compounds ("azocyanines" [2]) which occupy a position between the cyanine and azo dyes. On heating a solution of 10 mmoles of 1-ethyl-2-methylquinolinium fluoroborate *(1)* with 5 mmoles of phenylazomalondialdehyde *(3)* [3] (or a derivative of *(3)*) [4] in 25 ml pyridine/0.5 ml piperidine for 2 h at 100 °C, γ-phenylazopentamethinecyanines *(4)* are formed, usually in good yields. Using *(2)* instead of *(1)* and without addition of piperidine the dyes *(5)* are obtained.



(1) Z = -CH=CH-
(2) Z = -S-

(3)



(4) Z = -CH=CH-
(5) Z = -S-

	R^1	R^2	R^3	M.p. [°C]	Yield [%]	CH_3OH λ_{max} [mμ]	log ε
(4a)	H	H	H	240–241	71	688	5.10
(4b)	Cl	Cl	Cl	255–256	74	656	5.15
(4c)	H	NO_2	H	307–308	88	660	5.08
(4d)	NO_2	NO_2	H	259–260	35	622	4.94
(5a)	H	H	H	257–259	19	645	4.88
(5b)	Cl	Cl	Cl	244–245	76	615	5.15
(5c)	H	NO_2	H	255–256	18	617	5.00

The structures of the compounds *(4)* and *(5)* are supported by the similarity of their ultraviolet spectra with those of the unsubstituted pentamethinecyanines. The introduction of the phenylazo group (a substituent with −I and −M effects) results a hypsochromic shift of the long-wavelength bands, which in the unsubstituted cyanines are at 708 and 650 mμ. This shift is analogous to that occurring on replacement of the middle methine group of a symmetrical polymethine chain with a nitrogen atom (aza-perturbation). Increase in the electron-attracting effect of the phenylazo group by introduction of Cl or NO_2 groups magnifies the hypsochromic shift (see Table).

Received: April 15th, 1965 [Z 967/793 IE]
German version: Angew. Chem. 77, 508 (1965)

[1] 2nd Communication on syntheses with substituted malondialdehydes. – 1st Communication: *C. Reichardt*, Tetrahedron Letters *1965*, 429.

[2] *A. Treibs* and *R. Zimmer-Galler*, Liebigs Ann. Chem. *627*, 166 (1959).

[3] *L. Claisen*, Ber. dtsch. chem. Ges. *36*, 3664 (1903).

[4] *F. Mashio* and *Y. Kimura*, Nippon Kagaku Zasshi *83*, 303 (1962); Chem. Abstr. *59*, 3841 (1963); *H. R. Hensel*, Chem. Ber. *97*, 96 (1964). For the formulation of *(3)* in the phenylhydrazone form cf. *H. C. Yao*, J. org. Chemistry *29*, 2959 (1964).

β-Aminoethylation of CH-Acidic Compounds with N-Acylaziridines

By Dr. H. Stamm

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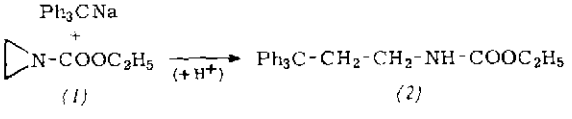
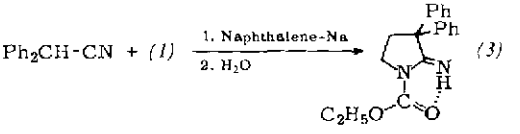
N-Acylated aziridines react with bases with ring opening [1]. We found that tritylsodium, prepared from triphenylmethane and naphthalenesodium, reacts in tetrahydrofuran at room temperature with 1-ethoxycarbonylaziridine *(1)* to give *N*-ethoxycarbonyl-3,3,3-triphenylpropylamine *(2)* in 30 % yield.



(1) *(2)*

Depending on the concentration, the product crystallizes from cyclohexane in one of two modifications, m.p. 126 to 128 °C and 133–134 °C, which have different infrared spectra in KBr, but identical spectra in CCl_4 ($\nu_{C=O}$ in CCl_4: 1727 cm^{-1}).

An analogous reaction was carried out with diphenylacetonitrile. 1-Ethoxycarbonyl-2-imino-3,3-diphenylpyrrolidine *(3)* [yield 24 %, m.p. 148–150 °C, ν_{N-H} in KBr: 3320 cm^{-1}, in



(3)

CCl_4: 3335 cm^{-1}, $\nu_{C=N}$ and $\nu_{C=O}$ ca. 1650 and 1608 cm^{-1}, respectively] can be saponified with alkali to give 2-imino-3,3-diphenylpyrrolidine [m.p. 213–213.5 °C, $\nu_{C=N}$ = 1663 cm^{-1} (KBr)] which is also formed in 3.5 % yield as a by-product in the synthesis of *(3)*.

Received: April 20th, 1965 [Z 968/794 IE]
German version: Angew. Chem. 77, 546 (1965)

[1] Ring opening using an *N*-base: *G. E. Ham*, J. org. Chemistry *29*, 3052 (1964).

Addition of Hydrogen Peroxide onto Schiff Bases

By Dr. E. Höft and Prof. Dr. A. Rieche

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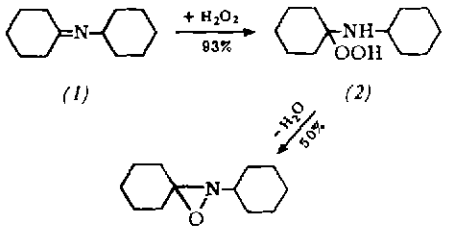
Schiff bases react with peroxyacids to give oxaziridines [1]. However, when solutions of *N*-cyclohexylidenecyclohexylamine and hydrogen peroxide in anhydrous ether are mixed,

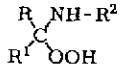
a good yield of a hydroperoxide is obtained whose elemental analysis and content of active oxygen indicate the structure *(2)*.



(1) *(2)* *(3)*

The infrared spectrum of *(2)* in KBr does not contain the band at 1660 cm^{-1} due to the C=N group which is observed in the spectrum of *(1)*; a new band at 3275 cm^{-1} can be ascribed to an N–H valence vibration. In solution at room temperature the hydroperoxide *(2)* is partially dissociated into starting components, but on heating for a short time at 80 °C in an inert solvent, *e.g.* benzene, it loses a molecule of water to yield pentamethylene-*N*-cyclohexyloxaziridine *(3)*.

The addition of hydrogen peroxide can also be effected with other Schiff bases; the products are invariably α-hydroperoxyamines *(4)*.



(4)

R	R^1	R^2	M.p. [°C]	Yield [%]
CH_3	H	cyclo-C_6H_{11}	69–73	77
C_2H_5	H	cyclo-C_6H_{11}	62–65	54
CH_3	CH_3	cyclo-C_6H_{11}	39–41	80
Pentamethylene		cyclo-C_6H_{11}	90–91	93
Pentamethylene		$C_6H_5CH_2$	86–89	81
Pentamethylene		C_6H_5	66–68	48

Received: May 3rd, 1965 [Z 974/800 IE]
German version: Angew. Chem. 77, 548 (1965)

[1] *H. Krimm*, Chem. Ber. *91*, 1057 (1958); *W. D. Emmons*, J. Amer. chem. Soc. *78*, 6208 (1956); *79*, 5739 (1957); *L. Horner* and *E. Jürgens*, Chem. Ber. *90*, 2184 (1957); *E. Schmitz* in *A. R. Katritzky*: Advances in Heterocyclic Chemistry. Academic Press, New York 1963, Vol. 2, p. 83.

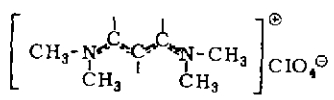
Photochemical trans-cis Rearrangement of Simple Polymethine Dyes. Determination of the Quantum Yield and Establishment of the Configuration Using the Oscillator Strength

By Prof. Dr. G. Scheibe, Dr. J. Heiss, and Dipl.-Chem. K. Feldmann

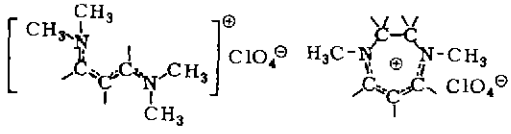
Gruppe „Strukturchemie" and Physikalisch-Chemisches Institut der Technischen Hochschule München (Germany)

Dyes containing polymethine chains can occur in different configurations, which are reversibly interconverted on irradiation with light of wavelength corresponding to the chief absorption band [1, 2]. The probable configuration of simple polymethine dyes is all-*trans*, and that of the photochemically produced dye is assumed to be mono-*cis* [3]. One may assume that in the excited singlet state, two parts of the molecule tend to be oriented at 90° to each other, so that the probabilities of obtaining the all-*trans* or a mono-*cis* form on return to the ground state are almost the same. According to this assumption, the quantum yield (based on one of the two forms) should be 0.5 or less. The value obtained [4] was 0.5 ± 0.1, independent of temperature within the limits of error between 130 and 220 °K. This means that a photorearrangement *via* metastable intermediates of both forms is very unlikely.

The configuration of the mono-*cis* form *(2)* produced photochemically from *(1)* was confirmed by synthesis of a di-*cis* form *(3)* and by calculation of the oscillator strengths f of the main absorption bands (see Table).



(1)



(2) *(3)*

	(1)	*(2)*	*(3)*
$\tilde{\nu}_{00}$ [cm^{-1}]	31800	29400	28400
f	0.63	0.47	0.27

The oscillator strengths calculated by the method of *H. Kuhn* [5] were found to be in good agreement with experimental values provided that a factor of two in *Kuhn*'s derivation is ignored. Comparison with previous results shows further that the oscillator strength is almost independent of whether the chromophore is partly built into an aromatic ring or not [6].

The synthesis of *(3)* is carried out as follows [7]: Equimolar amounts of 3-(*N*-methylanilino)prop-2-en-1-ylmethylphenylammonium perchlorate and *N,N'*-dimethylethylenediamine in methanol are added dropwise to a large volume of boiling methanol over a period of several hours, to give a final concentration of about 0.003 mole/l. The solution is concentrated (about 25 : 1), and *(3)* is precipitated with ether. After several recrystallizations from ethanol, the colorless crystals have m.p. 99.5 °C (yield 75 %).

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[1] *F. Baumgärtner, E. Günther*, and *G. Scheibe*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *60*, 570 (1956); *G. Scheibe*, Chimia *15*, 10 (1961).

[2] *F. Dörr, J. Kotschy*, and *H. Kausen*, Ber. Bunsenges. physik. Chem. *69*, 11 (1965).

[3] *W. Hoppe* and *F. Baumgärtner*, Z. Kristallogr., Kristallgeometr., Kristallphysik, Kristallchem. *108*, 328 (1957).

[4] *J. Heiss*, Ph.D. Thesis, Technische Hochschule München, 1964.

[5] *H. Kuhn*, Helv. chim. Acta *34*, 1308 (1951).

[6] *G. Scheibe, H. J. Friedrich*, and *G. Hohlneicher*, Angew. Chem. *73*, 383 (1961).

[7] *K. Feldmann*, Diploma Thesis, Technische Hochschule München, 1964.

Preparation of Oxaziridines from Olefins

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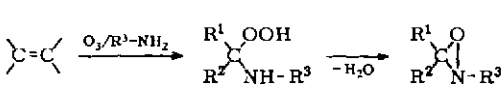
We have found that when olefins are ozonized in the presence of primary amines at −20 °C in carbon tetrachloride (molar ratio of olefin : amine = 1 : 1), oxaziridines *(2)* are formed *via* α-hydroperoxyamines *(1)*, which had already been postulated by other investigators [1] to occur during "amozonolysis". We managed to detect the α-hydroperoxyamines *(1)* [3] alongside *(2)* by thin-layer chromatography [2].



(1) *(2)*

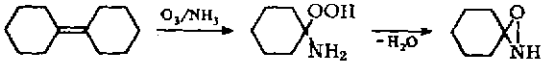
The oxaziridines *(2)* can be removed from the highly viscous products of ozonization by distillation *in vacuo*.

Ozonization of a mixture of 1-hexene and cyclohexylamine leads to crystalline *N*-cyclohexyl-*N*-(1-hydroperoxypent-1-yl)-amine *(1a)*, R^1 = n-C_4H_9, R^2 = H, R^3 = C_6H_{11}, m.p. 80 °C, in 20 % yield based on 1-hexene. When heated for 1 h in toluene at 80 °C, *(1)* was converted into n-butyl-*N*-cyclohexyloxaziridine *(2a)*.

Olefin	Amine	Oxaziridine *(2)*	Yield [%]	B.p. [°C/mm]	Purity [%]
1-Hexene	Cyclohexyl-amine	*(a)*, R^1 = n-C_4H_9; R^2 = H; R^3 = C_6H_{11}	33	70–72/0.01	97
1-Hexene	n-Butylamine	*(b)*, R^1 = n-C_4H_9; R^2 = H; R^3 = n-C_4H_9	23	58–61/0.01	93
1-Hexene	Isopropyl-amine	*(c)*, R^1 = n-C_4H_9; R^2 = H; R^3 = iso-C_3H_7	28	55–57/0.01	95
Tetramethyl-ethylene	Cyclohexyl-amine	*(d)*, R^1 = R^2 = CH_3; R^3 = C_6H_{11}	36	47–50/0.02	93 [4]
Tetramethyl-ethylene	Isopropyl-amine	*(e)*, R^1 = R^2 = CH_3; R^3 = iso-C_3H_7	25	32–34/0.1	94 [4]
Biscyclo-hexylidene	Cyclohexyl-amine	*(f)*, R^1–R^2 = $(CH_2)_5$; R^3 = C_6H_{11}	30	78–79/0.1	91 [4]

The ozonization reaction also leads to *N*-substituted amides in addition to *(2)*. After separation of *(2a)* and *(2b)* from the appropriate reaction products by vacuum distillation, *N*-cyclohexyl-n-valeramide, m.p. 208 °C, and *N*-n-butyl-n-valeramide, m.p. 181 °C, crystallize out of the residue in respective yields of 33 and 23 % based on 1-hexene.

Ozonolysis of biscyclohexylidene *(3)* in carbon tetrachloride at −35 °C in the presence of an equimolar amount of ammonia yields the isoxime of cyclohexanone *(5)*, which can be recovered in 18 % yield [based on *(3)*] in the form of its crystalline benzoyl derivative [5].



(3) *(4)* *(5)*

An unstable intermediate *(4)* can be detected by thin-layer chromatography.

Owing to the danger of explosions, not more than 0.5 g of olefin should be used, and all necessary precautions taken.

Received: May 3rd, 1965 [Z 975/801 IE]
German version: Angew. Chem. 77, 548 (1965)

[1] *M. J. Fremery* and *E. K. Fields*, J. org. Chemistry *29*, 2240 (1964).

[2] *A. Rieche* and *M. Schulz*, Chem. Ber. *97*, 192 (1964).

[3] Reference compounds of type *(1)* were made according to *E. Höft* and *A. Rieche*, Angew. Chem. *77*, 548 (1965); Angew. Chem. internat. Edit. *4*, 524 (1965).

[4] *H. Krimm*, Chem. Ber. *91*, 1057 (1958).

[5] This product is identical with that produced by *E. Schmitz*, *R. Ohme*, and *S. Schramm*, Tetrahedron Letters, in the press.

Photochemical Rearrangement of a Trimethinecyanine Dye from the all-trans Form to a mono-cis and a di-cis Form

By Dr. J. Heiss and Dipl.-Chem. K. Feldmann

Gruppe „Strukturchemie" and Physikalisch-Chemisches Institut der Technischen Hochschule München (Germany)

The cyanine dye *(1a)* [1] surprisingly shows the same absorption as the dye *(1b)* (in which there is no phenyl substituent in the meso position) except for the almost additively superposed benzene spectrum in *(1a)* around 10000 cm^{-1} [see Fig. 1: *(1b)* and *(1a₁)*]. This finding leads to the conclusion that the phenyl ring is perpendicular to the plane of the dye molecule and that therefore resonance cannot occur between the π-electron system of the ring and that of the cyanine system. When the dye *(1a)* is irradiated with light of wavelength corresponding to the principal absorption band this band disappears, accompanied as in previous investigations [2] by the appearance of a new band which is, however, displaced to unusually high wavelengths [cf. Fig. 1: *(1a₂)*]. This phenomenon can be explained with the assumption that a mono-*cis* form is obtained at first, as occurs with unsubstituted open-chain cyanines, and that the phenyl ring then turns into the plane of the dye because of the more favorable steric relationships. Resonance is then possible, which results in a red-shift of the absorption band by $\Delta\tilde{\nu}$ = 4700 cm^{-1}, compared with $\Delta\tilde{\nu}$ = 2500 cm^{-1} [3] for mono-*cis* forms of trimethinecyanines. When light corresponding to the new absorption band is now used, a further band displaced to high wavelengths appears [cf. Fig. 1: *(1a₃)*], which can be ascribed to the di-*cis* form, as could be confirmed by synthesis of a sterically fixed di-*cis* form [4]. Isosbestic points were found for both transformations which are completely reversible. The extinction of the original dye *(1a₁)* at the wavelength of maximum absorption is reduced by a factor of almost 100 during the rearrangement. These observations are readily made because the absorption maximum of *(1a)* almost coincides with the absorption minimum of the new dye [at 32000 cm^{-1} for *(1a₁)*, all-*trans*, ε = 54000, for *(1a₂)*, mono-*cis*, ε = 680]. Dyes of this kind could become

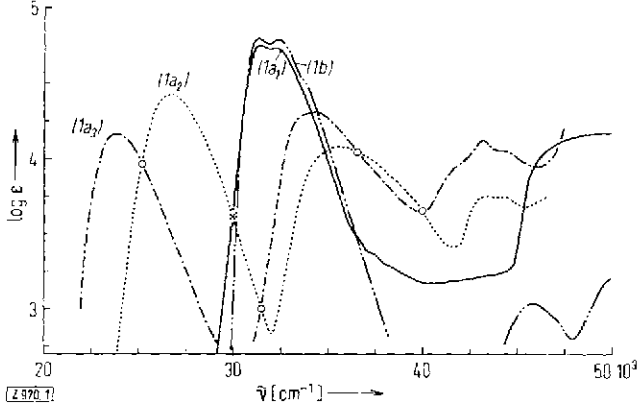


Fig. 1. Absorption spectra of the trimethinecyanine dyes *(1a)* [*(1a₁)*: all-*trans* form; *(1a₂)*: mono-*cis* form; *(1a₃)*: di-*cis* form] and *(1b)* [all-*trans* form].

× Isosbestic point for *(1a₁)* ⇌ *(1a₂)*.

○ Isosbestic points for *(1a₂)* ⇌ *(1a₃)*.

significant as passive Q-switches in the production of giant laser pulses [5].

Received: April 20th, 1965 [Z 970/796 IE]
German version: Angew. Chem. 77, 546 (1965)

[1] We thank Dr. *C. Jutz* for providing the dye.

[2] *F. Baumgärtner, E. Günther*, and *G. Scheibe*, Z. Elektrochem., Ber. Bunsenges. physikal. Chem. *60*, 570 (1956).

[3] *J. Heiss*, Ph.D. Thesis, Technische Hochschule München, 1964.

[4] Cf. *G. Scheibe, J. Heiss*, and *K. Feldmann*, Angew. Chem. *77*, 545 (1965); Angew. Chem. internat. Edit. *4*, 525 (1965).

[5] See, e.g., *F. P. Schäfer* and *W. Schmidt*, Z. Naturforsch. *19a*, 1019 (1964).

Course of the Microbial Conversion of Cobalamine Analogues into Vitamin B_{12} [1]

By Dr. P. Renz

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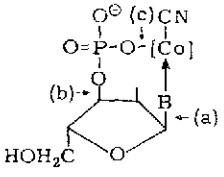
Dedicated to Prof. K. Bernhauer on the occasion of his 65th birthday

Cobamides containing various benzimidazole or purine bases, *e.g. (2)* or *(3)*, are converted into vitamin B_{12} *(1)* by *Propionibacterium shermanii* in the presence of 5,6-dimethylbenzimidazole [2].



(1), B = 5,6-Dimethylbenzimidazole
(2), B = Adenine
(3), B = Benzimidazole
[Co] = Cobinamide moiety

The bond (c) must remain intact during this process, for when [^{32}P]-adenylcobamide *(2)* [3] is transformed into *(1)* by *P. shermanii* [2], 93.5 % of the radioactivity recurs in *(1)*.

In order to differentiate between the two remaining possible positions of cleavage, *viz.* bonds (a) and (b), we synthesized [^{14}C]-benzimidazolylcobamide *(3)* from cobinamide, benzimidazole, and [u-^{14}C]-D-glucose using *P. shermanii*. It was shown by degradation with cerium hydroxide [5] that all the radioactivity [4264 counts/min/mg] was present in the ribosyl residue.

The vitamin B_{12} *(1)* formed from the ^{14}C-labelled *(3)* was not radioactive [2]. It must therefore be the bond (b) that is split during this transformation. The complete nucleoside is apparently replaced by preformed α-ribazole.

This conclusion is supported by the observation that α-ribazole can be detected in cultures [6] of *P. shermanii* and α-ribazole-5-phosphate in extracts [7] from the same microorganism.

Received: April 20th, 1965 [Z 977/803 IE]
German version: Angew. Chem. 77, 547 (1965)
Publication deferred until now at the author's request

[1] Biosyntheses in the Cobalamine Series, Part 7.-Part 6: *K. Bernhauer, E. Becher, G. Gross*, and *G. Wilharm*, Biochem. Z. *332*, 562 (1960).

[2] *K. Bernhauer, E. Becher*, and *G. Wilharm*, Arch. Biochem. Biophysics *83*, 248 (1959).

[3] Prepared from [32P]-cobinamide phosphate [4].

[4] *F. Wagner*, Biochem. Z. *336*, 99 (1962); *F. Wagner* and *D. Glatzle*, ibid., in the press.

[5] *W. Friedrich* and *K. Bernhauer*, Chem. Ber. *89*, 2507 (1956).

[6] *H. C. Friedmann* and *D. L. Harris*, Biochem. biophys. Res. Commun. *8*, 164 (1962).

[7] *H. C. Friedmann* and *D. L. Harris*, J. biol. Chemistry *240*, 406 (1965).

α-Aminoalkylation of White Phosphorus [1]

By Dr. Ludwig Maier

Monsanto Research SA., Zürich (Switzerland)

In continuation of studies on the direct synthesis of organophosphorus compounds from elemental phosphorus [2] we have found that the reaction of white phosphorus with *N*-hydroxymethyldialkylamines provides a simple method of preparing tertiary phosphine oxides. Phosphonic and phosphinic acids and sometimes even the tertiary phosphine are formed as by-products.

$$2\ P_4 + 19\ R_2NCH_2OH \rightarrow R_2NCH_2PO(OH)_2 + 3\ (R_2NCH_2)_2PO(OH) + (R_2NCH_2)_3P + 3\ (R_2NCH_2)_3P{=}O + 7\ H_2O$$

The yields of tertiary phosphine oxide depend upon the ratios of the reagents and upon the solvent used. The highest yield is obtained with a molar ratio phosphorus: *N*-hydroxymethyldialkylamine of 2:5 and with 50 % aqueous alcohol as solvent at 80 °C for 1-8 h; the phosphine oxide is isolated by extraction with benzene or ether and recrystallization from hexane or petroleum ether.

$(RR^1NCH_2)_3P{=}O$

R	R^1	M.p. [°C]	Yield [a] [%]	^{31}P-NMR chem.shift [ppm] [b]
CH_3	CH_3	158–159	44.6	
C_2H_5	C_2H_5	73.4–74.2	18.2 [c]	−43.2
cyclo-C_6H_{11}	cyclo-C_6H_{11}	214–215	3.2	
$-(CH_2)_4-$		151–153	35.0	
$-(CH_2)_5-$		119–120	37.2	−51.0 ± 0.5
$-CH_2CH_2OCH_2CH_2-$		160–161.3	20.3	−50.6

[a] Based on the amount of white phosphorus used.
[b] Based on 85 % H_3PO_4 as internal standard.
[c] In addition, 5.1 % $[(C_2H_5)_2NCH_2]_3P$, b.p. 110–115 °C/1.2 mm, was also isolated.

Received: May 7th, 1965 [Z 972/798 IE]
German version: Angew. Chem. 77, 549 (1965)

[1] Organophosphorus Compounds, Part 19.-Part 18: *L. Maier*, Helv. chim. Acta, in the press.

[2] *L. Maier*, Angew. Chem. *71*, 574 (1959); Helv. chim. Acta *46*, 2026 (1963).

A New Synthesis of γ-Pyrones

By Dipl.-Chem. H. Schiefer and Prof. Dr. G. Henseke

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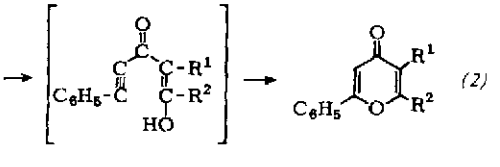
der Bergakademie Freiberg (Germany)

When phenylethynyl ketones *(1)* are acylated with carboxylic esters in the presence of strongly basic condensing reagents, *e.g.* sodium or sodium ethoxide, sodio derivatives of β-diketones are obtained which on protonation mostly cyclize immediately to γ-pyrone derivatives *(2a–g)*.

$$C_6H_5\text{-}C{\equiv}C\text{-}CO\text{-}CH_2\text{-}R^1 + R^2\text{-}COOC_2H_5$$

(1a), R^1 = H
(1b), R^1 = CH_3

$$\rightarrow C_6H_5\text{-}C{\equiv}C\text{-}CO\text{-}\underset{R^1}{CH}\text{-}CO\text{-}R^2$$



(2)

A mixture of 1 mole of ketone and 2 moles of ester is added dropwise within 1–4 h to a stirred solution in alcohol or ether of 2 moles of condensing agent. The whole is then left standing for 1–2 days at 0 °C. Alkaline alcoholic solutions are then acidified with alcoholic sulfuric acid, filtered, and concentrated *in vacuo*. If alcohol-free sodium ethoxide or metallic sodium in ether is used as condensing agent, the reaction mixture is subsequently treated with water, and the pyrone is isolated by acidification, extraction with ether, and vacuum sublimation of the residue left after evaporation of the ether from the extract. Compound *(2c)* is isolated as its picrate, made by boiling the β-dicarbonyl compound with picric acid in ethanol.

	R^1	R^2	Solvent	Condensing agent	Reaction temp. [°C]	Yield [%]	M.p. [°C]	Ref.
(2a)	H	$COOC_2H_5$	Alcohol	$NaOC_2H_5$	−15	75	118–119	[1]
(2b)	H	COOH	Ether	$NaOC_2H_5$	−15	80	238 (decomp.)	[1]
(2c)	H	H	Ether	$NaOC_2H_5$	0	40	103–104	[1]
(2d)	H	CH_3	Ether	$NaOC_2H_5$	0	25	86–87	[1, 2]
(2e)	H	$CHCl_2$	Ether	Na	−15	50	141–142	
(2f)	CH_3	H	Ether	$NaOC_2H_5$	−15	45	132–133	[3]
(2g)	CH_3	$COOC_2H_5$	Alcohol	$NaOC_2H_5$	0	40	127–128	
(2h)	CH_3	COOH	[a]				280 (decomp.)	
(2i)	H	CH_2Cl	[b]			90	124–125	
(2j)	H	CHO	[c]				121–122	

[a] Obtained from *(2g)* by hydrolysis with conc. HCl.

[b] Obtained from *(2e)* by refluxing in acetic acid for 1 h with $SnCl_2$.

[c] Obtained from *(2i)* via the pyridinium salt, m.p. 223–224 °C (decomp.), and the nitrone, m.p. 207 °C (decomp.).

The chlorine atoms in *(2e)* are very firmly attached and can be removed only under drastic conditions with simultaneous ring-opening. Catalytic hydrogenation of *(2e)* over palladium-charcoal in ethanol affords a 90 % yield of *(2d)*.

Received: April 8th and May 3rd, 1965 [Z 976/802 IE]
German version: Angew. Chem. 77, 547 (1965)

[1] *W. Borsche* and *W. Peter*, Liebigs Ann. Chem. *453*, 148 (1927).

[2] *S. Ruhemann*, J. chem. Soc. (London) *93*, 431 (1908).

[3] *W. Parker, R. A. Raphael*, and *D. I. Wilkinson*, J. chem. Soc. (London) *1958*, 3871.

CONFERENCE REPORTS

Colloquium on Macromolecular Chemistry

A Colloquium on Macromolecular Chemistry, organized by the Institut für Makromolekulare Chemie der Universität Freiburg/Breisgau, was held in Freiburg/Breisgau (Germany) on March 11–13th, 1965.

Chemical Synthesis and Biosynthesis of Coding Nucleic Acids

F. Cramer, Göttingen (Germany)

Condensation of thymidylic and adenylic acids with picryl chloride, *N,N*-dimethylformamide dichloride, $(CH_3)_2NCHCl_2$, or dicyclohexylcarbodiimide leads to oligothymidylic acids and oligoadenylic acids containing up to 20 units per chain. Dinucleotides and trinucleotides of the deoxy series can be condensed analogously to give oligodoublets and oligo-triplets. The method was used to make (pCpT)n and $(pGpApT)_n$. Some of the oligonucleotides prepared can be used for coding, *i.e.* in enzymatic tests they function as templates for the synthesis of "copied" deoxyribonucleic acids or messenger ribonucleic acids.

When protective groups are used, oligoribonucleotides also can be synthesized; the largest molecule of this type made so far is a trinucleoside diphosphate, *viz.* UpUpC. The enzyme polynucleotide phosphorylase was used to make mixed polynucleotides, for example poly-UG (79:1) This ribonucleic acid is cleaved by T_1 ribonuclease adjacent to the guanylic acid residues exclusively, yielding UpUp....UpG, a polynucleotide with the terminal triplet UUG. When this polynucleotide is used for ribosome adaptation, it codes the amino acid leucine, which proves that UUG is the code triplet for leucine.

On the Chemistry of the Recombination of Insulin Chains to Give Biologically Active Insulin

H. Zahn, B. Gutte [*], and *O. Brinkhoff*, Aachen (Germany)

Crystallized bovine insulin was reduced in urea solution with mercaptoethanol at pH 5. The mixture of SH-chains was oxidized with air at pH 9 and 4–8 °C and dialysed. Gel filtration on Bio-Gel P-150 in ammonium hydrogen carbonate buffer of pH 8.15 gave in 50 % yield a fraction with a molecular weight of about 140000. In this fraction, the proportion of B-chains was 70 % (determined by amino acid analysis, amperometric disulfide analysis, and lysine analysis with the FDNB method [1]). In the position of native insulin, the recombination product was found in only 5 % yield. In the last peak, the content of A-chains is higher. The main reason for the low yield on recombination of reduced A- and B-chains appears to be the formation of polydisulfides from B- and A-chains.

Du, Jiang, and *Tsou* [2] achieved yields of 50 % on the renaturation of insulin. Presumably polymerization is prevented here by the high pH of 10.6, since according to *Fredericq* [3] insulin does not aggregate at this pH.

Using another route up to 44 ± 14 % yields of insulin were obtained, as determined on the basis of the oxydation of

[*] *B. Gutte*, Diploma Thesis, Technische Hochschule Aachen 1964.

[1] FDNB = fluorodinitrobenzene.

[2] *Y.-C. Du, R.-Q. Jiang*, and *C.-L. Tsou*, Scientia Sinica (Peking) *14*, 229 (1965).

[3] *E. Fredericq*, Nature (London) *171*, 570 (1953).

glucose in rat adipose tissue: The reduced A-chain alone was oxidized with air at pH 8.8 for the time necessary in order to give an optimum yield of biologically active insulin on subsequent combination with the reduced B-chain. In one experiment, the regenerated activity was optimum after 60 min of preoxydation, in another after 100 minutes.

On gel-filtration on Sephadex G-25, these products of renaturation give a definite peak in the position expected for native insulin. They can also be extracted with acid/sec-butanol according to the method of *Du* et al. [4]. The yield of insulin crystals was about 20–25 % of the total activity.

Oligomerization of Peptides by Enzymatic Catalysis

H. Determann, Frankfurt/Main (Germany)

In the reverse reaction of peptide proteolysis, only condensation products of relatively low molecular weight are obtained when well-defined oligopeptides are used in the "plastein reaction"

oligopeptide $\xrightarrow{\text{pepsin}}$ polypeptide.

Thirty such peptide "monomers" – mostly pentapeptides – with acidic, basic, or neutral character, of very good to good solubilities, and with various amino acids in the chain and at the ends, gave rise to mixtures of homologous oligomers, provided they could be condensed at all. Earlier, however, the formation of protein-like macromolecules from protein hydrolysates of complex composition had been reported. Hydrolysates of this type were now separated according to molecular weight on Sephadex G-25; subsequent treatment of the low molecular-weight fractions with pepsin also produced only low molecular-weight plasteins. It is probable that the products of high molecular weight described in the older literature – where they are already contested – are to be explained by inclusion of larger aggregates in the peptide mixture used, or by association. – The specificity of pepsin for hydrolysis and condensations is the same with regard to the carboxyl groups involved. Attempts were made to explain the premature standstill that occurs in the condensation reaction on the basis of thermodynamic considerations and an assumption of the mechanism of pepsin catalysis.

Specific Polysaccharides of Enterobacteria

O. Westphal, O. Lüderitz, Barbara Jann, and *K. Jann*, Freiburg/Breisgau (Germany)

Comparative analyses of the cell-wall lipopolysaccharides of the S-forms of over one-hundred strains of *Salmonella* and as many *Escherichia coli* strains indicated that these bacteria can synthesize a large number of monosaccharides, including hitherto unknown deoxyhexoses and aminohexoses, and build them into their highly branched polysaccharides. All these polysaccharides are constructed according to the same principle: there is a main chain of poly(heptose phosphate) to which long side-chains are attached, which in turn may be branched. They are the carriers of the immunological species specificity (serotypes). The structures of the side chains were determined by chemical, immunochemical, and biochemical procedures; valuable information was derived from studies of mutants (R-forms) with enzyme blocks (of synthetases and transferases) in the polysaccharide biosynthesis. Serological and chemical analysis of the R-forms revealed that all the polysaccharides from *Salmonella* S-forms (wild strains) have a common basic skeleton (basal polysaccharide) in which short oligosaccharide chains containing glucose, galactose, and glucosamine are linked to poly(heptose phosphate). In S-forms, the recurrent units of the long O-specific side chains are attached to the terminal glucosamine residue of the basal polysaccharide.

Chemical and genetic classification of *Salmonella* and other enterobacterial genera will be possible on the basis of the structure of the recurrent oligosaccharide units and their structural variation. On treatment with phages, various structures can be transformed into others (lysogenic conversion). In this way, the serological classification (Kauffmann-White scheme) is supplemented by a biochemical-genetic system of classification.

Many strains of *E. coli* form not only cell-wall (lipo)polysaccharide (O-antigen) but also a capsule antigen (K-antigen), which forms a layer on the cell wall over the O-antigen. Many, but not all K-antigens have been found to be long-chain polysaccharides containing uronic acids. The structural principle of some K-antigens and the structures of their determinant group(s) were determined. – In addition to O- and K-antigens, mucoid coli bacteria produce another mucoid substance (M-antigen; called colanic acid by *W. F. Goebel*), which is also an acidic polysaccharide. With the aid of the phenol/water procedure, all the polysaccharides can be extracted from the bacteria and can then be separated with Cetavlon® [5] into purified K- and M-antigens (acidic polysaccharides) and O-antigen (lipopolysaccharide). Highly diverse sugar monomers can be involved in the construction of the K-, M-, and O-specific polysaccharides from one and the same bacterium.

An Enzymatic Method for Kinetic Investigations of Endohydrolases: Assay of the Activity of α-Amylase

R. Werner and *G. Keilich*, Freiburg/Breisgau (Germany)

The kinetics of the degradation of polysaccharides by endohydrolases – which split the macromolecule within the chain – normally can be studied accurately only if the alterations in molecular weight are followed. Determination of the number-average molecular weight is possible with the aid of an exohydrolase, which splits off single monomers from the chain ends, because the rate of reaction of the exohydrolase depends on the number of end groups available. Since the action of the endohydrolase gives rise to new end groups, the rate of the exohydrolase reaction increases; its acceleration is therefore a measure for the activity of the endohydrolase.

This new method for assaying endohydrolases was illustrated with α-amylase. The exohydrolase used was a polysaccharide phosphorylase. Its rate of reaction can be measured by determining spectrophotometrically the glucose-1-phosphate formed using phosphoglucomutase and glucose-6-phosphate dehydrogenase. The activity of the α-amylase is expressed directly in international units, namely μmoles of glucosidic bonds hydrolysed per minute. The method can in principle be applied to any endohydrolase, provided specific exohydrolases are known for its substrate.

The Molecular Weights of Native Dextrans

K. Ebert, München (Germany)

On the basis of determinations carried out in the ultracentrifuge or by light scattering, extremely high values, *viz.* about 5×10^8, had been obtained for the molecular weights of native dextrans. According to molecular kinetic estimations, based on the molecular activity of the synthesizing enzymes, such large molecules should be formed only after prolonged reaction times.

A method was developed for measuring the number-average molecular weights (M_n) of native dextrans: the terminal saccharose grouping is split off with an enzyme and the resulting aldehydic end group is reduced with tritium-labelled lithium

[4] *Y.-C. Du, Y.-S. Zhang, Z.-X. Lu*, and *C.-L. Tsou*, Scientia Sinica (Peking) *10*, 84 (1961).

[5] Cetyltrimethylammonium bromide.

borohydride; the specific radioactivity can then be correlated to M_n. In this way, M_n values of around 2×10^5 were obtained for dextrans formed at low substrate concentrations. These values are in agreement with the results of fractionation in a Baker-Williams column. The higher values previously found are ascribed to aggregates.

Kinetic Studies on the Biosynthesis of Cellulose

M. Marx-Figini, Mainz (Germany)

The amounts of cellulose and its degree of polymerization in hairs from cottonseed at different stages of ripening were determined and correlated with the age of the seeds.

The results showed that the biosynthesis of cellulose proceeds in two phases. In the first phase, the synthesis is slow, and only little cellulose is formed. The majority is produced during the second stage, which starts spontaneously; here the synthesis proceeds much faster. The assignment of the first and second phase to the formation of the primary and secondary cell wall, respectively, was confirmed by the values found for the degrees of polymerization (D. P.) and by the swelling properties of the seed hairs, the longitudinal growth, and the amount of non-cellulosic materials formed at the various stages of maturity.

The DP increases by almost one order of magnitude on passing from the first to the second reaction phase and then remains constant throughout the entire synthesis of the secondary cell wall. It is independent of the conversion and the rate of reaction and is practically completely uniform. It must therefore be concluded that during the biosynthesis of cellulose in higher plants, templates ensure the maintenance of a constant DP.

Model Concepts of Cellulose Synthesis and of the Formation of Plant Cell Walls

G. V. Schulz, Mainz (Germany)

The studies of *M. Marx-Figini* (see report above) make it appear probable that the biosynthesis of cellulose is controlled by templates. Attempts were made to develop concepts as to the nature of the synthesizing system on the basis of the properties of cellulose and of morphological observations. It follows from the molecular weight that the template must be about 5×14000 Å $= 7\,\mu$ long.

Electron micrographs of cell walls (*Frey-Wyssling*, *Mühlethaler*, *Preston*) reveal that the secondary cell wall consists of fibrils of uncertain lengths and with diameters between 50 and 150 Å. These are arranged parallel in layers which cross at definite angles. This structure excludes the possibility that cellulose molecules synthesized on the template are released directly into the cell plasma. If this were so, the long glucosidic chains would fold up into single molecule crystals (*Bittiger* and *Husemann*), which could afterwards hardly combine to form fibrils and become properly oriented in the highly organized tissue of the secondary cell wall. Moreover, a simple calculation, and degradation experiments carried out with cellulose (*Rånby*), have made it appear likely that the crystallographic micelle described by *Hengstenberg* and *Mark* [ca. $50 \times 100 \times (\leqslant 600)$ Å^3] is in reality a folded single molecule and that the fibrils are linear sequences of folded molecules.

By consideration of the electron-microscopical observations of *Mühlethaler* and *Ledbetter*, a mechanism is proposed for cellulose synthesis which incorporates three partial processes: (1) synthesis, (2) fibril formation (spinning process), and (3) deposition of fibrils in criss-cross layers (weaving process). The template occurs (stretched or spirally coiled) in a pipe- or tube-like structure. The interlinking of the glucose units begins at one end in such a way that a continuously folding chain molecule is formed which on completion reaches the other end of the tube in the form of a "folded package". There the loops of the folds become inserted into those of the end of the fibril already present there, and are bonded by hydrogen bridges. The layers of parallel fibrils result because a system of synthesis tubes slides along the cell wall, carried along by the flow of the cell plasma.

Fractionation of High Molecular-Weight Materials on Silica Gels Having a Defined Cavity Structure

H. W. Kohlschütter, Darmstadt (Germany)

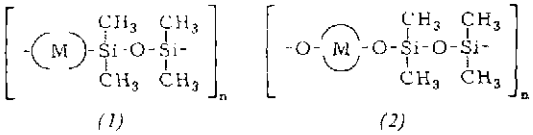
In connection with systematic investigations of the structural material, the cavity systems, the surface, and the natural grain formation of silica gel, high molecular-weight polystyrenes dissolved in chloroform were fractionated and polystyrene/paraffin mixtures were separated on silica gel columns. The separations are occasioned by partition of the dissolved materials between the mobile phase of the solvent flowing around the silica gel grains and the quasi-stationary phase of the solvent entrained within the large pores in the grains. The partition of the dissolved materials and the separatory efficiency of the column can be related by a simple equation. The chromatograms were evaluated with the aid of molecular-weight determinations. The component with the highest molecular weight correponds to the smallest, that with the lowest molecular-weight to the greatest retention volume. The efficiency of the columns increased when silica gel preparations with larger specific pore volumes were used.

The same silica gel preparations were used to separate inorganic salts and colloids in aqueous solutions. Analogous relationships were found between the particle weights and the retention volumes, and between the specific pore volume of the silica gel and the separatory efficiency of the columns.

Polychelated Siloxanes

A. Hofer [†], *H. Kuckertz*, and *M. Sander*, Frankfurt/Main (Germany)

Polymethylsiloxanes of types *(1)* and *(2)* containing metal chelate groups were synthesized in various ways. Type *(1)* compounds contained mainly M = Be or Al with β-diketones (acetylacetone) as chelating agents. The siloxanes containing



(1) *(2)*

beryllium attain a viscosity number of 0.4 dl/g, are solid at room temperature, and have a broad plasticity range between 60 and 200 °C. They decompose above 170 °C, the main pyrolysis gas being methane.

Type *(2)* compounds could be obtained only with titanium chelates (8-hydroxyquinoline). These polymers are generally brittle up to 100 °C. Above 200 °C, rearrangements of Si–O–Ti bonds to Si–O–Si and Ti–O–Ti bonds occur.

The Preparation and Polyaddition Reactions of Ferrocene Derivatives with Two Dimethylsilyl Groups

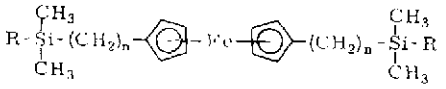
G. Greber and *M. L. Hallensleben*, Freiburg/Breisgau (Germany)

Reduction of 1,1′-bisdimethylethoxysilylferrocene and 1,1′-bis(dimethyl-n-butoxysilylmethyl)ferrocene with $LiAlH_4$ leads to good yields of 1,1′-bisdimethylsilylferrocene *(1a)* and 1,1′-bis(dimethylsilylmethyl)ferrocene *(1b)*, respectively.

In the presence of H_2PtCl_6 as catalyst, these add onto acetylene to form 1,1′-bis(dimethylvinylsilyl)ferrocene *(2a)* and 1,1′-bis(dimethylvinylsilylmethyl)ferrocene *(2b)*, respectively.

[†] Since deceased.

Polyaddition of *(1a)* and *(2a)* or of *(1b)* and *(2b)* as well as of *(1a)* or *(1b)* and other organosilicon compounds containing two alkenylsilyl end groups or of *(2a)* or *(2b)* and other organosilicon compounds containing two terminal H—Si groups



(1a), n = 0, R = H

(1b), n = 1, R = H

(2a), n = 0, R = $-CH=CH_2$

(2b), n = 1, R = $-CH=CH_2$

affords thermostable polymers containing ferrocene residues as links in the main chain. Depending on the ratio of the reagents used, the end groups in the final product may be either two hydrosilyl or two alkenylsilyl moieties.

On heating for 6 h at 300 °C, polyadducts made from *(1a)* and *(2a)* decrease in weight by only 0.1 %, whereas those from *(1b)* and *(2b)* by about 5 %.

Polymeric Reaction Products Made from Formaldehyde and Nitriles Containing Activated Methylene Groups

W. Funke, Stuttgart (Germany)

When phenylacetonitrile is condensed with formaldehyde in methanol in the presence of sodium methoxide as catalyst, liquid or crystalline polymeric products of relatively low molecular weights are obtained, depending on the molar proportions of the reactants and on the reaction conditions. Insoluble polymers are obtained similarly from phenylenediacetonitrile.

Experiments with low molecular-weight model substances based on phenylacetonitrile revealed that under the conditions used, the condensation reaction leads first to α-cyanostyrene and that it depends largely on the ratios of coreactants and on the temperature whether this product undergoes a Michael addition with unchanged phenylacetonitrile to form 2,4-diphenylglutarodinitrile or whether an anionic polymerization occurs in which low molecular-weight poly-α-cyanostyrene is formed as a result of premature chain termination. The polymers obtained contain methoxy and some hydroxymethyl end groups. In addition, some terminal nitrile groups are converted into imino ether groupings.

Oligomers Obtained in Cationic and Anionic Polymerization of ε-Caprolactam

M. Rothe, Mainz (Germany)

The mechanism of the cationic and anionic polymerization of ε-caprolactam and the structures of the resultant polymers were studied using oligomers of uniform molecular size [6]. Reaction of ε-caprolactam for short times with equimolar amounts of initiator (in cationic polymerization: HCl, sulfonic acids, ortho-, pyro-, or polyphosphoric acid, or BF_3-H_2O; in anionic polymerization: Na lactamate plus *N*-acyl-ε-caprolactam) yielded mixtures of oligomers which were separated by chromatography and electrophoresis; the products were studied by spectroscopy and identified by comparison with authentic synthetic samples of caprolactam oligomers.

On cationic polymerization, oligo-(ε-aminocaproyl)caprolactams up to the hexamer were detected and isolated on a micropreparative scale. Their structures were confirmed either by their synthesis from *N*-protected oligoaminocaproyl chlorides and caprolactam with subsequent removal of the protecting group (carbobenzoxy or azido residues) or by their reaction with hydroxylamine, which cleaves off the terminal lactam rings to give the corresponding oligoaminocaproylhydroxamic acids. The chain initiation and chain growth reactions were studied using the model reaction between caprolactam and *N*-methylacetamide hydrochloride, which gives rise to acetylcaprolactam and oligo(aminocaproyl)-*N*-methylacetamides.

In anionic polymerizations, the first three members of the series of *N*-acetyloligo(aminocaproyl)caprolactams were detected. In order to test for branching, bis-(ε-aminocaproyl)-ε-aminocaproic acid was synthesized.

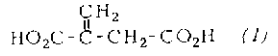
Cationic and anionic lactam polymerization lead *via* different mechanisms to polymers with the same lactam end-groups.

[6] In collaboration with *H. Boenisch, D. Essig, K. Gehrke, G. Reinisch*, and *I. Rothe*.

Radical Polymerization of Itaconic Acid

D. Braun and *I. A. Aziz El Sayed*, Darmstadt (Germany)

During free-radical polymerization of itaconic acid



(1)

the carboxyl group content in the polymerizing system decreases in proportion to the amount of polymer formed. At the same time, carbon dioxide is liberated to an extent independent of the nature of the initiator and of the solvent. The polymers have only about one-half of the carboxyl group content to be expected for poly(itaconic acid). — In free-radical copolymerizations of itaconic acid, carbon dioxide is also evolved.

The carbon dioxide liberated originates from the primary carboxyl group in the monomer *(1)*; no carbon dioxide is released during the polymerization of the corresponding monoester of itaconic acid.

Analytical and spectroscopic investigations of the polymers yield some information concerning their structures. Subsequent reactions of the carboxyl radicals split off give rise to hydroxyl and formyl radicals during the polymerization, and some of these are incorporated into the polymer and can later be determined therein.

The mechanism of the free-radical polymerization of itaconic acid is not yet completely explained, but model reactions permit conclusions to be drawn as to the nature of the course of reaction.

Metal Chelate Complexes as Polymerization Initiators

N. Naarmann, Ludwigshafen/Rhein (Germany)

Metal chelates (acetylacetonates) can be used to initiate vinyl polymerizations.

The efficiency of the complexes as initiators depends on the central atom and on the complexing ligand, as illustrated by the polymerization of styrene. Manganese(III) and cobalt(III) chelates of aliphatic β-dicarbonyl compounds are the most effective.

The metal chelate initiators can be activated by high-energy radiation or by combination with cocatalysts such as organic halogen compounds (*e.g.* n-amyl chloride) or polyunsaturated hydrocarbons (*e.g.* cyclooctadiene).

Several findings indicate a free-radical mechanism. The central metal atom influences the steric structure of the polymer chains. Thus the content of *cis*-1,4-residues in polybutadiene is particularly large when the chelated metals have ionic radii of 0.6—0.7 Å. A minimum content of *cis*-1,4-linkages occurs when the ionic radius lies around 1.0 Å.

Emulsion polymerization of butadiene with metal chelate complexes as initiators gives polymers with significantly higher contents of *cis*-1,4-configurations and correspondingly low glass transition temperatures.

Graft Polymerization of Vinyl Compounds onto Ethylene/Vinyl Acetate Copolymers

H. Bartl and *D. Hardt*, Leverkusen (Germany)

Because of their active hydrogen atoms, ethylene/vinyl acetate copolymers form good bases for graft polymers. They were used as substrates for graft polymers with vinyl acetate, acrylic and methacrylic esters, acrylonitrile, styrene, vinylidene chloride, and vinyl chloride. The greatest amount of grafting is achieved by using the technique of suspension polymerization; here the ethylene/vinyl acetate copolymer is dissolved in monomer, the solution is dispersed in water containing a protective colloid, and allowed to polymerize.

The tendency towards graft polymerization is proportional to the activity of the monomer radicals (under comparable conditions): vinyl chloride captures the greatest amounts of substrate, and the acrylic esters and acrylonitrile respectively less; styrene has only a very low capacity for grafting on ethylene/vinyl acetate copolymers.

The physical properties of the graft copolymers depend largely on whether the final products are mutually compatible. Styrene graft polymers have a low compatibility, while vinyl chloride graft polymers are compatible at all compositions and even in admixture with pure poly(vinyl chloride). Graft copolymers with high vinyl chloride contents have properties akin to hard poly(vinyl chlorides) of high impact strength, while those with high substrate contents are similar to soft poly(vinyl chlorides).

Polymerization of Formaldehyde by Adsorbed Water

G. Schröder, Darmstadt (Germany)

If anhydrous gaseous formaldehyde is passed into a suspension of an inorganic salt in a hydrocarbon, high molecular-weight polyoxymethylene dihydrates are obtained under certain conditions. Experimental findings lead to the conclusion that the polymerization proceeds by an anionic mechanism. The reaction is started at the crystal surface by the water adsorbed there. Although the polymer deposited is compact, the inorganic salt can be readily extracted with water.

This process has the following technical advantages over the polymerization of formaldehyde in the presence of tertiary amines:

1. Because of the compactness of the polymer formed, reactors of a given capacity can be used more economically.

2. Any traces of catalyst remaining in the polymer do not accelerate degradation of the polymer during subsequent processing.

3. The demands placed on the purity of the monomer and solvents in order to attain technically utilizable molecular weights are less stringent.

Transfer Reactions during the Cationic Polymerization of Trioxane

V. Jaacks, Mainz (Germany)

During the cationic polymerization of trioxane in the presence of low molecular-weight esters, anhydrides, acetals, or readily hydrolysable ethers, transfer reactions occur leading to thermostable polyoxymethylenes containing ester or ether end-groups. Analogous transfer reactions can also occur at the C–O–C groups of high molecular-weight polyesters, polyethers, or polyacetals. The products are then thermostable block or graft polymers, depending on whether the transferring group is in the main chain of the polymer, as for example in poly-1,3-dioxolane or poly(ethylene terephthalate), or in a side group as in poly(vinyl acetate). The influence exerted on the transfer reaction by water was discussed.

It is surprising that polyoxymethylenes stable to heat and alkalies are obtained in yields up to 65 % of the total products during homopolymerization of highly purified trioxane as well; this is ascribed to intramolecular transfer reactions.

Copolymerization of Formaldehyde with Cyclic Formals

H.-D. Hermann, Frankfurt/Main-Höchst (Germany)

Formaldehyde was copolymerized with cyclic formals in the presence of cationic catalysts. Pure monomeric formaldehyde was passed into an inert hydrocarbon in which the catalyst was dissolved, the comonomer being added simultaneously. Series of experiments were conducted by varying the polymerization temperature between −20 and +80 °C, the catalyst concentration between 0.01 and 0.2 % by weight (based on the monomers), and the comonomer concentration between 2 and 20 % by weight. The comonomers used were 1,3-dioxolane, 1,3-dioxane, 1,3-dioxacycloheptane, 1,3,6-trioxacyclooctane, and 1,3-dioxa-5-cycloheptene. The catalysts were $TiCl_4$, $BF_3{\cdot}(C_4H_9)_2O$, $SbCl_5$, and $SnCl_4$.

The copolymerization did not follow the equation of *Mayo* and *Lewis*. It is striking that the incorporation of comonomer is favored by increase in temperature and catalyst concentration. The nature of the catalyst is also an important factor influencing the composition of the copolymer. Antimony pentachloride and tin tetrachloride proved to be particularly effective catalysts.

Chemically uniform copolymers of high molecular weight, stable towards alkali, were obtained only over a restricted range of polymerization conditions, *e.g.* from formaldehyde plus 10 % by weight of 1,3-dioxacycloheptane with about 0.05 % by weight (based on monomers) of $SnCl_4$ at 60–80 °C.

The anomalous behavior of the copolymerization reaction is explained by transacetalizations between polymer molecules. This transacetalization [7] is promoted by increases in temperature and catalyst concentration, and its occurrence is proved by the fact that a uniform copolymer was obtained on polymerization of formaldehyde in the presence of a prepolymer containing formal groups.

Synthesis and Autoxidation of Poly(vinylthiol)

W. H. Daly, *K. Burg*, and *C. G. Overberger*, Brooklyn New York (U.S.A.) and Mainz (Germany)

S-Vinyl-*O*-t-butyl thiocarbonate was produced by simultaneous esterification and dehydrohalogenation of *S*-(β-chloroethyl) chlorothioformate with potassium t-butoxide. On polymerization with free-radical initiators, it yielded poly-(*S*-vinyl-*O*-t-butyl thiocarbonate), which was transformed into poly(vinylthiol) by removal of the t-butoxycarbonyl groups either by treatment with anhydrous hydrogen bromide or by thermolysis of the thiocarbonate substituents. The course of the latter reaction is analogous to that of the decomposition of methyl xanthate according to *Tschugaeff*.

The autoxidation of poly(vinylthiol) to the disulfide was studied in dimethyl sulfoxide using ferric sulfate as catalyst. The rates of oxidation of low molecular-weight dithiols were measured under standardized conditions and compared with that of the polymer; the following sequence of reactivities was observed: poly(vinylthiol) > 2,4-pentanedithiol > 2,5-hexanedithiol > 2,6-heptanedithiol. The reaction was of the

[7] *Cf. K. Weissermel, E. Fischer, K. Gutweiler*, and *H. D. Hermann*, Kunststoffe *54*, 410 (1964).

first order with respect to the Fe(III) ion and zero order with respect to the thiol content of the dithiols within the concentration range examined. A redox reaction between an Fe(III)- and an Fe(II)-thiol complex is postulated as a step of the autoxidation. The oxidation of the poly(vinylthiol) was not independent of the thiol concentration. Shielding of mercapto groups within the polymer coil and their reduced mobility may be possible explanations.

Investigations on the Molecular-Weight Jump Reaction of 1,4-cis-Polybutadiene

W. Ring and *H.-J. Cantow*, Marl (Germany)

The stereospecific polymerization of butadiene according to *Ziegler* to give *cis*-polybutadienes with a catalyst system containing an organocobalt and an organoaluminum compound occurs in homogeneous solution. Limits are set to the technical polymerization by the increase in viscosity resulting from the progress of the reaction and the increase in molecular weight of the polymer. However, an increase in molecular weight can be achieved after conclusion of the polymerization by adding reagents such as alkyl or acyl halides [8].

The mechanism of this molecular-weight jump reaction and its influence on the structure of the molecules was studied. It was shown that a cationic reaction mechanism is involved by using [^{14}C]-t-butyl chloride as reagent for boosting the molecular weight, by determining the molecular-weight distribution using a Baker-Williams column, and by viscometry and light-scattering photometry.

The average molecular weight, the distribution of molecular weights, and the molecular configuration can be controlled by selecting suitable reaction conditions.

Oxidation of Transition Elements by Organic Halides; Detection of Radicals by Polymerization Kinetics

G. Henrici-Olivé and *S. Olivé*, Zürich (Switzerland)

Colloidal suspensions of transition elements in tetrahydrofuran undergo electron transfer reactions with organic halides such as carbon tetrachloride or benzyl chloride. The metal is oxidized, *e.g.* $Co^0 \rightarrow Co^{2\oplus}$, and the carbon-halogen bond is split, giving rise to a free radical capable of initiating the polymerization of vinyl compounds.

Polymerization of methyl methacrylate was started in this way with the following metals: V^0, Cr^0, Fe^0, Co^0, Ni^0, and Pt^0. The free-radical mechanism of the polymerization was proved by the observed validity of the usual rate equations for free-radical kinetics and by copolymerization of methacrylate and styrene.

The rate of formation of the free radicals can be estimated from the overall rate of polymerization by following the reaction dilatometrically, and is different from one metal to another. For example, under comparable conditions at 90 °C, it is at least 300 times slower for vanadium than for cobalt.

Consequently, the polymerizations can be carried out with V^0 at this temperature to high conversions with a practically constant free-radical concentration, whereas the concentration of free radicals from Co^0 falls off with a half-life of 4–5 min.

Some New Aspects for the Quantitative Interpretation of Flow Birefringence

H. Janeschitz-Kriegl and *U. Daum*, Delft (Holland)

The flow properties of solutions of macromolecular substances are generally characterized by two phenomena: a) the dependence of the viscosity on the velocity gradient, and b) the occurrence of elastic stresses.

Investigation of flow birefringence proves to be a powerful tool for appraisal of the elastic properties. With this technique, the average coil expansion occurring during flow can be determined for dilute solutions at least [9]. This parameter can be considered as a (reduced) contribution of the individual molecules to the (elastic) tensile stress in the direction of flow. The experimental results obtained with solutions of anionically prepared polystyrenes show that the theory developed by *Zimm* [10] for the dynamic behavior of macromolecules applies up to an expansion which corresponds to an average increase in the end-to-end distance of about 10 % (relative to the value at rest). Surprisingly, even for these small expansions, tensile stresses can be expected in dilute solutions of a magnitude corresponding to viscometrically determined shearing stresses.

The situation becomes more complicated with polydisperse substances. The coil expansion corresponding to the tensile stress becomes an effective parameter which can be referred to the average expansion of the molecules with the aid of a polydispersity factor (*Peterlin*). The polydispersity factor increases sharply as the molecular-weight distribution becomes wider. When the distribution of molecular weights is broad, it also depends critically on the form of the distribution function. For example, the applicability of a Schulz distribution could be excluded for Marlex 5065 – a linear polyethylene – on the basis of the flow birefringence of its solution in *trans*-decalin at 135 °C.

Crystalline Compounds of Poly(ethylene oxides) and Polyesters with Urea and Thiourea

A. Kohler, *G. Hild*, and *R. Mayer*, Strasbourg (France)

Crystalline adducts of urea with poly(ethylene oxide), its derivatives containing end groups, or its block copolymers, are formed in a heterogeneous reaction on saturation of crystalline urea with a solution of the polymer in benzene. On the average, these adducts contain 28 % poly(ethylene oxide).

These compounds have a hexagonal crystal lattice which however does not resemble that of the channel-like inclusion compounds of urea.

Thiourea behaves similarly, but the content of poly(ethylene oxide) in its adducts is much higher.

Adducts of urea with polyesters are obtained in both heterogeneous and homogeneous media. They have a maximum polymer content of 33 % and belong to the hexagonal crystal system which characterizes the classical inclusion compounds of paraffins in urea.

We can now interpret the fractionation of polyesters on urea observed by *W. Kern* as being due to selective addition of the urea to the polymer fractions with the highest molecular weights. Poly(ethylene oxides) can also be fractionated by formation of their urea adducts.

Chlorinated Poly(vinyl chloride)

W. Trautvetter, Troisdorf (Germany)

The technical chlorination of poly(vinyl chloride) is carried out mainly by two methods: 1. in solution, and 2. in gels made by swelling PVC in a non-solvent. The products have the same chlorine contents but different properties (shape retention, solubility, stability, *etc.*).

The causes for the differences in properties were investigated, assuming that chlorinated products with approximately equal amounts of $-(CH_2-CHCl)-$, $-(CHCl-CHCl)-$, and $-(CH_2-CCl_2)-$ units are formed by both processes. Cross-linking during the chlorination of the gels or great non-

[8] *E. F. Engel*, Marl (Germany), 3rd International Synthetic Rubber Symposium, London, October 13-15th, 1964.

[9] *A. Peterlin*, J. chem. Physics *39*, 224 (1963).

[10] *B. H. Zimm*, J. chem. Physics *24*, 269 (1956).

uniformity in the degree of chlorination as possible explanations may be excluded. It is probable that products are formed during the chlorination in gels with great differences in the lengths of the sequences of the three basic structural units.

Elucidation of the Microstructure of Polymers by Nuclear Magnetic Resonance Spectroscopy

U. Johnsen, Darmstadt (Germany)

The proton resonance spectra of vinyl polymers with a simple α-substituent are much easier to analyse when the coupling between the α- and β-protons is cancelled by double resonance. This method was used to elucidate the microstructures of some poly(vinyl chlorides).

The spectra reveal that on chlorination of PVC, the methylene groups are substituted with three to four times higher probability than the chloromethylene groups. In addition to non-chlorinated monomer units, the chains contain only the structural units $-(CHCl-CHCl)-$ and $-(CCl_2-CH_2)-$. The frequency of recurrence of these structural units, the average lengths of uniform blocks made up of these units, and the chlorine contents of the products studied were determined.

[VB 910/228 IE]
German version: Angew. Chem. 77, 509 (1965)

On the Chemistry of Amphoteric Oxides

R. Hoppe, Münster (Germany)

Amphoteric metal oxides can react with "acidic" non-metal oxides [*e.g.* $Tl_2O_3 + 3\ SO_3 \rightarrow Tl_2(SO_4)_3$] as well as with "basic" metal oxides [*e.g.* $Tl_2O_3 + Na_2O \rightarrow 2\ NaTlO_2$]. Little has been reported on ternary oxides of the alkali metals which, like $NaTlO_2$, belong to the second group of compounds.

Many new oxides have been prepared which, according to their crystal structure, represent transitions between the extreme types "mixed oxide" and "oxo complex". Of these, the following are noteworthy:

The previously unknown oxogallates $KGaO_2$, $RbGaO_2$, and $CsGaO_2$ were prepared at 400–450 °C in 20–24 hours under dry nitrogen, *e.g.*

$$2\ CsO_{1.25} + Ga_2O_3 \rightarrow 2\ CsGaO_2$$

They are colorless powders and extremely sensitive to moisture. The crystal structure of $KGaO_2$ was determined on single-crystals using Fourier methods. $KGaO_2$ crystallizes pseudocubic, orthorhombic with $a = 5.51_5$ Å, $b = 11.07_6$ Å, and $c = 15.81_8$ Å, with $Z = 16$ formula units per unit cell [$d_{x\text{-}ray} = 3.87$ and $d_{pyk} = 3.78$ g·cm^{-3}] in the space group D_{2h}^{15}-Pbca. All particles occupy the equivalent position 8 (c) with the following provisional parameters:

	x	y	z	−B
Ga_1	0.260	0.008	0.189	0.59
Ga_2	0.279	0.264	0.065	0.68
K_1	0.749	0.014	0.062	1.71
K_2	0.796	0.264	0.186	1.12
O_1	0.578	0.298	0.014	2.46
O_2	0.170	0.404	0.100	0.46
O_3	0.286	0.173	0.155	1.75
O_4	0.905	0.479	0.224	2.77

Of 976 possible reflections (0kl) to (4kl), 663 have been observed; Mo–K_α radiation; I_o determined photometrically from "integrated" Weissenberg photographs, $R = 0.15_3$ and $R' = 0.25$.

$KGaO_2$ is the first compound of the $KFeO_2$ structure-family with a proven structure. According to powder photographs this family includes the cubic or pseudocubic compounds $KFeO_2$ ($a = 7.95_8$ Å) [1], $RbFeO_2$ ($a = 8.10$ Å) [2], $CsFeO_2$ ($a = 8.32$ Å) [2], $KAlO_2$ ($a = 7.79$ Å) [3], $RbAlO_2$ ($a = 7.73$ Å) [4], $CsAlO_2$ ($a = 8.10$ Å) [4], $RbGaO_2$ (rhombic, $a = 5.64$ Å, $b = 11.37$ Å, $c = 16.19$ Å, isotypic with $KGaO_2$) [4], $CsGaO_2$ (rhombic, $a = 5.83$ Å, $b = 11.68$ Å, $c = 16.50$ Å, perhaps isotypic with $KGaO_2$, possibly also cubic with $a = 16.50$ Å) [4], and, according to single-crystal investigations, the cubic $CsScO_2$ ($a = 17.45$ Å) [4]. As already supposed from powder photographs these compounds have a "filled framework structure" of the β-cristobalite type. Distances for $KGaO_2$: Ga–O = 1.68–1.95 Å (4×); K–O = 2.53–3.52 Å (8×).

$NaGaO_2$ [5] occurs as two modifications; the low-temperature form (α) is of the β-$NaFeO_2$ type according to single-crystal investigations, and is a variant of the wurtzite-type. The rhombic unit cell with $a = 5.30_1$ Å, $b = 5.51_9$ Å, $c = 7.20_1$ Å, space group C_{2v}^9–$P2_1nb$, contains four formula units; all particles occupy the equivalent positions 4 (a), with the parameters:

	x	y	z	−B
Na	0.240	0.410	0.126	2.70
Ga	0.746	0.061	0.123	1.05
O_1	(0.81)	0.395	0.173	1.70
O_2	0.418	0.060	0.102	1.60

38 of 49 possible reflections (0kl) with $R = 0.12$ and $R' = 0.14$, and 26 of 28 possible reflections (h0l) with $R = 10.7$ and $R' = 10.7$ were observed, Cu–K_α radiation, "integrated" Weissenberg photographs, I_o determined photometrically. Distances: Ga–O = 1.75–1.98 Å (4×); Na–O = 2.16–2.43 Å (4×). Refinement is in progress [$x(O_1)$ still uncertain].

β-$NaGaO_2$, prepared by heating α-$NaGaO_2$, crystallizes analogous to $KGaO_2$ according to powder photographs.

[GDCh-Ortsverband Nordwürttemberg (Germany), December 17th, 1964]. [VB 914/219 IE]
German version: Angew. Chem. 77, 551 (1965)

Recent Investigations on Oxidases and Peroxidases

C. Baron, Dijon (France)

Preparative, enzymological, and physiological investigations of two liver enzymes were discussed. These enzymes play a role in the metabolism of healthy and cancerous cells which has but little been studied. They are catalase, an otherwise well-investigated enzyme, and amine oxidase, of the properties of which relatively little is known.

As catalase has a healing effect on skin injuries, experiments with artificially (by calcium triphosphate) produced granulomas were performed. Catalase caused intensive fibroblast proliferation and the formation of collagen fibres.

The enzyme preparations were crystalline catalase and less pure amine oxidase preparations. This second enzyme is firmly attached to mitochondria and thus difficult to enrich. Detergents, especially a 0.2 % solution of sodium lauryl sulfate at pH 7 and 20 °C, proved most effective in loosening this attachment. In this way, it was possible to bring into solution about 30 % of the enzyme, without loss of activity, in the first step, and a further 20 % in the second step. The preparations were free from diamine oxidase activity.

[1] *S. Hilpert* and *A. Lindner*, Z. physik. Chem. B *22*, 395 (1933).

[2] *C.-J. Brendel*, *G. Wehrmeyer*, and *W. Klemm*, unpublished work; cf. *G. Wehrmeyer*, Ph. D. Thesis, Universität Münster 1959.

[3] *L. T. Brownmiller*, Amer. J. Sci. *29*, 260 (1935); *T. F. W. Barth*, J. chem. Physics *3*, 323 (1935).

[4] Author's own investigations.

[5] Recently prepared by *B. N. Ivanov-Emin* and *J. I. Rabovik*, Zhur. obshch. Khim. *17*, 1061 (1947).

Metabolic products of cancer cells have an inhibiting action on catalase. That healthy cells also contain catalase inhibitors was shown by inhibition experiments, chiefly with cell extracts from chicken embryos, which are characterized by accelerated cell growth similar to cancer tissue. Thermostable, dialysable catalase-inhibitors were found in decreasing concentrations in liver, heart, and brain. In the cells of these organs, the inhibitors are distributed in decreasing amounts in mitochondria, cell nuclei, and cell membranes.

Nothing is known about the chemical character of these inhibitors. Catalase-inhibitors of known constitution fall into three groups: diphenols, metabolic products of tryptophane or 5-hydroxytryptophane, and quaternary ammonium compounds. Tryptamine and serotonin, which are substrates of amine oxidase, belong to the second group.

Besides the hydrazides, iodine derivatives of noradrenaline and tyramine are inhibitors for amine oxidase. It must be assumed that amine oxidase-inhibiting substances also occur in cell extracts.

[GDCh-Ortsverband Mainz (Germany), January 7th, 1965] [VB 902/208 IE]
German version: Angew. Chem. 77, 549 (1965)

Preparation and Rearrangement of Distyrylmethanol Derivatives and a New Route to Reductones

G. Hesse, Erlangen (Germany)

The alcohols *(1a)–(1d)* were prepared from dibenzylideneacetones with $NaBH_4$ [1]. The reduction proceeds the more slowly, the richer the allyl system is in electrons. $NaBH_4$ does not attack compounds where $X = Y = N(CH_3)_2$, while on reduction with $LiAlH_4$ the hydroxy group is eliminated and 1,5-bis-(*p*-dimethylaminophenyl)-1,3-pentadiene is formed. Acids or activated aluminum oxide cause an *allylic* rearrangement of the alcohols *(1)* to the alcohols *(2)*. The reaction is of first order with regard to the alcohol concentration. The rate constants are proportional to the H^+ ion concentration. The methyl ethers of *(2)* are formed in methanol. The rearrangement proceeds $^1/_{10}$ as fast in dioxane or methanol containing 20 % water as in the anhydrous solvents. Its rate increases again at higher water content. Compound *(1c)* rearranges more slowly, *(1b)* and *(1d)* rearrange more rapidly than *(1a)*. This corresponds to the basicity of the hydroxy group in these compounds. The reaction probably takes the following course:

$$X\text{-}C_6H_4\text{-}CH{=}CH\text{-}CHOH\text{-}CH{=}CH\text{-}C_6H_4\text{-}Y \rightarrow X\text{-}C_6H_4\text{-}CHOH\text{-}(CH{=}CH)_2\text{-}C_6H_4\text{-}Y$$

(1) *(a)*: X = Y = H; *(c)*: X = Y = Cl — *(2)* *(b)*: X = Y = OCH_3; *(d)*: X = H, Y = OCH_3

$$R\text{-}OH + H^{\oplus} \xrightarrow{\text{slow}} R\text{-}\overset{\oplus}{O}H_2 \xrightarrow{-H_2O}$$

(1)

$$R^{\oplus} \leftrightarrow R'^{\oplus} \xrightarrow{H_2O} R'\text{-}OH + H^{\oplus}$$

(2)

$$R'^{\oplus} \xrightarrow{CH_3OH} R'\text{-}OCH_3 + H^{\oplus}$$

The (colored) carbonium ions can be rendered visible during the rearrangement by a special procedure: If the rearrangement is carried out in absolute benzene in the presence of acidic anhydrous silica gel, the reactants of the final step – water and $R'^{\oplus}$ – are adsorbed at separate points for a short time before they react with each other. Distyrylmethanol and its derivatives absorb oxygen after a long induction period, which can be abolished by the addition of dibenzoyl peroxide. The stability of the preparations increases in the order *(1b)* < *(1d)* < *(1a)* < *(1c)*.

[1] Experiments in cooperation with *P. Thieme*.

Compound *(1c)* yields triose reductone on ozonolysis, followed by catalytic hydrogenation. The formation of reductic acids from α,α-dibenzylidenecyclopentanol and -hexanol was shown in preliminary experiments [2].

[GDCh-Ortsverband Saarbrücken (Germany), January 22nd, 1965] [VB 909/215 IE]
German version: Angew. Chem. 77, 550 (1965)

An Oscillating Fermentation System from Yeast

B. Hess, Heidelberg (Germany)

Fermentation by *Saccharomyces carlsbergensis* (inositol-lack mutant) begins to oscillate when oxidative phosphorylation is prevented. By means of gentle high-pressure extraction or ultrasound treatment, the oscillating system can be obtained as a homogeneous cell-free extract of high concentration. Warming or addition of glucose 6-phosphate causes the system to oscillate with a period of about 0.1 min^{-1}, a damping factor of 1.1–1.4 and a Q-value of 4–6 at 25 °C. Analysis of the enzyme distribution pattern indicates that all known components of fermentation are present, but the activity of phosphofructokinase is relatively low. The metabolite pattern of the cold extract (+2 °C) shows the proportions and levels of an almost frozen fermentation with a relatively high magnesium concentration and a pyridine nucleotide concentration of 48 % which takes part in the oscillations. The rest of the metabolite pattern corresponds to the concentrations which are necessary for a feedback control of phosphofructokinase and of the glyceraldehyde-3-phosphate dehydrogenase/phosphoglycerate kinase system. Addition of substrates and metabolic intermediates can influence the partly sinusoidal wave forms, in part with a shift in phase. Additions of pure fermentation enzymes lead to shifts of the stationary equilibria of the components involved in the oscillation. Additions of phosphoglycerate kinase, phosphoglycerate mutase, and enolase sufficient to cause a doubling of the endogenous enzyme concentration lead to a raise in the frequency of the oscillations and to their stabilization. The activity of these enzymes decreases in the order given. They cause the average redox state of the pyridine nucleotides to be shifted toward the oxidized side. Conversely, the addition of highly purified phosphofructokinase brings about an increase in frequency and a shift of the average redox state of the pyridine nucleotide system to the reduced side. These findings demonstrate the cooperative activity of the glycolytic enzymes during oscillation. It may be assumed that oscillation is a phenomenon which can be induced in many varieties of cells and which is of importance for periodic biological processes.

[Biochemical Colloquium, Gießen (Germany), January 29th, 1965] [VB 911/222 IE]
German version: Angew. Chem. 77, 550 (1965)

New Aspects of the Koch Carboxylic Acid Synthesis

K. E. Möller, Mülheim/Ruhr (Germany)

The addition of CO and CH_3OH to cyclic mono-olefins in the presence of $H[BF_3\text{-}OCH_3]$ as catalyst [3] does not lead, in the case of cyclo-octene, cyclononene, and cyclodecene, to the expected methyl esters of secondary cycloalkanecarboxylic acids. Instead, the methyl esters of tertiary

[2] Experiments in cooperation with *E. Bayer*.

[3] *K. E. Möller*, Angew. Chem. 75, 1122 (1963); Angew. Chem. internat. Edit. 3, 148 (1964).

1-alkylcycloalkane carboxylic acids are formed by ring contraction. The secondary cycloalkyl cation first formed in the proton-catalysed reaction therefore isomerizes to the tertiary alkylcycloalkyl cation before it reacts with CO. Since the stability of a tertiary carbonium ion is greater than that of a secondary carbonium ion the Koch carboxylic acid synthesis starting from 1-methylcycloalkenes should yield tertiary 1-methylcycloalkanecarboxylic acids with preservation of the ring system. All the 1-methylcycloalkenes from 1-methylcyclobutene to 1-methylcyclododecene were reacted at 15 °C and a CO-pressure of 150 atmospheres in the presence of $H[BF_3{\cdot}OCH_3]$. In every case the methyl ester of the expected 1-methylcycloalkanecarboxylic acid was formed. A yield of only 10 % of methyl 1-methylcyclononanecarboxylate in the isomer mixture shows that under the conditions used the nine-membered ring possesses the lowest stability; the eight- and the seven-membered rings follow, with yields of 50 % and 60 % respectively. All the other methylcycloalkenes react to give exclusively, or at least over 90 %, methyl 1-methylcycloalkanecarboxylate.

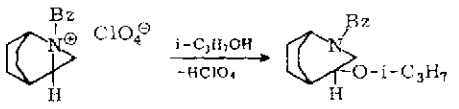
[GDCh-Ortsverband Marl/Kr. Recklinghausen (Germany),
March 3rd, 1965] [VB 921/227 IE]

German version: Angew. Chem. 77, 551 (1965)

Experiments with Bridged Cyclic Systems Containing Nitrogen

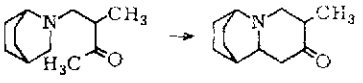
W. Schneider, Karlsruhe (Germany)

On dehydrogenation with mercuric acetate, tertiary isoquinuclidines are dealkylated or converted into imonium salts, depending on the nature of the substituent on the nitrogen [1]. The action of diazomethane on the *N*-benzylimonium salt yields the tricyclic aziridinium salt *(1)*, which reacts with isopropanol to afford *(2)*:



(1) *(2)*

With formaldehyde and CH-acidic compounds, isoquinuclidine yields Mannich bases, *e.g. (3)*; on dehydrogenation with mercuric acetate, *(3)* is cyclized to *(4)*.



(3) *(4)*

The *N*-acetyl derivative of nortropinone can be converted *via* the dicyanomethylene compound (70 % yield) by successive hydrolysis, hydrogenation, and esterification into ethyl nortropanyl 3-acetate, which possesses α-configuration and is not suitable for cyclization to quinuclidine derivatives. *N*-Acetylpseudopelletierine affords the dicyanomethylene compound in only 14 % yield, which suggests a diminished reactivity at C-3 as a result of steric hindrance.

1,2,6-Trimethyl-4-piperidone is converted, like nortropinone, *via* analogous intermediates into ethyl 1,2,6-trimethylpiperidin-4-yl malonate or acetate. 1,2,6-Trimethylpiperidin-4-ylethyl chloride, obtainable from the corresponding alcohol, can be cyclized to the 1,2,6-trimethylquinuclidinium salt.

[Chemische Gesellschaft Karlsruhe (Germany),
February 18th, 1965] [VB 915/217 IE]

German version: Angew. Chem. 77, 550 (1965)

[1] Cf. *W. Schneider*, Angew. Chem. *76*, 605 (1964).

SELECTED ABSTRACTS

The amino-acid sequence of ferredoxin from *Clostridium Pasteurianum* has been elucidated by *M. Tanaka* and collaborators. The molecule has a molecular weight of about 6000 and contains 55 amino acids, including 8 cysteine residues, and 7 atoms of iron. The analysis was facilitated by the presence of only one lysine and one phenylalanine but is still extremely difficult because of the large number of cysteine molecules. *S*-(β-Aminoethyl)cysteinylferredoxin, cysteinylferredoxin, and *S*-carboxamidomethylcysteinylferredoxin were hydrolysed with trypsin, pepsin, and chymotrypsin. In the following scheme for the complete amino-acid sequence, R can be either a disulfide bridge or an iron ion, for the distribution

Ala-Tyr-Lys-Ileu-Ala-Asp-Ser-$\overset{R}{C}$ys-Val-Ser-$\overset{R}{C}$ys-

Gly-Ala-$\overset{R}{C}$ys-Ala-Ser-Glu-$\overset{R}{C}$ys-Pro-Val-$AspNH_2$-Ala-

Ileu-Ser-$GluNH_2$-Gly-Asp-Ser-Ileu-Phe-Val-Ileu-

Asp-Ala-Asp-Thr-$\overset{R}{C}$ys-Ileu-Asp-$\overset{R}{C}$ys-Gly-$AspNH_2$-

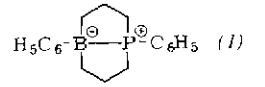
$\overset{R}{C}$ys-Ala-$AspNH_2$-Val-$\overset{R}{C}$ys-Pro-Val-Gly-Ala-Pro-

Val-$GluNH_2$-Glu

of these two species is still unknown. / Biochem. biophysic. Res. Commun. *16*, 422 (1964) / –Hö. [Rd 212/421 IE]

A new amino peptidase from kidney particles has been concentrated and characterized by *G. Pfleiderer*, *G. Braunitzer*, et al. The preparation differs in its specificity, cofactor requirements, and pH optimum from classical leucine-amino peptidase (LAP). Experiments with the synthetic pentapeptide Tyr-Leu-Gly-Glu-Phe showed that the new enzyme is more suitable for kinetic amino-acid sequence analyses than LAP: glycine and alanine are hydrolysed off much faster. D-Amino acids block further hydrolysis. Thus, when the L-glutamic acid in the above peptide is replaced by D-glutamic acid, the hydrolysis stops after release of the tyrosine and leucine residues. Proline linkages are also split, but more slowly than the bonds joining other amino acids. / Biochem. Z. *340*, 552 X (1964) / –Hö. [Rd 215/424 IE]

1,5-Diphenyl-1-bora-5-phosphabicyclo[3,3,0]octane *(1)*, m.p. 75.5–76.5 °C (from acetone), was obtained by *G. B. Butler* and *G. L. Statton* in 28 % yield by boiling a dilute solution of equimolar quantities of triethylamine-phenylborane and diallylphenylphosphine in toluene. The compound is unusally stable towards heat. Thermogravimetry showed that it retains 95 % of its original weight at 350 °C and 30 % at 500 °C. Its



(1)

NMR spectrum is in complete accordance with the proposed structure. / J. Amer. chem. Soc. *86*, 5045 (1964) / –Ma. [Rd 209/418 IE]

The OH···N bridges in pyridine/methanol mixtures formed the subject of valence bond calculations and ^{14}N nuclear magnetic resonance studies by *H. Saito, K. Nukada, H. Kato, T. Yonezawa*, and *K. Fukui*. If the OH···N bridges are regarded to be formed by delocalization of the proton, then three structures, *viz.* I: X–H Y (covalent); II: $X^{\ominus}H^{\oplus}$ Y (ionic); and III: $X^{\ominus}$ $H{-}Y^{\oplus}$ (charge transfer), must be considered; the coefficients of the complete wave function then give the percentage weights w of the structures I, II, and III shown in the table.

X–H···Y	X···Y [Å]	X–H [Å]	Bridge bond energy [kcal/mole]	w_I [%]	w_{II} [%]	w_{III} [%]
O–H···N	2.80	1.05	12.0	76.7	14.1	9.2
O–H···O [1]	2.80	0.986	6.8	85.2	12.0	2.8

The shift of the ^{14}N–NMR signal in pyridine/methanol at the mole fraction $x = 0.5$ is 9 ± 3 ppm compared to the signal of pure pyridine. The shift of the proton signal for the methanol hydroxy group is greatest at $x = 0.5$; this indicates that a 1:1 complex with a bridge stronger than the OH···O bridge is present. For the actual structure, the effective shift is calculated to be $\delta = w_I\delta_I + w_{II}\delta_{II} + w_{III}\delta_{III}$. Since $\delta_I = 0$ and $\delta_{II} \approx 0.2$ ppm, then $\delta \approx w_{III}\delta_{III}$. If it is assumed that the $^{\ominus}N$–H distance, the paramagnetic shielding, and the excitation energy in the (pyridine·H)$^{\oplus}$ ion and in structure III are almost identical, then δ_{III} can be taken as 123 ± 11 ppm, *i.e.* as the shift of the (pyridine·H)$^{\oplus}$ signal relative to that of free pyridine. It follows that $w_{III} = 7 \pm 3$ %, a value in satisfactory agreement with that given in the table. Previously, a structure III had been assumed, but no evidence for it was available. / Tetrahedron Letters *1965*, 111 / - Jg. [Rd 242/452 IE]

Charge-transfer complexes between rhodane and aromatic hydrocarbons have been observed and characterized by spectroscopy by *W. Scholz, A. Trutia*, and *V. Vantu*. The absorption spectra were independent of the concentration

λ_{max}, ε_{max}, and the equilibrium constants K_{CT} for the 1:1 charge-transfer complexes between $(SCN)_2$ and aromatic hydrocarbons in n-heptane at 20 °C.

Donor	λ_{max}	ε_{max}	K_{CT}
Benzene	279	5720	0.98
Toluene	286	3490	2.35
o-Xylene	290	4200	2.55
m-Xylene	290	3890	2.94
p-Xylene	293	2750	3.35
Mesitylene	303	3285	5.01
m-Dioctylbenzene	–	–	≈18

and could be evaluated using the simple Benesi-Hildebrand equation [Equation (a)] for 1:1 equilibria. The rhodane absorption (in n-heptane: $\lambda_{max} = 294$ mμ, $\varepsilon_{max} = 203$; $\lambda_{max} = 240$–230 mμ, $\varepsilon_{max} = 689$–1052) overlaps the strong charge-transfer band with all donors.

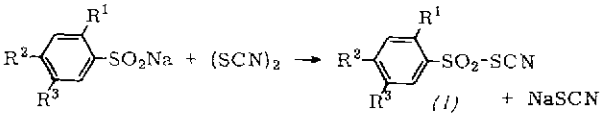
$$1/(\varepsilon_a - \varepsilon_A) = 1/(\varepsilon_C - \varepsilon_A) + [(1/K_{CT})(\varepsilon_C - \varepsilon_A)]/d \qquad (a)$$

ε_A and ε_C = molar extinction coefficients for the acceptor and complex, respectively; $\varepsilon_a = m/a$; m = optical density of the solution; a and d = amounts of acceptor and donor taken.

Photochemical reactions or polymerization of the $(SCN)_2$ did not occur; however, the solutions of the mesitylene complex decompose after a few minutes. The values for K_{CT} are very similar to those of the analogous bromine and iodine complexes. / Tetrahedron Letters *1965*, 57 / –Jg. [Rd 240/451 IE]

[1] Values for comparison taken from *C. A. Coulson* and *U. Danielsson*, Ark. Fysik *8*, 239, 245 (1954).

Arylsulfonyl thiocyanates have been obtained by *J. Goerdeler* and *P. Rosenthal* by adding sodium or silver salts of a sulfinic acid at 0 °C to a solution of dithiocyanate ($C_2N_2S_2$) in CCl_4. The products decompose on heating. Nucleophilic reagents attack mainly their S–S bond. Diazomethane becomes inserted between the two sulfur atoms to give for example *(3)*. The sulfonyl thiocyanates *(1)* add onto olefinic bonds to give β-thiocyanato sulfones *(2)*; this reaction is accelerated by radical formers. Products prepared include *(1)*, $R^1 = R^2 = R^3 = H$, m.p. 28–29 °C, in 49% yield, *(1)*, $R^1 = R^3 = H$, $R^2 = CH_3$, m.p. 35–36 °C, in 84% yield, *(1)*, $R^1 = CH_3O$, $R^2 = R^3 = H$, m.p. 47–48 °C, in 71% yield, and *(1)*, $R^1 = Cl$,



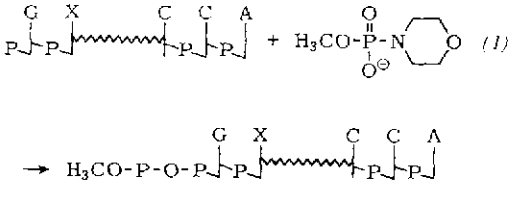
(1) + NaSCN

H_5C_6-CH(SCN)-CH_2-SO_2-C_6H_4-Cl(p) *(2)*

(p)Cl-C_6H_4-SO_2-CH_2-SCN *(3)*

$R^2 = R^3 = H$, m.p. 76–77 °C, in 75% yield. / Tetrahedron Letters *1964*, 3665 / –Ma. [Rd 203/412 IE]

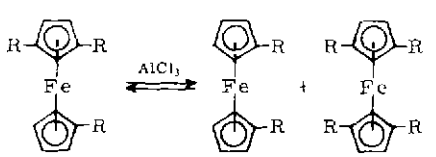
The labelling of terminal groups in polynucleotides can be achieved by two new methods discovered by *H. G. Khorana* et al. Both ribopolynucleotides and deoxyribopolynucleotides can be phosphorylated at the terminal phosphoric monoester group using methyl phosphoromorpholidate *(1)*. The cetyltrimethylammonium salt of the polynucleotide is made at pH 7.5 with cetyltrimethylammonium bromide and dissolved in dimethylsulfoxide, where it reacts slowly with *(1)* at room temperature (100 h), 70–85% of the end groups being phosphorylated. Amino-acid transfer RNA (sRNA) labelled in this way retains its full capacity as an amino-acid acceptor. The second method entails specific acetylation of terminal hydroxy groups with acetic anhydride in aqueous solution at



(1)

pH 7 and room temperature, but is restricted to deoxyribopolynucleotides. Here 60–90% labelling occurs, and the resultant esters are stable below pH 8. / J. biol. Chemistry *239*, 3875, 3885 (1964) / –Hö. [Rd 213/422 IE]

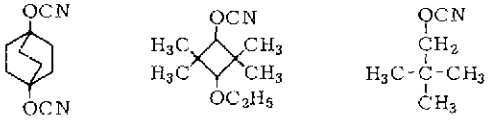
Ring migration and transalkylation in alkylated ferrocenes has been observed by *D. E. Bublitz*. Alkylferrocenes undergo disproportionation in boiling methylene dichloride under nitrogen in the presence of $AlCl_3$ or $GaCl_3$ to give ferrocene and 1,1′-dialkylferrocenes. For example, equilibrium mixtures containing 1,1′,3-triethylferrocene *(1)*, 1,1′-diethylferrocene *(2)*, and 1,1′,3,3′-tetraethylferrocene *(3)* were obtained in this



(1) R = C_2H_5 *(2)* *(3)*

way. 1,1′-Diethylferrocene becomes equilibrated with ethylferrocene (3.88%) and 1,1′,2-triethylferrocene (2.70%). Partial dealkylation also occurs, although only to a small extent. / Canad. J. Chem. *42*, 2381 (1964) / –Ma. [Rd 205/414 IE]

The synthesis of aliphatic cyanates ROCN has been carried out by *J. C. Kauer* and *W. W. Henderson*. Stable products are obtained only if the alkyl group R is bulky enough to prevent trimerization of the cyanates and if the carbonium ion $R^{\oplus}$ has enough energy to suppress solvolysis. Thus, for example, the action of either NaH or butyl-lithium plus ClCN on 1,4-dihydroxybicyclo[2,2,2]octane, 3-ethoxy-2,2,4,4-tetramethyl-1-cyclobutanol, and neopentyl alcohol gives rise to the cyanates *(1)*, m.p. 155–156 °C (41% yield), *(2)*, b.p. 63 °C/0.1 mm (30%), and *(3)*, b.p. 123 °C/185 mm (4.4%), respectively.

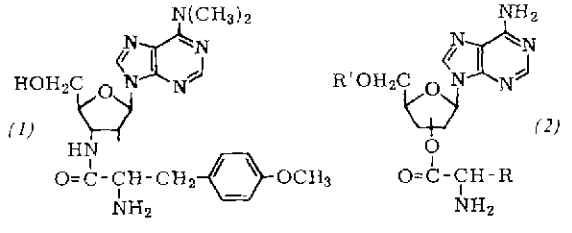


(1) *(2)* *(3)*

The dicyanate *(1)* rearranges on treatment with BF_3 etherate to the diisocyanate, m.p. 111.5–112 °C. / J. Amer. chem. Soc. *86*, 4732 (1964) / –Ma. [Rd 207/416 IE]

The synthesis of organophosphorus compounds by alkylation of elemental phosphorus is described by *H. P. Angstadt*. Phosphorus reacts with alkylcarbonium ions to give alkylphosphorus compounds. When 1.5 mole of t-butyl chloride is added dropwise to a solution of 1.0 mole of white phosphorus in CS_2 containing 1.5 mole of $AlCl_3$ at –10 °C under an atmosphere of HCl and the resultant mixture is poured into ice-cold 4 N HNO_3 (or 30% H_2O_2), di-t-butylphosphinyl chloride $(C_4H_9)_2POCl$, m.p. 80.1–80.9 °C, is obtained in 30% yield, together with some di-t-butylphosphine oxide. Other alkyl halides and Lewis acids alkylate phosphorus analogously. t-Amyl chloride gives rise to di-t-amylphosphinyl chloride, di-t-butylphosphinyl chloride, and t-amyl-t-butylphosphinyl chloride, together with the corresponding secondary phosphine oxides, since disproportionation occurs under the influence of the $AlCl_3$. Isopropyl, n-butyl, cyclohexyl, and n-octyl chlorides also react smoothly. / J. Amer. chem. Soc. *86*, 5040 (1964) / –Ma. [Rd 210/419 IE]

Inhibition of protein synthesis by puromycin has been observed by *D. Nathans*. The reason for this inhibition probably is the similarity between puromycin *(1)* and the adenosine end of aminoacyl-5RNA *(2)*, which enables puromycin to become incorporated into the growing amino-acid chain instead of *(2)*. This reaction is catalysed by an amino-acid transfer enzyme. The oligopeptide chain cannot continue to grow after incorporation of the puromycin and is released from the ribosome.

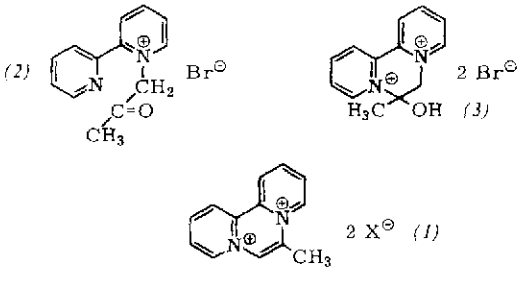


(1) *(2)*

Hence only oligopeptides are produced in protein-synthesizing systems in the presence of puromycin; these cannot be precipitated with trichloroacetic acid. It was shown that radioactively labelled puromycin is incorporated into these oligopeptides. Uniform results were obtained with the following systems: polyuridylic-acid controlled polyphenylalanine synthesis in *E. coli* extracts, synthesis of the protein fraction of RNA coliphages MS2 in *E. coli* extracts, and hemoglobulin synthesis in rabbit reticulocytes. / Federat. Proc. *23*, 984 (1964) / –Hö. [Rd 214/423 IE]

A regulator gene determines a protein. *A. Garen* and *N. Otsuji* proved this for the repression of the alkaline phosphatase from *E. coli* by isolating, purifying, and identifying the protein determined by the regulator gene R2a. Three functions are essential for repression of the alkaline phophatase; these are directed by the regulator genes R1, R2a, and R2b. Mutants which are constitutive for alkaline phosphatase have one protein less than the wild strain. This protein, which is determined by the regulator gene R2a, was purified by ammonium sulfate fractionation and high-voltage electrophoresis; its purity was checked by sedimentation analysis and by its immunochemical properties. Its connection with gene R2a was proved by the fact that mutations of R2a alter the electrophoretic mobility of the protein. The formation of the protein is induced and repressed by the same factors as the formation of alkaline phosphatase. It is therefore thought that the R2a protein is not the repressor itself, but either a precursor of the repressor or a substance which participates in the synthesis of the repressor. The alkaline phosphatase constitutes about 6% of the total cell protein, and the R2a protein 0.25%. / J. molecular. Biol. *8*, 841 (1964) / –Hö. [Rd 216/425 IE]

The 9-methyl-8a,10a-diazoniaphenanthrene cation *(1)*, an aromatic ring system containing two quaternary nitrogen atoms in a single ring, has been made by *I. C. Calder* and *W. H. F. Sasse*. 1-Acetonyl-2-(α-pyridyl)pyridinium bromide *(2)*, m.p. 163–164 °C, was prepared from 2,2'-bipyridyl and bromoacetone in 73% yield and reacted with 48% HBr at room temperature to give 9-hydroxy-9-methyl-9,10-dihydro-8a,10a-diazoniaphenanthrene dibromide *(3)*, m.p. 220–225 °C (decomp.). The latter could be converted with refluxing $SOCl_2$ into a mixture of the dibromide and dichloride of *(1)*; its



(2) *(3)* *(1)*

picrate melts at 243–245 °C (decomp.). Aqueous solutions of *(1)* are stable in diffuse daylight but are decomposed by ultraviolet light. / Tetrahedron Letters *1964*, 3871 / –Ma. [Rd 208/417 IE]

The crystal structure of methyl-lithium has been worked out from its Debye-Scherrer diagram by *E. Weiss* and *E. A. C. Lucken*. Its body-centered cubic unit cell has a = 7.24 ± 0.01 Å and contains 8 CH_3Li. Groups of four lithium atoms form regular tetrahedra with an Li–Li distance of 2.56 Å. There is a methyl group situated above the center of every tetrahedral surface. Within this tetrameric structural unit $(CH_3Li)_4$, the carbon atoms form a system of polycentered bonds with the three neighboring lithium atoms and the other three carbon atoms. The molecular-orbital term series for the tetrameric methyl-lithium was set up on the assumption that the lithium atoms make their s and p orbitals available. There is one non-degenerate lowest state and a slightly higher threefold degenerate state in which the eight valence electrons can be distributed. Interaction of each tetrameric molecule with its neighbors causes an association of discrete terms to bands with simultaneous lowering of the total energy content. It is this effect which causes the three-dimensional interlinking of methyl-lithium by bonds which are stronger than normal van der Waals forces, and this determines essentially the properties of methyl-lithium (*e.g.* its low volatility and solubility). / J. organometallic Chem *2*, 197 (1964) / –Eb. [Rd 192/401 IE]

Anorganische Chemie [Inorganic Chemistry]. By *K. A. Hofmann*. Edited by *U. Hofmann* and *W. Rüdorff*. Verlag Friedrich Vieweg & Sohn, Braunschweig 1963. 17th completely revised and extended edit., XII + 862 pp., 122 figs., 10 colored spectra, linen DM 28.– (about $ 7.–).

Even the exterior of this new edition of "Hofmann-Rüdorff" differs from its predecessors; the format of the book is larger, and the typographic appearance has been improved. The individual chapters are now organized more clearly; simultaneously, numerous significant transpositions and revisions have taken place in many sections, with great benefit to the book as a whole. Numerous illustrations have been modernized or replaced, without significant increases in the length of the book. The well proved division into metals and nonmetals has been retained, and a good supplementary chapter deals with organometallic compounds, water-like solvents, the solid state, catalysis, molecular structure, atomic nuclei, and extraterrestial chemistry.

After an introduction comes the discussion of the elements oxygen and hydrogen and of the properties of water, including osmosis, the ionic theory, the law of mass action and its applications, followed by sections on the rare gases and the periodic system, and explanations of ionization, oxidation, and reduction. Next nitrogen and its compounds and the Group VI elements and their compounds are discussed. Sections on atomic structure and the chemical bond follow. The reviewer suggests that in future editions, atomic structure and the fundamentals of the chemical bond should be described immediately after the laws of stoichiometry, for then numerous phenomena such as oxidation and reduction and concepts involved in the ionic theory can be explained and derived in the logical manner.

The treatment of the chemical bond, particularly in complexes, where recourse is made to valence bond methods and the ligand field theory, is particularly good. The descriptions of the elements and their compounds are mostly brought up to date. A few minor errors may be referred to here: nitrous acid is known in the gaseous – *i.e.* the free – state; the so-called stannic acids are not oxide hydrates; the dark red polyvanadate that occurs transiently on acidification of vanadate solutions is not an octavanadate, but probably a dodecavanadate; the existence of trichromate and tetrachromate ions is very questionable; in the formula CrO_5, the ligand occupying the fourth coordination site (ether, pyridine, *etc.*) is missing; $Mn^{3\oplus}$ ions and not $MnO_4^{\ominus}$ are formed during the oxidation of manganese(II) sulfate with peroxodisulfate in the presence of $Ag^{\oplus}$ ions.

All in all, this is a praiseworthy textbook which will certainly gain many new friends in addition to its old acquaintances.

O. Glemser [NB 354/212 IE]

Chemisches Praktikum für Mediziner und Studierende sonstiger an Chemie interessierter Wissenschaften (Practical Chemistry for Medical Students and Students of Other Sciences Affiliated to Chemistry). By *R. Schwarz* and *P. W. Schenk*. Verlag Johann Ambrosius Barth, Leipzig 1964. 13th Edit., 152 pp., 3 figs., stiff covers, DM 4.20 (about $1.10).

The group of students for whom this book is intended consists mainly of medicine and biology students. Consequently the principles of chemical education conveyed – experiments in the chemistry of the individual elements, wet separation of cations, anion analysis – are tailored to fit the needs of this group. However, there is a lack of experiments acquainting the student with biochemically important methods of analysis (*e. g.* adsorption and extraction, including chromatography, pH measurements and titrations using the glass electrode, colorimetric and photographic experiments, ion-exchange techniques, *etc.*). Instead of a chapter on the standardization of sodium hydroxide solutions for titrations with oxalic acid, a short note on commercially available ampoules containing standardized solutions would have sufficed .– The theoretical discussions are sometimes good (*e. g.* bases) but often too short (*e. g.* the chemical bond). It might be more advantageous to omit this chapter on the chemical bond and refer the student to good textbooks – for it is not intended to spare the student the study of these – and instead to give a more profound treatment to topics (*e. g.* the law of mass action, the ionic theory, buffers, and pH) that are of prime importance for medical and biology students. The formula for nitric acid with two double bonds should be modernized.

Ulrich Schmidt [NB 320/178 IE]

Diuretics. Chemistry and Pharmacology. By *G. de Stevens*. Vol. I of the Series: Medicinal Chemistry. Edited by *G. de Stevens*. Academic Press, New York-London 1963. 1st Edit. XIII + 186 pp., numerous illustrs., linen $7.00.

George de Stevens, who is well known on account of his fundamental work on diuretics, presents with his monograph on the pharmacology and chemistry of diuretics the first volume of a new series on medicinal chemistry.

The book is divided into nine chapters. Following general physiological and pharmacological considerations, xanthenes and pyrimidines, triazines, organomercury compounds, sulfonamides, thiazides and hydrothiazides, aldosterones, and compounds which do not belong to any of these classes are dealt with in seven separate chapters. The final chapter is devoted to therapeutic applications of diuretics for treatment of hypertonic disturbances.

The first chapter contains two sections, one on the functions of the kidneys, and the other on the pharmacological use of diuretics. The latter section (2 pp.) is unfortunately far too short and does not do justice to the vast importance of this field. – The xanthenes and pyrimidines receive attention on about 15 pp., the triazines on 6, and the organomercury compounds on 10. In view of the diminished practical importance of these groups, this treatment is absolutely adequate. – Sulfonamides, thiazides, and hydrothiazides are dealt with thoroughly on about 70 pp., and the aldosterone derivatives on about 25, with coverage of all aspects. The concluding chapter on the therapeutic applications of diuretics for reducing high blood-pressure is well written and gives valuable information and incentives for further work on this extremely important field of indications.

In contrast to the series "Fortschritte der Arzneimittelforschung" founded in 1959 and the series "Progress in Medicinal Chemistry" started in 1961, *de Stevens* appearently wants to treat a single field of chemico-medical research in each individual volume. The volumes planned for the future will sometimes deal with research topics that have so far not been reviewed comprehensively, and hence the series is to be welcomed. However, monographs on analgetics and psychopharmaceuticals are stated to be in preparation, and it is therefore questionable whether this duplicity and overlapping of topics with analogous articles which have, in some cases, been published only recently is worthwhile and advantageous. However, if we are to restrict our criticism to the present first volume, then the author/editor is to be commended for his comprehensive and fine presentation of this difficult material, and the publishers for the purposeful outlay and orderly appearance of the book.

E. Jucker [NB 329/187 IE]

Infrared Spectroscopy of High Polymers. By *R. Zbinden*. Academic Press, New York-London 1964. 1st. Edit., XII + 264 pp., numerous figures and tables, linen, $9.50.

This book is a valuable aid to chemists and physicists who wish to apply infrared spectroscopy for studying the structures of polymers. The first of its five chapters gives a general survey

of the fundamentals of the subject matter dealt with in the subsequent sections. Thereafter, selection rules, the calculation of structural vibrations, and the infrared dichroism of high polymers are discussed in detail. Here some knowledge of the fundamentals is assumed, and only references to standard textbooks on this subject are given. The list of references at the end of each chapter and in the appendix is remarkably comprehensive, but only goes up to the beginning of 1961.

The section on the analytical applications of infrared spectroscopy to high polymers is unfortunately restricted to 12 pages and deals with relatively trivial examples; it is therefore not up to the standards of the other chapters. Extension of this part would be desirable. The parts of spectra used as illustrations are occasionally unsatisfactory because of poor measurement technique and reproduction.

Special praise must be given to the complete and comprehensive manner in which the calculation of the normal vibrations of linear high polymers is derived from theory and illustrated with examples. To those intending to do work in this field the book can be recommended. *H. Günzler* [NB 336/194 IE]

Recent Progress in Microcalorimetry. By *E. Calvet* and *H. Prat*, edited and translated from the French by *H. A. Skinner*. Pergamon Press, Oxford-London-New York-Paris 1963. Ist Edit., XII + 178 pp, numerous illustrs., linen £3.0.0 (about $8.25).

This book is a revised transcription and partly mere translation into English of the volumes "Microcalorimétrie; Applications physico-chimiques et biologiques", Masson Ed., Paris 1956, and "Récents Progrès en Microcalorimétrie", Dunod Ed., Paris 1958. It is divided into three parts: 1.apparatus and microcalorimetric methods,2.physico-chemical applications, and 3. biological applications.

Part 1 gives a terse description of the principle and construction of differential calorimeters of the Tian-Calvet type. The theory of the gain and loss of heat in calorimeters, the methods for determining the constants which occur in the equations for thermal equilibrium, and the evaluation of the thermovoltages registered are lucidly described. In explaining the construction of the calorimeter and its accessories, particular attention is paid to details which make the calorimeter a precision instrument. – In the second part of the book, a host of examples of applications are given: measurements of specific heats, thermal conductivities, heats of mixing, heats of reaction, *etc.* with samples weighing only a few milligrams. The high sensitivity and precision of the calorimeter are particularly striking in studies of absorption kinetics. – The third part of the book deals with applications in zoology and botany; here the thermogenesis of insects and of germinating seeds are worthy of mention.

The book is a kind of progress report from the Institute of Microcalorimetry and Thermogenesis in Marseilles (France) which propagates the use of the microcalorimetric methods, but it will be of service to anyone interested in the construction and use or improvement of calorimeters of any type.

H. Schreiber [NB 319/177 IE]

Computation of Molecular Formulas for Mass Spectrometry. By *J. Lederberg*. Holden-Day Series in Physical Techniques in Chemistry. Edited by *C. Djerassi*. Holden-Day, Inc., San Francisco-London-Amsterdam 1964. 1st Edit., VII + 69 pp., paperback, $ 4.25.

High resolution mass spectrometry can he used to determine the masses of ions with molecular weights of up to about 1000 with an accuracy of a few thousandths of a mass unit. This permits to cut down to relatively few the many molecular formulae which can be assigned to an ion whose molecular weight is not known with such precision. However, for this purpose, all the molecular formulae differing in a thousandths of a mass unit, which are possible for a whole mass number, must be tabulated. As the molecular weight increases, the number of the molecular formulae also increases, and thus the size of the tables becomes larger and larger. *Lederberg* has found an amazingly simple method of limiting the tables to 48 pages by taking recourse to a few mathematical operations, which can be mastered in a few minutes. Consequently, his book becomes an indispensible tool in all laboratories in which organic compounds are investigated with high-resolution mass spectrometers. This verdict of the reviewer is not at all modified by the fact that the example used for demonstration on p. 8 is rather unfortunate: a structural formula is derived for the compound $C_7H_{15}NO_3$ which contains two pentavalent carbon atoms, and in which one carbon atom is missing.

G. Spiteller [NB 346/203 IE]

Gas Analysis by Gas Chromatography. By *P. G. Jeffery* and *F. J. Kipping*. International Series of Monographs on Analytical Chemistry, Volume 17. Edited by *R. Belcher* and *L. Gordon*. Pergamon Press, Oxford-London-Edinburgh-New York-Paris-Frankfurt 1964. 1st Edit., XI + 216 pp., 68 figures, 11 tables, linen £3.10.0 (about $10.00).

Because it is so difficult to survey the literature on gas chromatography, every monograph covering some specialized section of this field is to be welcomed. However, a monograph on gas analysis using gas chromatography should fit the specific needs of gas analysis alone and keep any discussion of the well known fundamentals of gas chromotagraphy as short as possible. This is not the case in all parts of this book. On the other hand, a comparison of the value of gas chromatography with that of other physical and chemical methods of gas analysis would have been useful.

The book is doubtlessly useful for the gas analyst because of the large number of practical examples; nevertheless it can be recommended only with some reservations:

The treatment given to methodical questions is often neither thorough nor critical (*e. g.* calibration procedures, sample injection). The discussion of instrumentation does not do enough justice to commercially available apparatus and overlooks special set-ups such as multicolumn chromatographs, apparatus for reaction gas chromatography, *etc.* There are no numerical data given for the response factors of the most important gases in detectors such as heat conductivity cells and flame ionization detectors, and comparative data for the properties of the various detectors such as sensitivity, linear dynamic range, dead volume, *etc.* are lacking as well. Too much space is allocated to argon detectors.

G. Schomburg [NB 337/195 IE]

Nucleophilic Substitution at a Saturated Carbon Atom. By *C. A. Bunton*. Volume 1 of the Series: Reaction Mechanisms in Organic Chemistry. Edited by *E. D. Hughes*. Elsevier Publishing Co., Amsterdam-London-New York 1963. 1st Edit., X + 172 pp., 4 figs. 9 tables, linen DM 22.50 (about $ 5.75).

It is a commonplace statement to remark that the flood of chemical publications – even on a limited topic – has nowadays become almost unsurveyable for the individual. The consequent necessity of procuring information through review articles has led to the ever increasing appearance of specialized series within recent years, so that the publication of a new series of monographs can be justified only by excellent presentation of the subject matter.

The series on mechanisms in organic chemistry initiated in 1963 has made a promising start with this first volume, which deals with substitutions at saturated carbon atoms. The book is divided into six chapters; three of these deal with the fundamental phenomena, structural effects, and the stereochemistry of substitutions, while the other three (about one-third of the book) deal with solvent, salt, and catalytic effects. Here the reader finds all the significant results, and despite the straightforwardness and lucidity of the discussion, at least attention is called to controversial interpretations. The book is therefore not only suitable as an introduction to

this subject, but also welcome as a work of reference on account of its ample references to the literature (mainly up to 1962), which might however have been better collected into a single list.

G. Köbrich [NB 311/170 IE]

Progress in Physical Organic Chemistry. Vol. 1, Edited by *S. G. Cohen, A. Streitwieser, Jr.*, and *R. W. Taft*. Interscience Publishers, a Division of John Wiley & Sons, New York-London 1963. 1st Edit., X + 411 pp., numerous tables, linen $ 15.00.

The stream of publications, in which organic chemical reactions are dealt with from the viewpoint or with the quantitative methods of physical chemistry, has become so fast flowing that physical-organic chemistry must now be veriewed periodically by volumes in the "Progress" series. The first volume in such a series has appeared under the editorship of three leading capacities in this field. It presents critical, detailed reviews of current problems and is intended to stimulate further work and discussions. As stated in the foreword, the editors have encouraged their authors to give comprehensive reports, with enough numerical data, and without disdaining speculative outlooks for the future.

The present volume begins with a relatively short review (30 pp.) by *A. Streitwieser* of the ionization potentials of organic radicals, hydrocarbons, and compounds with heteroatoms. *S. N. Ross* then reports on nucleophilic aromatic substitution (44 pp.), and *N. N. Lichtin* deals with ionization and dissociation equilibria in liquid sulfur dioxide (34 pp.). Two long articles by *E. A. Halevi* and *E. M. Arnett*, respectively, give abundant data on secondary isotope effects (182 pp.) and on the quantitative comparison of weak organic bases (114 pp., including about 80 pp. with basicity values). All the articles are supplemented with numerous references and are written clearly and intelligibly. Because the theory of the topics is dealt with first, and then sometimes the experimental methods are described, the experimental results being given at the end, the essays will supply information and incentives not only to the theoretician, but also to the organic chemist engaged in synthetic work. The next volumes of this series can be looked forward to.

W. Lüttke [NB 328/186 IE]

Comprehensive Analytical Chemistry, Vol. II A: Electrical Methods. Edited by *C. L. Wilson* and *D. W. Wilson* in cooperation with *C. R. N. Strouts*. Elsevier Publishing Co., Amsterdam-London-New York 1964. 1st Edit., XVI + 268 pp., numerous illustrs. and tables, linen, price for separate volume DM 33.50 (about $ 8.50).

The series "Comprehensive Analytical Chemistry" by *C. L. Wilson* and *D. W. Wilson* is continued by the appearance of this first part of Volume II. This part contains the sections "Electrogravimethy" by *A. J. Lindsey*, "Potentiometric Titration" and "Conductometric Titrations", both by *D. G. Davis*, and a chapter on "Impedimetric Titration" (high frequency titration) by *T. S. Burkhalter*. The outward appearance of the book is excellent.

All chapters are built up according to the same pattern: a short introduction describing the fundamentals and principles followed by a discourse on methods with data on commercially available apparatus and their mode of functioning. Each section is closed by indications of the applications, together with a number of analytical procedures and with occasionally very comprehensive lists of references. The treatment of polarography, amperometry, and coulometry and related electrical analytical methods is reserved for Volume II B.

Despite the lucid and terse style of the readable text, the editors' original aim of presenting the book as a practical manual is, in the reviewer's opinion, only partially fulfilled, and this for two reasons: first, whenever points come up which cannot be described in detail in the space available, references to explicatory literature should be given to support the argument; second, a good survey of the analytical methods available for solving definite problems should be given, together with information on the apparatus to be used. Both of these requirements are insufficiently fulfilled when it is considered that in a manuscript completed in 1963, the latest reference is from 1959 – and this only in the section on potentiometry – and no notice is taken of recent handbooks, monographs, and journal publications, and that in the chapter on impedimetry – the latest technique discussed and one that is still developing – the literature has only been checked up until 1957. Furthermore, the significant contributions that all European countries have made to the development of the instrumentative side of the fields discussed by the production of reliable analytical apparatus are hardly mentioned.

K. Cruse [NB 309/168 IE]

Synthetic Methods of Organic Chemistry. By *W. Theilheimer*. Vol. 18, Annual for 1964, with a key to the index in German. Verlag S. Karger AG., Basel-New York 1964. 1st Edit., XVI + 565 pp., linen DM 170.– (about $ 43.00).

The form and quality of the 1964 volume of "Theilheimer" are completely in keeping with the high standards of the well known earlier volumes. A selection of 998 characteristic reactions has been made from publications in the field of preparative organic chemistry which appeared in the years 1961–1963. The examples include both stereospecific reactions and transformations of numerous hetero-organic compounds. Pared out of the cumbersome context of the original publications, the vast array of reactions given here appear in a readily surveyable form which provoke the reader to attempt analogous syntheses. Readers who encounter difficulties with the classification scheme used, which is not very simple to grasp but which is used with unerring uniformity throughout, will find welcome assistance in the excellent key-word index (102 pp.), which covers Vols. 16–18. However, it remains a moot point whether an additional punched card catalogue would not augment the value of this series.

S. Hünig [NB 323/181 IE]

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The Hetarynes

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Dedicated to Professor Fritz Micheel on the occasion of his 65th birthday

Investigations carried out during the last six years have shown that, as in the case of benzene, an extra bond can be introduced into heteroaromatic rings. Since this possibility does not appear to be confined to exceptional cases, the heterocyclic arynes (hetarynes) promise a much wider variety than the carbocyclic arynes. Hetarynes occur mainly as intermediates in nucleophilic substitutions on halogenated heterocyclic compounds. Since the replacement of a CH group in dehydrobenzene by a nitrogen atom and the condensation of benzene rings have stabilizing effects, the stability of hetarynes is expected to increase with the number of N atoms and with the number of condensed aromatic rings.

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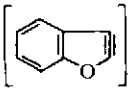
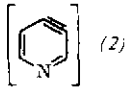
I. Introduction

The discovery of dehydrobenzene [1], which is associated with the names *G. Wittig*, *J. D. Roberts*, and *R. Huisgen*, raised the question of whether heteroaromatic compounds could also, like benzene, be converted into *o*-dehydro compounds.

Chance observations suggested that this conversion is in fact possible. Thus *Stoermer* and *Kahlert* [2] observed the formation of 2-ethoxycoumarone when sodium ethoxide was treated with 3-bromocoumarone; they explained this as resulting from the intermediate formation of 2,3-dehydrocoumarone *(1)*. Similarly the reactions of 3-bromothionaphthene with potassium hydroxide and with piperidine yield 2-hydroxythionaphthene (15 %) [3] and 2-piperidinothionaphthene (20 %) [4] respectively. Furthermore, 4-aminopyridine (10 %) and 4-phenacylpyridine (13 %) are obtained by the reaction of 3-bromopyridine with sodamide in liquid NH_3 containing acetophenone; this was explained by the intermediate formation of 3,4-dehydropyridine *(2)* [5].

(1)   *(2)*

[*] New address: Organisch-Chemisches Institut der Universität Münster (Germany).

[1] Most recent review on dehydrobenzene and related compounds: *H. Heany*, Chem. Reviews *62*, 81 (1962).

[2] *R. Stoermer* and *B. Kahlert*, Ber. dtsch. chem. Ges. *35*, 1633 (1902).

[3] *G. Komppa* and *S. Weckmann*, J. prakt. Chem. [2] *138*, 125 (1933).

[4] *K. R. Brower* and *E. D. Amstutz*, J. org. Chemistry *19*, 411 (1954).

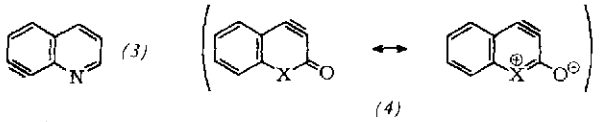
[5] *R. Levine* and *W. W. Leake*, Science (Washington) *121*, 780 (1955).

In spite of these observations, it was only at the end of the 1950's that any systematic studies on heterocyclic *o*-dehydroaromatic compounds were undertaken. Within a short time it was shown, for pyridine [6–14], quinoline [9, 15], thiophene [16, 17], and coumarone [17, 18], that an extra bond can be introduced into six- and five-membered heteroaromatic rings [19].

II. Nomenclature

The term "hetarynes" has been proposed [9, 21] for *o*-dehydroaromatic compounds (arynes [20]) with heteroatoms in the ring. This permits the formation of simple compound names such as hetaryne *N*-oxides or hetarynium ions, and appears to be gaining wide acceptance.

In order to define the applicability of the term "hetarynes", it is necessary first to settle two questions, namely whether the term is to include *o*-dehydroaromatic compounds in which, as in the case of 7,8-dehydroquinoline *(3)*, the extra bond is situated in a carbocyclic ring, and what criterion of aromaticity is to be used. It seems reasonable to answer the first of these questions in the affirmative, since heteroatoms in neighboring rings affect the reactions of the extra bond (cf. the addition of piperidine to 7,8-dehydroquinoline; Section III,7); this answer is also consistent with the fact that the individual compounds are best named on the basis of the parent heterocyclic system, as in "7,8-dehydroquinoline". With regard to the second question, we suggest that, as in the textbook by *Katritzky* and *Lagowski* [23], the criterion of aromaticity adopted should be that proposed by *Hückel*, *i.e.* the possibility of cyclic mesomerism involving six π-electrons. According to this criterion, compounds such as 3,4-dehydrocoumarin *(4)* (X = O) [24] and 1-methyl-2-phenyl-4,5-dehydropyridazine-3,6-dione *(70)* should also be regarded as hetarynes.



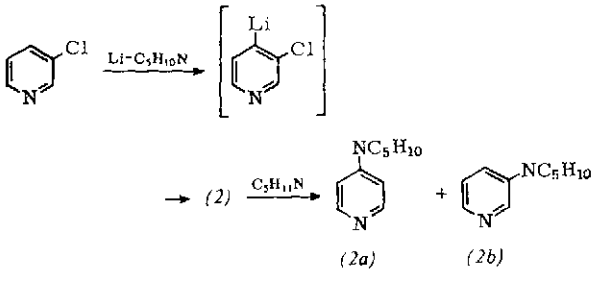
(3) *(4)*

III. Hetaryne Intermediates in Nucleophilic Substitutions

1. The EA, AE_n, and AE_a Mechanisms

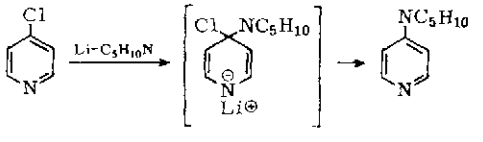
The hetarynes are particularly important as intermediates in nucleophilic substitutions on heterocyclic aryl halides. There are three possible mechanisms for these reactions:

(a) The elimination-addition (EA) mechanism [24, 25], *e.g.* [11]:



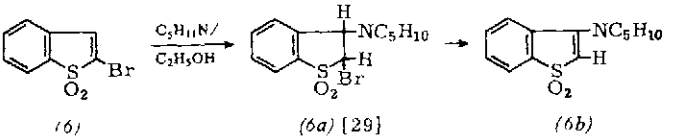
(2) *(2a)* *(2b)*

(b) The normal addition-elimination (AE_n) mechanism [24, 25], *e.g.* [11]:



(5) [27]

(c) The abnormal addition-elimination (AE_a) mechanism [24, 28]:



(6) *(6a)* [29] *(6b)*

[6] *R. Huisgen* in *H. Zeiss*: Organometallic Chemistry. Reinhold Publishing Corp., New York 1960, p. 78.

[7] *R. Huisgen* and *A. Hauser* (1959), and *K. Herbig* (1961), personal communications.

[8] *Th. Kauffmann* and *F.-P. Boettcher*, Angew. Chem. *73*, 65 (1961).

[9] *Th. Kauffmann*, *F.-P. Boettcher*, and *J. Hansen*, Angew. Chem. *73*, 341 (1961).

[10] *Th. Kauffmann* and *F.-P. Boettcher*, Chem. Ber. *95*, 949 (1962).

[11] *Th. Kauffmann* and *F.-P. Boettcher*, Chem. Ber. *95*, 1528 (1962).

[12] *M. J. Pieterse* and *H. J. den Hertog*, Recueil Trav. chim. Pays-Bas *80*, 1376 (1961).

[13] *R. J. Martens* and *H. J. den Hertog*, Tetrahedron Letters *1962*, 643.

[14] *M. J. Pieterse* and *H. J. den Hertog*, Recueil Trav. chim. Pays-Bas *81*, 855 (1962).

[15] *Th. Kauffmann*, *F.-P. Boettcher*, and *J. Hansen*, Liebigs Ann. Chem. *659*, 102 (1962).

[16] *G. Wittig* and *V. Wahl*, Angew. Chem. *73*, 492 (1961).

[17] *G. Wittig*, Angew. Chem. *74*, 479 (1962); Angew. Chem. internat. Edit. *1*, 415 (1962).

[18] *G. Wittig*, Pure appl. Chem. *7*, 173 (1963).

[19] The detection of *o*-dehydro compounds in the case of thiophene is still rather uncertain.

[20] *R. Huisgen* and *H. Rist*, Naturwissenschaften *41*, 358 (1954).

[21] *H. J. den Hertog's* review [22] on heterocyclic *o*-dehydroaromatic compounds is entitled "Hetarynes".

[22] *H. J. den Hertog* and *H. C. van der Plas* in: Advances in Heterocyclic Chemistry. Academic Press. New York 1965, Vol. 4, in the press.

[23] *A. R. Katritzky* and *J. M. Lagowski*: Heterocyclic Chemistry. Methuen and Co. Ltd., London 1960.

[24] *Th. Kauffmann*, *A. Risberg*, *J. Schulz*, and *R. Weber*, Tetrahedron Letters *1964*, 3563.

[25] Reviews on nucleophilic aromatic substitution: a) elimination-addition mechanism: [26]; b) normal addition-elimination mechanism: *J. Sauer* and *R. Huisgen*, Angew. Chem. *72*, 294 (1960).

[26] Cf. *R. Huisgen* and *J. Sauer*, Angew. Chem. *72*, 91 (1960).

[27] Adducts such as *(5)*, in which the anionic group becomes attached to the C-atom that carried the halogen, are referred to in the present paper as "normal", whereas adducts in which this is not the case are referred to as "abnormal". The corresponding addition reactions are designated in a similar manner.

[28] *F. G. Bordwell*, *B. B. Lampert*, and *W. H. McKellin*, J. Amer. chem. Soc. *71*, 1702 (1949).

[29] The structure of the adduct *(6a)* melting at 139–140 °C has not been established.

In the EA mechanism, which is of particular interest here, the halogeno compound is first deprotonated or else gains a metal atom from the base, this first attack taking place in the *o*-position with respect to the halogen. This is followed by the elimination of halide or metal halide. The resulting aryne generally adds on bases in both of the possible orientations, so that the usual product is a mixture of an "unrearranged" and a "rearranged" substitution product. The AE_n and AE_a mechanisms, on the other hand, lead to uniform products ("unrearranged" and "rearranged", respectively).

The only halogenated quasi-aromatic heterocyclic compound for which the AE_a mechanism has been observed is 2-bromothionaphthene *S*-dioxide *(6)* [28]; thus this mechanism appears to be very rare. Where a "rearranged" substitution product ("cine-substitution" [30]) is obtained, therefore, the EA mechanism is likely, but by no means certain since competition between an AE_n and an AE_a mechanism would also be possible. If, however, the ratio of the isomers in the product is independent of the nature of the halogen in the starting compound, it is reasonable to conclude that the reaction follows the EA mechanism [26], since this is the only mechanism in which the isomer ratio depends entirely on reactions of halogen-free compounds (addition of base to the aryne). In the case of competition between an AE_n and an AE_a mechanism, on the other hand, this ratio is determined by reactions of the halogenated compound (attachment of base to the aryl halide or elimination of halide from the adducts). The ratio also depends on reactions of the halogenated compound in the case of competition between an EA and an AE_n or AE_a mechanism.

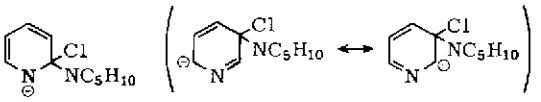
Another method often used to show that a reaction proceeds by an EA mechanism is to intercept the aryne intermediate by means of a weak base that does not react with the aryl halide (cf. Section III.6) or by means of a diene (cf. Section IV).

2. Hetarynes with the Grouping —C≡C—C=N— in the Ring

a) 3,4-Dehydropyridines and 3,4-Dehydroquinoline

α) Lithium Amides as Bases

In the "normal" addition [27] of an anion to 2- and 4-halogenopyridines or 2- and 4-halogenoquinolines, the negative charge can be taken over by the N-atom of the heteroaromatic compound, as shown in *(7)* and *(5)*; this should favor an AE_n mechanism. In agreement with this, the reactions of 2-chloro-6-methylpyridine, 4-chloropyridine, 2-chloroquinoline, and 4-chloroquinoline with lithium piperidide/piperidine in boiling ether yield exclusively or almost exclusively the 2- or 4-piperidino compound, as shown in Table 1 [11,15,31, 32]. The only exception is, rather surprisingly, 2-chloropyridine [11] (cf. Section VIII).



(7) *(8)*

The conditions favoring the AE_n mechanism are less satisfactorily fulfilled in the case of the 3-halogeno derivatives of pyridine and quinoline. In these cases the "normal" anion adducts [27], *e.g. (8)*, should be less stable, since the negative charge cannot be taken over by the pyridine or quinoline N atom as in *(5)* or *(7)*. In this case, therefore, the EA mechanism is most likely. In fact, the reactions of 3-halogenopyridines [6,7,11] or 3-halogenoquinolines [9,15] with lithium piperidide/piperidine in boiling ether lead to mixtures of the 3- and 4-piperidino compounds. The isomer ratios are independent of the nature of the halogen (Cl, Br, and Cl, Br, I, respectively) within the limits of accuracy of the measurements (cf. Table 1). Therefore, these reactions can be assumed to proceed largely or entirely by the EA mechanism, *i.e. via* 3,4-dehydropyridine *(2)* or 3,4-dehydroquinoline *(9)*.

It should be pointed out that these hetarynes have also been detected, although in a different reaction (cf. Section IV), by interception with furan.

Table 1. Yield of aromatic piperidino compounds and percentages of the two isomers on reaction of halogenopyridines [7, 11] and halogenoquinolines [15] with lithium piperidide/piperidine in boiling ether.

Starting compound	Aromatic piperidino compound			
	Total yield [%]	Distribution of x-isomers [%]		
		x = 2	x = 3	x = 4
Halogenopyridines				
2-F	97	100	—	—
2-Cl	< 1 (resin)	traces	—	—
2-Cl; 6-CH_3 [31]	75 [11]	100	—	—
3-F	84 [7]; 92 [11]	—	100 [7]; 96 [11]	0 [7]; 4 [11]
3-Cl	66 [7]; 87 [11]	—	52 [7]; 48 [11]	48 [7]; 52 [11]
3-Br	78 [7]; 88 [11]	—	48 [7]; 48 [11]	52 [7]; 52 [11]
4-Cl	88 [7]; 95 [11]	—	0 [7]; 0,4 [11]	100 [7]; 99,6 [11]
Halogenoquinolines				
2-Cl [32]	93	100	—	—
3-F	75	—	100	0
3-Cl	45	—	48	52
3-Br	61	—	50	50
3-I	58	—	49	51
4-Cl [31]	85	—	1	99

Since the aromatic piperidino compounds are stable under the reaction conditions [33], the percentages of the isomers as given in Table 1 correspond to the frequencies of the addition of piperidine to *(2)* and *(9)* in the two possible orientations. A comparison of these ratios [which are given in formulae *(2')* and *(9)*] with corresponding values for the addition of piperidine to

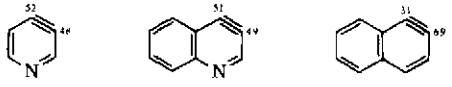
[30] *J. F. Bunnett*, Quart. Rev. (chem. Soc., London) *12*, 1(1958); *J. F. Bunnett* and *R. E. Zahler*, Chem. Reviews *49*, 294 (1951).

[31] *Th. Kauffmann* and *R. Weber*, unpublished work, 1964.

[32] *R. Wirthwein*, Doctorate Dissertation, Technische Hochschule Darmstadt.

[33] *R. Nürnberg*, Diploma Thesis, Technische Hochschule Darmstadt, 1965.

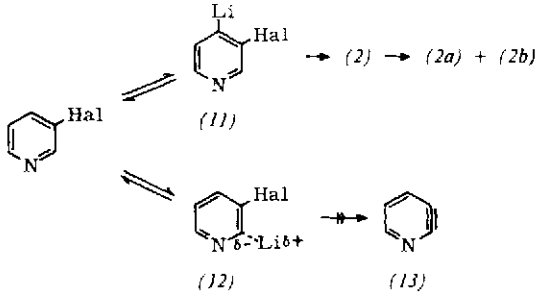
1,2-dehydronaphthalene *(10)* under the same conditions [26] shows that the fusion of a benzene ring to 3,4-dehydropyridine has hardly any effect on the orientation of the addend, whereas the replacement of a CH group in 1,2-dehydronaphthalene by a nitrogen atom profoundly influences the orientation (cf. Section VII).



(2') *(9)* *(10)*

As can be seen from Table 1, the 3-fluoro compounds represent a special case. In these compounds, substitution proceeds largely or entirely "without rearrangement", *i.e.* probably by the AE_n mechanism. This agrees with the finding [34] that the AE_n mechanism is more strongly favored by aromatic fluoro compounds than by other aromatic halogeno compounds. It is only when 3-fluoropyridine is treated with lithium piperidide in the absence of piperidine that the resulting piperidinopyridine contains 30% of the 4-isomer in addition to the 3-isomer [7].

In the reactions of the 3-halogenopyridines and 3-halogenoquinolines, no trace of the aromatic 2-piperidino compounds has been obtained. Thus the intermediate formation of 2,3-dehydropyridine *(13)* or 2,3-dehydroquinoline is unlikely, since the piperidino group should become attached to these mainly in position 2 [35]. Since we cannot assume that there is absolutely no attachment of the metal to C-2 of the 3-halogeno compound [11], and since 2,3-dehydropyridine and 2,3-dehydroquinoline should be more stable than the 3,4-isomers (cf. Section VI), this finding can only be explained as follows: The partial negative charge on C-2 of the hypothetical 3-halogeno-2-lithiopyridine, which is a result of the polarization of the C-Li bond, is strongly attracted by the adjacent nitrogen atom; consequently the halogen atom does not receive a sufficiently large negative charge to permit its elimination as a halide ion [11]. The isomeric 4-lithio compounds *(11)* which are in equilibrium with the 2-lithio compounds, on the other hand, lose LiHal.



[34] AE_n substitution also occurs in the reaction of fluoronaphthalenes with lithium piperidide/piperidine [*R. Huisgen, J. Sauer, W. Mack*, and *I. Ziegler*, Chem. Ber. *92*, 441 (1959)] or of *p*-fluorotoluene with sodium hydrazide/hydrazine [*Th. Kauffmann* and *H. Henkler*, Chem. Ber. *96*, 3159 (1963)], whereas the corresponding chloro and bromo compounds under the same conditions react by the EA mechanism.

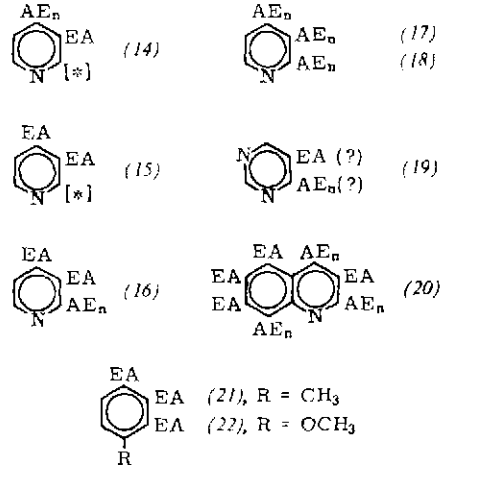
[35] Nothing is known about the rate constants for the addition of bases onto 2,3-dehydropyridine and 2,3-dehydroquinoline in the two possible orientations.
However, since the addition of anionic groups onto 4,5-dehydropyrimidine [36,37] and onto 2-methyl-4,5-dehydropyrimidine [38] takes place predominantly at the end of the extra bond α to the ring nitrogen, this is also to be expected for 2,3-dehydropyridine and 2,3-dehydroquinoline.

The nucleophilic substitution of aryl halides can be represented by "mechanism maps", as shown in Table 2. The mechanism maps *(14)*, *(17)*, and *(20)*, are essentially based on results given in Table 1 and in Section III.7. As is shown in *(15)*, the reaction of 4-chloropyridine with lithium diethylamide, unlike the reaction with lithium piperidide, proceeds largely or wholly by the EA mechanism, possibly owing to the bulky nature of the diethylamide ion. The ratio of 3- and 4-diethylaminopyridine in the product is approximately 1:1, irrespective of whether the starting material is 3- or 4-chloropyridine. In the case of 2-chloropyridine, surprisingly, resinification also takes place with lithium diethylamide (cf. Section VIII).

In contrast to their behavior towards lithium piperidide/piperidine, the chloropyridines react with piperidine alone at 140 °C by an AE_n mechanism to give "unrearranged" substitution products, as is shown by *(18)*. It can be seen from *(19)*, however, that "cine-substitution" can also occur, probably by the EA mechanism (cf. Section III.3.b), on heating with piperidine.

Table 2. "Mechanism maps" for the nucleophilic substitution of heterocyclic and carbocyclic aryl halides. (The reaction mechanisms observed for the various substitution positions are indicated in these positions).

Mechanism map	Substituent	Base	Temp. [°C]	Ref.
(14)	Cl	$LiC_5H_{10}N/C_5H_{11}N$	35	[6,7,11]
(15)	Cl	$LiN(C_2H_5)_2/HN(C_2H_5)_2$	35	[31,33]
(16)	Cl	KNH_2/NH_3	−33	[12,22]
(17)	F	$LiC_5H_{10}N/C_5H_{11}N$	35	[11,31]
(18)	Cl	$C_5H_{11}N$	140	[11,39,40]
(19)	Br	$C_5H_{11}N$	106	[36,37]
(20)	Cl	$LiC_5H_{10}N/C_5H_{11}N$	35	[15,32,41]
(21)	Br	$Li_5H_{10}N/C_5H_{11}N$	35	[26]
(22)	Cl, Br	KNH_2/NH_3	−33	[26]



[*] The reaction of 2-chloropyridine leads to resinification.

[36] *Th. Kauffmann, J. Hansen, K. Udluft*, and *R. Wirthwein*, Angew. Chem. *76*, 590 (1964); Angew. Chem. internat. Edit. *3*, 650 (1964).

[37] *K. Udluft*, Doctorate Dissertation, Technische Hochschule Darmstadt.

[38] *Th. J. Schwan* u. *H. Tieckelmann*, J. org. Chemistry *29*, 941 (1964).

[39] *R. Graf*, J. prakt. Chem. [2] *138*, 239 (1933).

[40] *J. P. Wibaut* and *G. Tilmann*, Recueil Trav. chim. Pays-Bas *52*, 987 (1933).

[41] *Th. Kauffmann, J. Hansen*, and *R. Wirthwein*, Liebigs Ann. Chem. *680*, 31 (1964).

Thus the nucleophilic substitution of heterocyclic aryl halides is much more complicated than that of the halides of typical benzene derivatives such as toluene or anisole, which on reaction with lithium piperidide or KNH_2 undergo substitution exclusively by the EA mechanism [26], as is shown in *(21)* and *(22)*.

β) Potassium Amide as Base

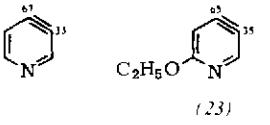
While the work described above was being carried out, *den Hertog* and his co-workers [12, 14, 22, 42, 43] studied the action of KNH_2 in liquid NH_3 (−33 °C) on halogenopyridines. Pyridines containing halogen (Cl, Br, I [44]) in position 3 give 60 to 70 % yields of a mixture of 3- and 4-aminopyridine. The ratio of the isomers is constant (1:2) and independent of the halogen, indicating that the reaction proceeds entirely *via* 3,4-dehydropyridine. No 2-aminopyridine is formed [12, 22]. For reasons that are not yet known, pyridines containing halogen (Cl, Br, I) in position 4 give the same reaction mixture [12, 22] (in contrast to the reactions with lithium piperidide, cf. Section 2.a.α), *i.e.* they probably react quantitatively *via* 3,4-dehydropyridine, whereas the reaction with 2-chloropyridine leads to 2-aminopyridine, and does not result in resinification. The AE_n mechanism is more likely for this last reaction than the equally feasible EA mechanism *via* 2,3-dehydropyridine [35], since no trace of 3-aminopyridine is found, and since the yield of 2-aminopyridine is the same as in the reaction with 2-fluoropyridine, which almost certainly proceeds by the AE_n mechanism [34].

The influence of the ethoxy group on the orientation of the amino group in the addition of NH_3/KNH_2 [45] to ethoxy-3,4-dehydropyridines can be found from extensive experimental data (Table 3) regarding the action of KNH_2/liquid ammonia on ethoxybromopyridines [12, 42]. As can be seen from Table 4, the ethoxy group in the β-position to the extra bond in *(23)* has practically no effect. The ethoxy groups in the α-position to the extra bond in *(24)* and *(25)*, on the other hand, profoundly influence the orientation. Like the methoxy group of 2,3-dehydroanisole *(26)* [46], they force the amino group into the position farther away from the substituent.

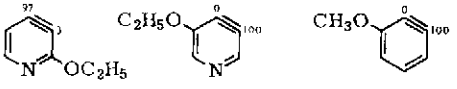
Table 3. The reaction of substituted bromopyridines with liquid NH_3 at −33 °C.

Starting pyridine	Pyridine obtained	Isomer distribution [%]	Total yield [%]
3-Bromo-2-ethoxy-	3-Amino-2-ethoxy-	3	90
	4-Amino-2-ethoxy-	97	
3-Bromo-5-ethoxy-	3-Amino-5-ethoxy-	100	90
3-Bromo-6-ethoxy-	3-Amino-6-ethoxy-	35	95
	4-Amino-6-ethoxy-	65	
4-Bromo-3-ethoxy-	5-Amino-3-ethoxy-	100	90
3-Bromo-4-ethoxy-	2-Amino-4-ethoxy-	100	55–60
3-Bromo-4-methyl-	2-Amino-4-methyl-	main product	5
	3-Amino-4-methyl-	by-product	

Table 4. Distribution of products [47] obtained by the addition of NH_3/KNH_2 [45] to 3,4-dehydropyridines [12, 22, 42] and 2,3-dehydroanisole [46].



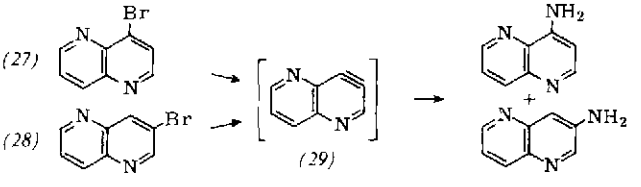
(23)



(24) *(25)* *(26)*

b) 3,4-Dehydro-1,5-naphthyridine

The action of KNH_2 in liquid NH_3 at −33 °C on the bromo-1,5-naphthyridines *(27)* and *(28)* again leads to mixtures of the 3-amino and 4-amino compounds, so that both reactions probably proceed *via* the common hetaryne intermediate *(29)*. Depending on whether the starting material is the 3-bromo or the 4-bromo compound, the ratio of the 3- and 4-amino derivatives in the product is 85:15 or 78:22. One or both of these substitutions, therefore, probably involve competing EA and AE_n mechanisms [48]. Since, as we have seen above, 3- and 4-bromopyridines react quantitatively by the EA mechanism under the same conditions [12, 22], the heterocyclic ring fused to the brominated ring in *(27)* and *(28)* evidently favors the AE_n mechanism.



(27) *(28)* *(29)*

The same phenomenon (which we shall meet again in Section III.7) is found in the case of 3-bromo-2-ethoxy-1,5-naphthyridine. In contrast to 3-bromo-2-ethoxypyridine (EA mechanism, cf. Table 3), this compound reacts with KNH_2/NH_3 (−33 °C) to give only the 3-amino compound [48], *i.e.* the reaction seems to proceed entirely by the AE_n mechanism.

[42] *H. J. den Hertog, M. J. Pieterse,* and *D. J. Buurman,* Recueil Trav. chim. Pays-Bas *82*, 1173 (1963).

[43] *R. J. Martens* and *H. J. den Hertog,* Recueil Trav. chim. Pays-Bas *83*, 621 (1964).

[44] According to *R. J. Martens, H. J. den Hertog,* and *M. van Ammers,* Tetrahedron Letters *1964*, 3207, the corresponding reaction with 3-fluoropyridine leads to several fluorinated dipyridyls; when excess KNH_2 is present, a little 3-aminopyridine is also formed.

[45] It is not yet known whether, in the reactions of heterocyclic aryl halides with KNH_2/NH_3, the compound that adds onto the intermediate hetaryne is mainly the potassium compound or the free base. Since the NH_3 is present in large excess, and since it is known that lithium piperidide and piperidine add equally rapidly to the aryne 9,10-dehydrophenanthrene [26], it is likely that the addition of NH_3 predominates.

[46] *J. D. Roberts, C. W. Vaughan, L. A. Carlsmith,* and *D. A. Semenow,* J. Amer. chem. Soc. *78*, 611 (1956).

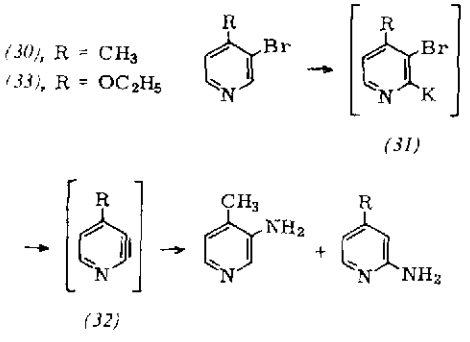
[47] It is assumed that the addition products are stable under the experimental conditions.

[48] *W. Czuba,* Recueil Trav. chim. Pays-Bas *82*, 997 (1963).

3. Hetarynes with the Grouping —C≡C—X– (X = N, O, S) in the Ring

a) 2,3-Dehydropyridines and 3,4-Dehydroisoquinoline

The fact that the action of alkali metal amides on 3-halogenopyridines yields only 3,4-dehydropyridine *(2)* with no 2,3-dehydropyridine *(13)* was ascribed (cf. Section III.2.a) to the much more rapid elimination of metal halide from 3-halogenopyridines with a metal atom on C-4 than from those with a metal atom on C-2. In agreement with this explanation, 3-bromo-4-methylpyridine *(30)*, in which the metal cannot become attached to C-4, reacts only slowly with KNH_2/NH_3 (–33 °C) [22], and gives only a small yield (5 %) of a mixture of the 2- and 3-amino compounds, in which the former predominates [22]. Thus the 2,3-dehydro compound *(32)*, R=CH_3, is probably formed when reaction *via* the 3,4-dehydro compound is blocked; since the bromine carries only a small negative charge (cf. Section III. 2a), however, the reaction is very slow.



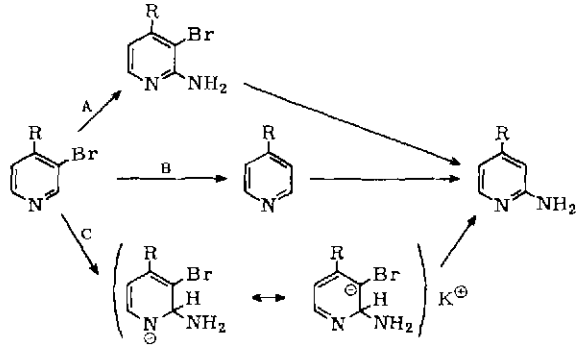
(30), R = CH_3
(33), R = OC_2H_5

(31)

(32)

A group on C-4 that tends to impose a negative charge on the halogen should facilitate the removal of halide from compounds such as *(31)*. This explains the fact that *(33)* reacts rapidly with KNH_2/NH_3 (–33 °C) to form 2-amino-4-ethoxypyridine (55–60 %). The 3-isomer is apparently not formed [12,42].

Apart from the route involving the hetaryne intermediates *(32)* routes A, B, and C in Scheme 1 are also feasible for these cine-substitutions. Of these, A and B are particularly important possibilities in the case of the ethoxy compound *(33)*, since *o*-bromoanisole is reductively dehalogenated by metal amides [49], and since up to 5 % of 4-ethoxypyridine has been isolated from the reaction mixture. Both of these routes, however, have been ruled out by experiment [14]. Until route C (AE_a mechanism) can also be ruled out, the occurrence of *(32)* as an intermediate cannot be regarded as certain.

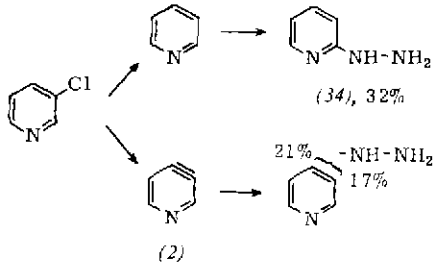


Scheme 1. Possible routes for the cine-substitution of pyridines not involving hetaryne intermediates.

[49] *R. A. Benkeser* and *C. E. De Boer*, J. org. Chemistry *21*, 281 (1956).

It should be pointed out that 2,3-dehydropyridine has been intercepted by furan in another type of reaction, which is discussed in Section IV.

The need for caution in the interpretation of cine-substitutions on the pyridine system when the point of attachment of the new substituent is α to the nitrogen atom can be seen from the fact that the reaction of 3-chloropyridine with sodium hydrazide in ether at 20 °C to form 2-hydrazinopyridine *(34)* [50] involves pyridine as an intermediate [51]. An AE substitution with formation of 3- and 4-hydrazinopyridine competes with this reaction.



(34), 32%

21% 17%

(2)

The amination of pyridine with $NaNH_2$ (Chichibabin reaction) was assumed by *L. S. Levitt* and *B. W. Levitt* [52] to proceed *via* 2-pyridylsodium and 2,3-dehydropyridine. This mechanism cannot, however, be generally applicable, since 3-substituted pyridines, which cannot form 2,3-dehydro intermediates, are also aminated on C–2. Other impressive arguments against this mechanism have also been advanced [53 to 56]. It is clear, however, that the possibility of the formation of hetaryne intermediates makes it necessary sometimes to reconsider currently accepted views on mechanism.

In 4-bromoisoquinoline *(35)*, as in *(30)* and *(33)*, the *p*-position with respect to the heteroatom is occupied. Consequently, the reaction of *(35)* with lithium piperidide/piperidine was expected to result in cine-substitution with formation of 3-piperidinoisoquinoline *(36a)*. However, neither *(36a)* nor the 4-isomer *(36b)* is formed at 35–80 °C. Instead, most of the compound *(35)* is recovered unchanged after hydrolysis of the reaction mixture [57]; this could be due to introduction of the metal in the "wrong" position to form *(37a)* (cf. Section III.7.b), or alternatively the "correct" product *(37b)* may be very stable [58]. Compound *(36a)* and the 4-isomer (ratio 1:9) are, however, formed when 4-bromoisoquinoline is heated to 180 °C with anhydrous piperidine. Under these conditions, therefore, 3,4-de-

[50] *H. Henkler*, Doctorate Dissertation, Technische Hochschule Darmstadt, 1962.

[51] *Th. Kauffmann* and *J. Schulz*, unpublished work.

[52] *L. S. Levitt* and *B. W. Levitt*, Chem. and Ind. *1963*, 1621.

[53] Cf. *G. C. Barrett* and *K. Schofield*, Chem. and Ind. *1963*, 1980.

[54] *R. A. Abramovitch*, *F. Helmer*, and *J. G. Saha*, Chem. and Ind. *1964*, 659; Tetrahedron Letters *1964*, 3445.

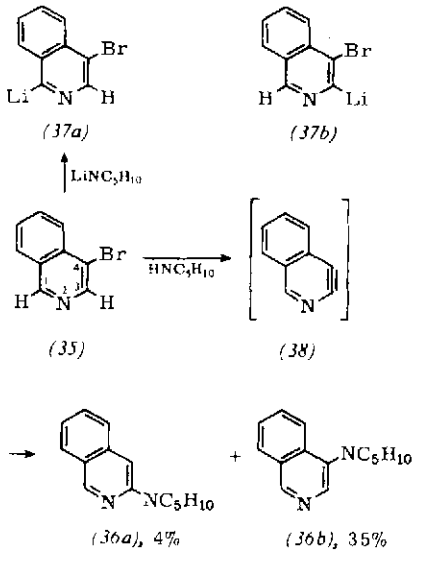
[55] *Th. Kauffmann*, Angew. Chem. *76*, 209 (1964); Angew.Chem. internat. Edit. *3*, 344 (1964).

[56] *Y. Ban* and *T. Wakamatsu*, Chem. and Ind. *1964*, 710.

[57] *J. Hansen*, Doctorate Dissertation, Technische Hochschule Darmstadt.

[58] The attachment of the metal to C-1 is not unlikely, since calculations by *H. C. Longuet-Higgins* and *C. A. Coulson*, Trans. Faraday Soc. *43*, 87 (1947), have shown that the π-electron density in unsubstituted isoquinoline is lowest on C-1 (0.767). The value for C-3 is much higher (0.942).

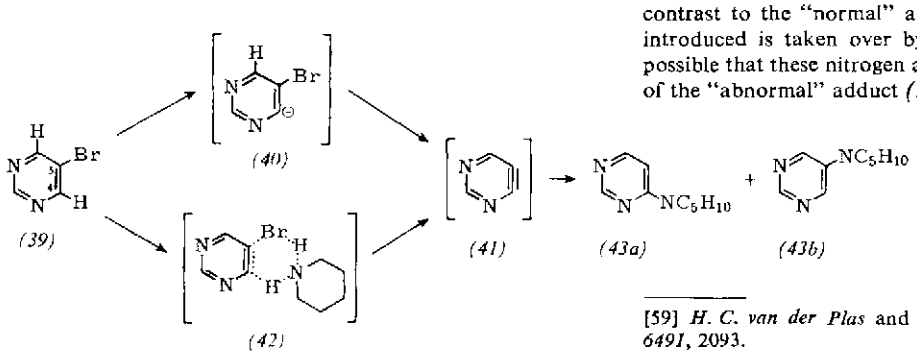
hydroisoquinoline *(38)* may be assumed to be formed as an intermediate. The proton affinity of piperidine is apparently sufficient to permit the removal of the hydrogen atom in position 3 of 4-bromoisoquinoline, from which electrons are withdrawn by the neighboring



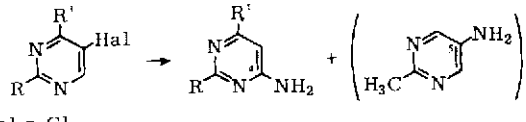
nitrogen and Br atoms. The high proportion of the "unrearranged" substitution product suggests competition between EA and AE_n mechanisms.

b) 4,5-Dehydropyrimidines

In 5-bromopyrimidine *(39)*, which contains two electronegative ring members, the hydrogen *ortho* to the bromine should carry an even stronger positive charge than that in *(35)*. It is not surprising, therefore, that *(39)* reacts with piperidine at 106 °C to give 4-piperidinopyrimidine *(43a)* in 29 % yield [36,37]. Possibly the 5-isomer *(43b)* is also formed in small amounts. The reaction of *(39)* with lithium piperidide/piperidine in benzene at 80 °C also gives rise to *(43a)* in 7 % yield. In a similar experiment in ether at 35 °C, the starting material *(39)* was recovered unchanged on hydrolysis of the reaction mixture, indicating that the hypothetical 5-bromo-4-lithio-pyrimidine has a relatively high stability. If the reaction of 5-bromopyrimidine with piperidine proceeds *via* the anionic intermediate *(40)* and 4,5-dehydropyrimidine *(41)* (a synchronous elimination of HBr, *e.g.* involving the transition state *(42)* would also be feasible), the reaction should be inhibited by a proton donor stronger than piperidine, owing to protonation of *(40)*. At 106 or 160 °C, in fact, the reaction is completely suppressed by the addition of aniline or ethanol. This is reminiscent of the inhibition [26] of the EA mechanism in the reaction of lithium piperidide and 1-fluoronaphthalene by the addition of free piperidine.

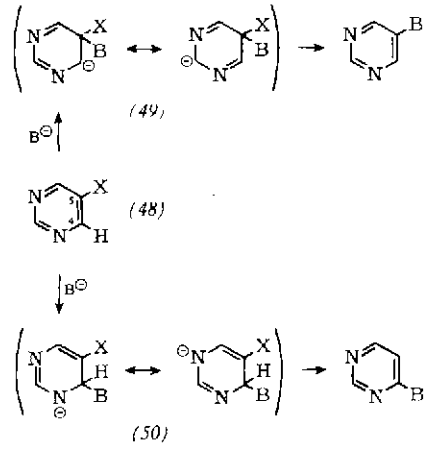


The occurrence of a substituted 4,5-dehydropyrimidine was first indicated by the formation of small quantities of the isomers *(46)* and *(47)* during the reaction of 5-chloro-2-methylpyrimidine *(44)* with KNH_2/NH_3 (−33 °C) [38]. *Van der Plas* and *Geurtsen* [59] obtained much better yields of cine-substitution product (Table 5) under the same conditions from 5-bromopyrimidines *(45)* containing (-I)-substituents (OCH_3 and OH) α to the halogen (cf. Section III.3a); no "unrearranged" substitution products were detected in these cases.



(44): Hal = Cl
R = CH_3; R' = H (5%)
R = H; R' = C_6H_5 (15%)
(45): Hal = Br
R = H; R' = OCH_3 (70%)
R = H; R' = OH (75%)

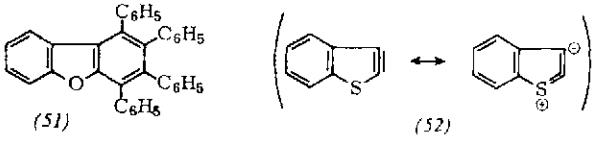
Although there is much to suggest that the cine-substitutions observed with 5-halogenopyrimidines are due to the EA mechanism, it should not be overlooked that there is as yet no proof of this (*e.g.* evidence that the ratio of the isomers is independent of the halogen), and that these compounds also present favorable conditions for the AE_a mechanism (cf. Section III.1): since the attachment of an anion ($B^{\ominus}$) to C—4 of compound *(48)* would lead to a product *(50)* in which, in contrast to the "normal" adduct *(49)*, the negative charge introduced is taken over by two nitrogen atoms, it seems possible that these nitrogen atoms would force the formation of the "abnormal" adduct *(50)*.



[59] *H. C. van der Plas* and *G. Geurtsen*, Tetrahedron Letters *6491*, 2093.

c) 2,3-Dehydrocoumarone and 2,3-Dehydrothionaphthene

Stoermer and *Kahlert*'s theory [2] that the conversion of 3-bromocoumarone to 2- and 3-ethoxycoumarone at 200 °C involves 2,3-dehydrocoumarone *(1)* as an intermediate was convincingly corroborated by *Wittig* and *Boos* [18], who found that in the presence of tetraphenylcyclopentadienone (tetracyclone), the adduct *(51)* of the latter with 2,3-dehydrocoumarone (20 %) as well as the ethoxycoumarones are formed.

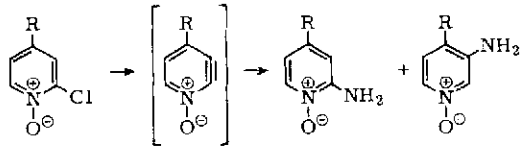


(51) *(52)*

Cine-substitutions were observed during the reaction of 3-bromothionaphthene with KOH (24 h at 200–220 °C in ethanol) [3] or with piperidine (46 h at 250–260 °C) [4]. In these reactions, which have not yet been reinvestigated, only 2-hydroxy- (15 %) and 2-piperidinothionaphthene (20 %) were isolated, but not the 3-isomers. If 2,3-dehydrothionaphthene *(52)* (which has been detected elsewhere, cf. Section IV) is involved as an intermediate, the preferred position for the entry of anionic groups into this molecule is probably on C-2.

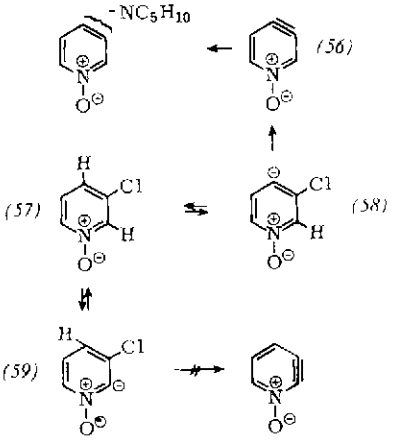
4. Hetaryne N-Oxides

Martens and *den Hertog* [43] have reported findings that point to the occurrence of 2,3-dehydropyridine-*N*-oxides *(54)* as intermediates. Thus in contrast to 3-chloropyridine *N*-oxide, from which only the 3-amino compound was obtained, the 2-chloropyridine *N*-oxides *(53)* reacted with KNH_2/NH_3 at −33 °C to form a mixture of the 2-amino (15 % and < 1 %) and 3-amino (1 % and 13–14 %) compounds *(55a)* and *(55b)*. These results have been confirmed by Japanese workers [60].

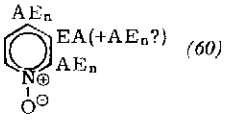


(53): R = H, OC_2H_5 *(54)* *(55a)* *(55b)*

Our own investigations [61], in which piperidine was used as the base, gave different results. Both 3-chloropyridine *N*-oxide *(57)* and 3-bromoquinoline *N*-oxide reacted at about 100 °C to give a mixture of the 3-piperidino (82 % and 20 %) and 4-piperidino (4 % and 22 %) compounds; no 2-isomer was formed in either case. This is in complete agreement with the results obtained in the reactions of 3-halogenopyridines and 3-halogenoquinolines with lithium piperidide, which have been shown to proceed by the EA mechanism. Consequently the reactions of these *N*-oxides probably also proceed by an EA mechanism involving 3,4-dehydropyridine *N*-oxide *(56)* and 3,4-dehydroquinoline *N*-oxide as intermediates, particularly since, owing to the electron-attracting properties of the NO group, it is to be expected that *(57)* and 3-bromoquinoline *N*-oxide can be deprotonated by piperidine. In addition to *(58)*, the deprotonation product *(59)* is probably also formed; owing to the withdrawal of electrons from C-2 by the nitrogen atom, however, *(59)* would lose halide only very slowly or not at all (cf. Section III.2.a).



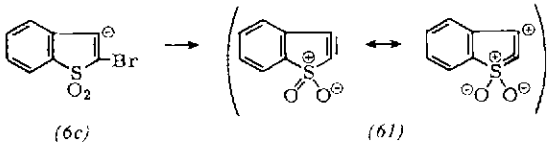
The *N*-oxides of 2-chloropyridine, 4-chloropyridine, and 4-chloroquinoline, when heated at about 100 °C with piperidine, give only the "unrearranged" substitution product in almost quantitative yield, so that these reactions may be assumed to proceed by the AE_n mechanism. The current views regarding the mechanisms followed by the reactions of chloropyridine *N*-oxides with piperidine are summarized in the mechanism map *(60)*.



(60)

5. Hetaryne S-Oxides

The reaction of 2-bromothionaphthene *S*-dioxide *(6)* (cf. Section III.1) with piperidine in ethanol follows the AE_a mechanism, yielding the 3-piperidino compound *(6b)* (90 %) *via* the "abnormal" adduct *(6a)* [28]. The reaction in benzene is five times as fast, and although the end product is the same (71 % yield), it can be shown [28] that the adduct *(6a)* does not occur as an intermediate. If the faster reaction is assumed to proceed *via* the carbanion *(6c)* and 2,3-dehydrothionaphthene *S*-



(6c) *(61)*

[60] *T. Kato*, *T. Niitsuma*, and *N. Kusaka*, J. pharmac. Soc. Japan (Yakugakuzasshi) *84*, 432 (1964).

[61] *Th. Kauffmann* and *R. Wirthwein*, Angew. Chem. *76*, 993 1964); Angew. Chem. internat. Edit. *3*, 806 (1964).

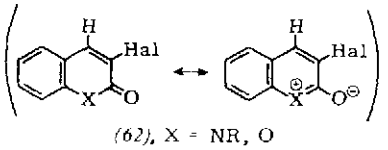
dioxide *(61)* [24], it is easy to see that this reaction would be suppressed by ethanol (cf. Section III.3.b). It has not been established whether small quantities of the 2-piperidinocompound are formed during the reaction in benzene.

The detection [62] of another hetaryne *S*-oxide, namely 4,5-dehydro-2,3;6,7-dibenzothiepin *S*-dioxide *(96)*, as an intermediate in a substitution will be described in Section IV.

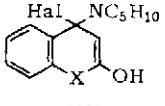
6. Hetarynes with the Grouping —C≡C—CO—X— (X = N, O) in the Ring

a) 3,4-Dehydrocarbostyrils and 3,4-Dehydrocoumarin

The hydrogen atom adjacent to the halogen in halides of the type *(62)*, as in the halogenated *N*-oxides, probably carries a relatively strong positive charge. It was therefore likely that piperidine would again be able to react by the EA mechanism. The halides listed in Table 5 do, in fact, react with anhydrous piperidine to give a mixture of two piperidino compounds [24, 36].



(62), X = NR, O



(63)

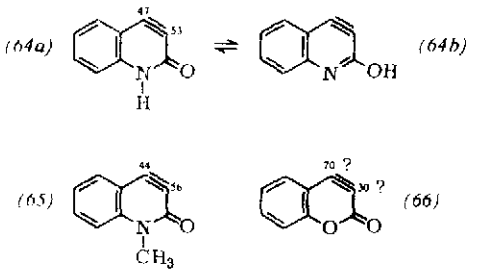
In the case of the 3-halogenocarbostyrils and 3-halogeno-1-methylcarbostyrils, the ratio of the 3- and 4-piperidino compounds is practically the same for the chloro as for the bromo compound. A pure EA mechanism involving 3,4-dehydrocarbostyril *(64)* [63] or 1-methyl-3,4-dehydrocarbostyril *(65)* as the intermediate is therefore likely [24].

Table 5. Reactions of halogenocarbostyrils and halogenocoumarins with piperidine [64].

Halogeno compound	Temp. [°C]	Piperidino compound [a] Total yield [%]	Isomer distribution [%] 3-isomer	4-isomer
3-Chlorocarbostyril	180	96 (0)	54	46
3-Bromocarbostyril	180	90 (65)	52 (62)	48 (38)
3-Chloro-1-methylcarbostyril	180	90 (0)	55	45
3-Bromo-1-methylcarbostyril	180	98 (0)	57	43
3-Chlorocoumarin	80	52 (27)	39 (60)	61 (40)
3-Bromocoumarin	80	79 (44)	30 (72)	70 (28)

[a] Values not in brackets: reaction with excess piperidine in dry benzene or with piperidine alone. Values in brackets: reaction in ethanol under otherwise identical conditions (lower yields owing to incomplete reaction of the halogen).

Table 5 also shows the good agreement between the ratios of the isomeric piperidino compounds obtained from 3-halogenocarbostyrils and 3-halogeno-1-methylcarbostyrils; the oxo form *(64a)* is therefore more likely as an intermediate than the tautomeric hydroxy form *(64b)*.



(64a) *(64b)* *(65)* *(66)*

The ratio of the isomers obtained from the reactions of 3-halogenocoumarins was found to depend on the halogen (cf. Table 5). This could be due to competition between EA and AE_n, EA and AE_a, or AE_n and AE_a mechanisms. It has been shown [31, 36], however, that 3-bromocoumarin gives 4-methoxycoumarin or 4-anilinocoumarin, as well as the piperidino compound when treated with piperidine in the presence of methanol or aniline. Since 3-bromocoumarin is stable towards methanol or aniline under the experimental conditions, this indicates the occurrence of 3,4-dehydrocoumarin *(66)* as an intermediate, so that the change in the ratio of the isomers must be due to competition between EA and AE_n, or EA and AE_a.

The reactions of halogenocarbostyrils and halogenocoumarins with piperidine are inhibited by ethanol. Where the inhibition is not complete, the isomer ratio is displaced in favor of the "unrearranged" product (cf. Table 5); as a result of blockage of the EA mechanism (cf. Section III.3.b), therefore, substitution by the AE_n mechanism becomes dominant.

The 4-isomers of the halides listed in Table 5 give only the 4-piperidino compounds on reaction with piperidine [24]. The adducts *(63)* postulated as intermediates appear to be readily formed.

b) 1-Methyl-2-phenyl-4,5-dehydropyridazine-3,6-dione and 4,5-Dehydrouracil

Druey [65] treated *(67)* (Hal = Cl) with sodium methoxide and obtained only the 5-methoxy compound *(68)*. This and similar [65] cine-substitutions with secondary amines have not yet been explained. Detailed investigations [24, 66, 67] showed that the reactions of the 4-halogeno compounds *(67)* of Table 6 with piperidine always give both the 4-piperidino and 5-piperidino compounds. Since the ratio of the isomers is independent

[62] *W. Tochtermann, K. Oppenländer,* and *U. Walter,* Angew. Chem. *76*, 612 (1964); *W. Tochtermann,* personal communication.

[63] *A. Baeyer* and *F. Bloem,* Ber. dtsch. chem. Ges. *15*, 2151 (1882) formulated 3,4-dehydrocarbostyril and tried to prepare it more than 80 years ago.

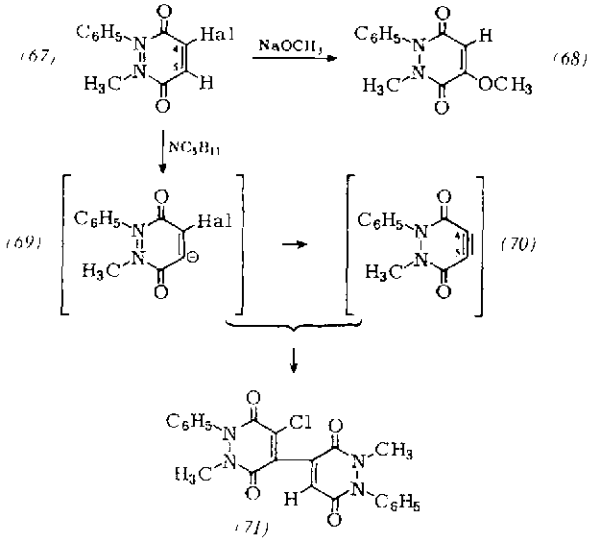
[64] 3-Bromo-1,1-dimethyl-2-oxo-1,2-dihydronaphthalene [*N.H. Cromwell* and *R. D. Compbell*, J. org. Chemistry *22*, 520 (1957)] and 8-bromoperinaphthen-7-one [*N. H. Cromwell, D. B. Capps,* and *S. E. Palmer*, J. Amer. chem. Soc. *73*, 1226 (1951)] react similarly with morpholine to give 4-morpholino-1,1-dimethyl-2-oxo-1,2-dihydronaphthalene and 8- and 9-morpholinoperinaphthen-7-one. The mechanism of this reaction has not been established.

[65] *J. Druey*, Angew. Chem. *70*, 12 (1958); *J. Druey, K. Meier,* and *A. Staehelin*, US.-Pat. 3004972 (Oct. 1961); Chem. Abstr. *56*, 12909 (1962).

[66] *Th. Kauffmann* and *A. Risberg*, Tetrahedron Letters *1963*, 1459.

[67] *A. Risberg*, Doctorate Dissertation, Technische Hochschule Darmstadt.

of the halogen, the reaction probably involves the halogen-free intermediate 1-methyl-2-phenyl-4,5-dehydropyridazine-3,6-dione *(70)*. This view is supported by the inhibition of the reaction and the pronounced change in the isomer ratio (see Table 6) caused by

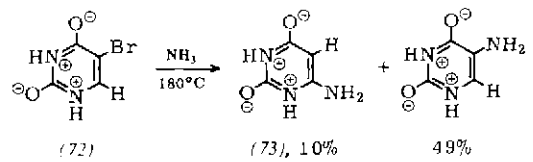


ethanol (cf. Section III.3.b), and by the formation of the 5-methoxy compound *(68)* (yield = 63 %) when piperidine and methanol are reacted simultaneously with *(67)*, Hal = Cl, (which is inert towards methanol alone). The ratio of the isomeric piperidino derivatives obtained from the 5-chloro compound in Table 6 indicates that the AE_n mechanism is involved in this case as well as the EA mechanism.

Table 6. Reaction (22 hours at about 20 °C) of halogenopyridazinediones with excess piperidine in benzene or in ethanol (values for ethanol in brackets).

Halogeno-1-methyl-2-phenylpyridazine-3,6-dione	Piperidino compound		
	Total yield [%]	Isomer distribution [%]	
		4-isomer	5-isomer
4-Chloro-	86 (78)	17 (77.5)	83 (22.5)
4-Bromo-	96 (81)	15.5 (53)	84.5 (47)
5-Chloro-	90	7	93

Attempts have been made [67] to intercept the hypothetical hetaryne *(70)* with furan or phenyl azide during the reaction of *(67)* (Hal = Cl) with strong bases (piperidine, potassium t-butoxide, azaquinuclidine). However, no adducts have so far been isolated. Apart from substitution products, these attempts yielded only ring cleavage products and a "dimer" with the overall formula $C_{22}H_{17}ClN_4O_4$. This "dimer" is presumably formed by the addition of the anion *(69)* to *(70)*, and probably has the structure *(71)*. The electron attraction of two oxygen and two nitrogen atoms probably makes *(70)* so strongly electrophilic that it adds on strong bases such as *(69)* much more rapidly than the weakly basic phenyl azide or the non-basic furan. Owing to the failure of the attempted interceptions, however, the assumption of a mechanism involving *(70)* must be viewed with caution.



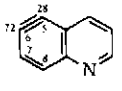
(72) *(73)*, 10% 49%

The recently observed [68], but not yet closely studied formation of 4-aminouracil *(73)* when 5-bromouracil *(72)* is heated at 180 °C in liquid ammonia, may result from the intermediate formation of 4,5-dehydrouracil. Ethanol again retards the reaction and directs it in such a way that only the "unrearranged" isomer is formed [68].

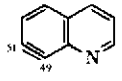
7. Hetarynes Containing a Dehydrobenzene Ring

a) 5,6- and 7,8-Dehydroquinolines

The reactions of 5-, 6-, and 7-halogenoquinolines (Hal = Cl, Br) with lithium piperidide/piperidine in boiling ether apparently proceed entirely (the isomer ratio is independent of the halogen) *via* 5,6-dehydroquinoline *(74)*, or in the case of the 7-halogenoquinolines, *via* 7,8-dehydroquinoline *(3')*, the products being mixtures of 5- and 6-, or 7- and 8-piperidinoquinolines [41]. 8-Halogenoquinolines (Hal = Cl, Br, I), on the other hand, react under the same conditions by the AE_n mechanism, giving only 8-piperidinoquinoline [41]. These results are indicated in the mechanism map *(20)* (Table 2) together with other results described earlier (Section III.2.a).

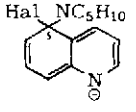


(74)

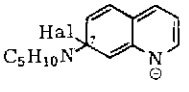


(3')

The exceptional behavior of the halogen in position 8 is surprising and has not as yet been satisfactorily explained. The AE_n mechanism is more likely with the 5- and 7-halogenoquinolines, since the negative charge in the hypothetical piperidine adducts of these halides can be taken over by the quinoline nitrogen as shown in *(75)* and *(76)*; this is impossible in the corresponding adducts of the 6- and 8-halogenoquinolines.



(75)



(76)

6- and 7-halogenoquinolines yield 5,6- and 7,8-dehydroquinolines, respectively, but no 6,7-dehydroquinoline [41]. This corresponds to *Huisgen*'s observation [26] that the elimination of hydrogen halide from 2-halogenonaphthalenes under the same conditions leads only to 1,2-dehydronaphthalene, but not to the 2,3-isomer [69].

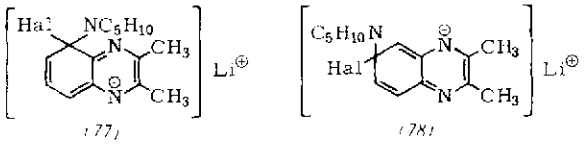
[68] *K. Forberger*, Diploma Thesis, Technische Hochschule Darmstadt.

[69] A change of the α-/β-piperidinonaphthalene ratio in favor of the β-isomer when the reaction temperature is raised from 35 °C (ether) to 106 °C (boiling piperidine) has been explained [*J. Sauer*, *R. Huisgen*, and *A. Hauser*, Chem. Ber., *91*, 1468 (1958)] by partial elimination to form 2,3-dehydronaphthalene at the higher temperature. This appears questionable, as the β-isomer (6-isomer) is also favored at the higher temperature in the corresponding reactions with 6-chloroquinoline (ratio of 5- and 6-isomers = 20:80 [32] instead of 28:72 [41]); the fact that no 7-piperidinoquinoline is formed practically rules out the occurrence of 6,7-dehydroquinoline as an intermediate, and points to competition between the EA and AE_n mechanisms.

The partial rate constants [47] [cf. *(74)* and *(10)*] as determined from the yields of aromatic piperidino compounds are almost the same in the addition of piperidine to 5,6-dehydroquinoline [41] as in the addition of piperidine to 1,2-dehydronaphthalene [26] in boiling ether; thus the nitrogen atom has practically no effect on the yields. In 7,8-dehydroquinoline *(3')* [41], on the other hand, the closer proximity of the nitrogen atom to the extra bond favors the introduction of the piperidino group into the α-position.

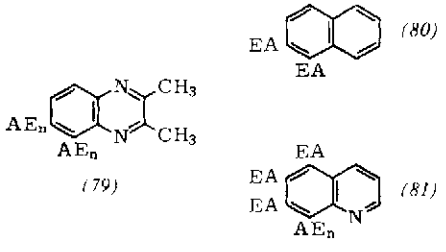
h) Attempts to Detect 5,6-Dehydroquinoxalines

5- and 6-chloro-2,3-dimethylquinoxalines react slowly with lithium piperidide/piperidine in boiling toluene, yielding only 5- and 6-piperidino-2,3-dimethylquinoxalines, respectively. It is very probable, therefore, that these reactions do not involve 2,3-dimethyl-5,6-dehydroquinoxaline as an intermediate, but that they proceed by the AE_n mechanism with the adducts *(77)* and *(78)*, respectively, as intermediates [32].



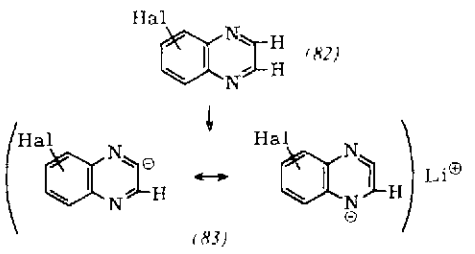
(77) *(78)*

A comparison of this result, as expressed in the mechanism map *(79)*, with the mechanism maps *(80)* and *(81)* for the analogous reactions of the halogenonaphthalenes [26] and quinolines having a halogen substituent on the carbocyclic ring [41] shows that the AE_n mechanism is favored by increasing substitution of nitrogen atoms for CH groups in the unhalogenated ring (cf. Section III.2.b).



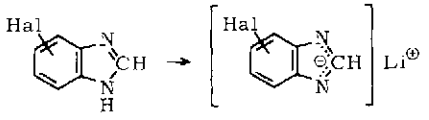
(79) *(80)* *(81)*

In contrast to the behavior of the chloro-2,3-dimethylquinoxalines, 5- and 6-chloroquinoxalines *(82)* are largely recovered unchanged after treatment with lithium piperidide/piperidine in boiling toluene; only traces of the piperidino compounds are formed, and these have been found to be the "unrearranged" products [32]. It may be assumed that the electron attraction of two nitrogen atoms leads to the replacement of a hydrogen atom of the heterocyclic ring by lithium, and that the negative charge of the resulting mesomeric anion [*e.g.* *(83)*] prevents the first step of the substitution, *i.e.* the introduction of metal in the *o*-position with respect to the halogen or the addition of lithium piperidide.



(82) *(83)*

A similar inhibition of substitution by the introduction of metal in the "wrong" place could also explain the resistance of the halogen in halides of the type *(84)* [51] and in 4-bromoisoquinoline (cf. Section III.3.a) and 5-bromouracil [68] towards lithium piperidide.

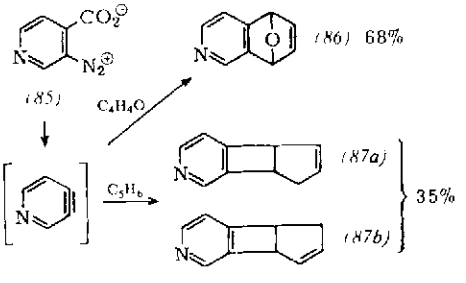


(84)

IV. Cycloadditions with Hetarynes

Although the results described in Section III.2 provide evidence for the occurrence of 3,4-dehydropyridine *(2)*, it could be objected that *(2)* might be capable of existing only in loose association with a metal cation or a halide ion. That this is not the case is shown by the production of 3,4-dehydropyridine during the thermal decomposition of pyridine-3-diazonium-4-carboxylate *(85)* [10].

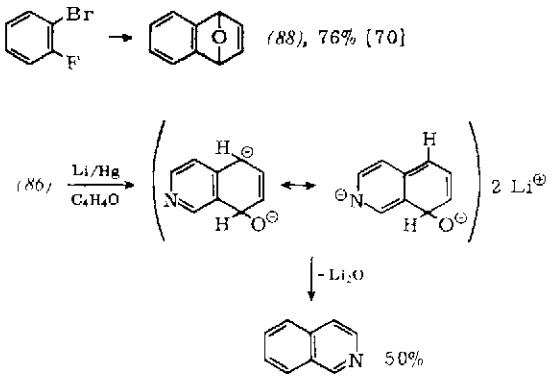
Like dehydrobenzene [70], the 3,4-dehydropyridine obtained in this way combines with furan in a Diels-Alder reaction [10]; unlike dehydrobenzene [71], however, it reacts with cyclopentadiene to form a cyclobutene derivative having the structure *(87a)* or *(87b)* [36, 37]. The lower reactivity of 3,4-dehydropyridine as compared with dehydrobenzene is shown by the fact that the former, unlike dehydrobenzene [72, 73], does not undergo appreciable addition to anthracene or bicyclo-[2,2,1]hepta-2,5-diene [36, 74], as well as by selectivity studies (cf. Section VI).



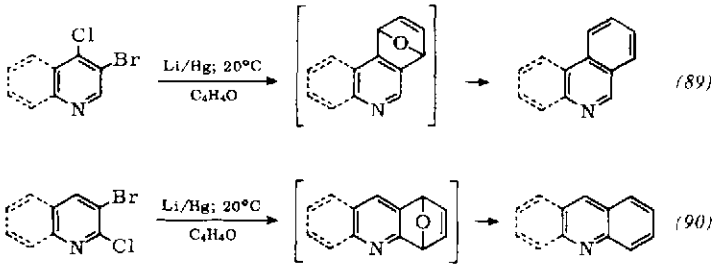
(85) *(86)* 68% *(87a)* *(87b)* 35%

[70] *G. Wittig* and *L. Pohmer*, Chem. Ber. *89*, 1334 (1956).
[71] *G. Wittig* and *E. Knauss*, Chem. Ber. *91*, 895 (1958).
[72] *G. Wittig*, Org. Syntheses *39*, 75 (1959).
[73] *H. E. Simmons*, J. Amer. chem. Soc. *83*, 1657 (1961).
[74] The products, which are formed only in small quantities, have not yet been subjected to gas-chromatographic analysis.

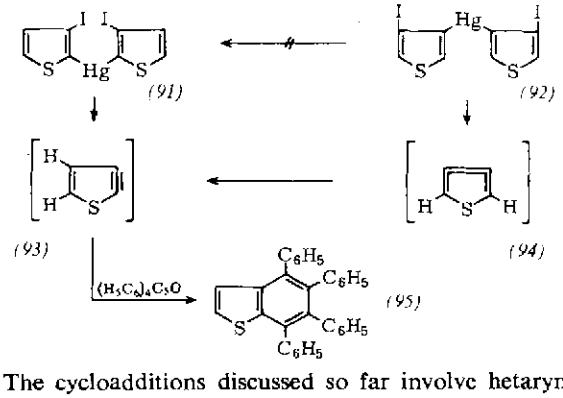
In contrast to the 1,4-dihydronaphthalene-1,4-epoxide *(88)*, which can be prepared from *o*-bromofluorobenzene, the analogous 5,8-dihydroisoquinoline-5,8-epoxide *(86)* rapidly loses oxygen to form isoquinoline on shaking with lithium amalgam in furan [10].



This explains why the reactions of heteroaromatic *o*-dihalogeno compounds with lithium amalgam in furan lead to the oxygen-free heteroaromatic compounds *(89)* (14 % of isoquinoline [10] and 9 % of phenanthridine [15]) and *(90)* (2 % of quinoline [13,43] and 4 % of acridine [37,75]), and not to the hetaryne-furan adducts

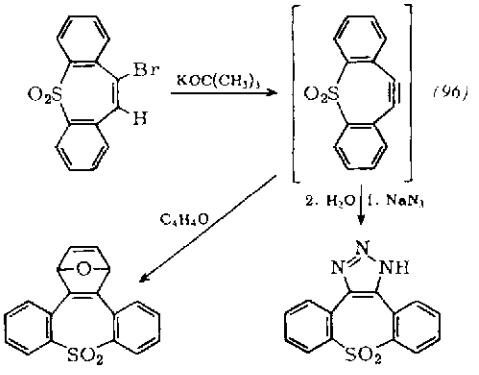


corresponding to *(86)*. The preparations of quinoline and acridine from 3-bromo-2-chloropyridine and 3-bromo-2-chloroquinoline, respectively, are important in spite of the low yields obtained, since they point to the intermediate formation of 2,3-dehydropyridine *(13)* and 2,3-dehydroquinoline; these compounds, unlike the 3,4-analogues, have not so far been detected by any other means (cf. Section III.3.a).



The cycloadditions discussed so far involve hetarynes with a six-membered ring. *Wittig* and *Wahl* [16] were the first to intercept a five-membered ring hetaryne by cycloaddition: on fusion with tetraphenylcyclopentadienone, the mercury compound *(91)* obtained from 3-iodo-2-lithio-thiophene gives a 12 % yield of 4,5,6,7-tetraphenylthionaphthene *(95)*, indicating the intermediate formation of 2,3-dehydrothiophene *(93)*. Compound *(95)* is also formed when *(92)* is fused with tetraphenylcyclopentadienone. Since *(92)* does not isomerize to *(91)* under the conditions of this reaction, it is assumed that the 2,3-dehydrothiophene is formed by rearrangement of the initially formed 3,4-isomer *(94)* [17,18].

1-Methyl-2,3-dehydroindole[18], 2,3-dehydrocoumarone *(1)* [17], and 2,3-dehydrothionaphthene *(52)* [76] have also been produced and intercepted in a similar manner (adduct yields of 13 %, 70 %, and 54 %, respectively). The detection of 2,3-dehydrocoumarone as an intermediate in the reaction of 3-bromocoumarone with sodium ethoxide by interception with tetraphenylcyclopentadienone was mentioned in Section III.3.c. *Tochtermann* [62] first demonstrated the intermediate formation of a seven-membered cyclic hetaryne, namely 4,5-dehydro-2,3;6,7-dibenzothiepin *S*-dioxide *(96)*, as shown in Scheme 2.



Scheme 2. Detection of a hetaryne containing a seven-membered ring [62].

It should be noted, finally, that the isolation of a diene adduct does not in itself constitute satisfactory proof of the existence of an *o*-dehydroaromatic compound. If this is the only evidence available, it must be shown by experiment that no other reaction route is possible (cf. [77]); alternatively, further evidence must be found, as in the cases of 3,4-dehydropyridine and 3,4-dehydroquinoline (cf. Section III.2.a).

V. Hetarynium Ions

When heated without solvent, the compound *(98)* decomposes into 2-hydroxypyridine (93 %), N_2, and sulfur. If the thermal decomposition is carried out in chloroform containing HN_3, or in methanol, the products include tetrazolopyridine (9 %) or 2-methoxypyridine (36 %) [78]. It is therefore assumed that the decom-

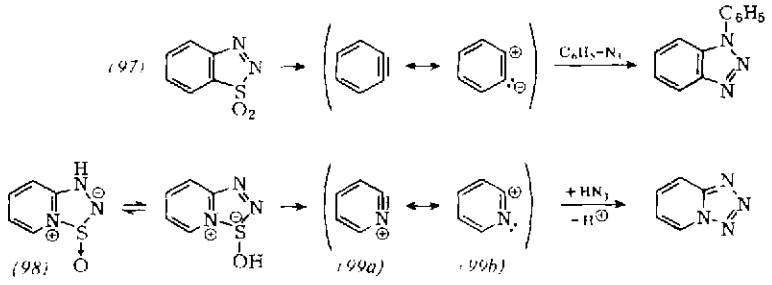
[75] *Th. Kauffmann* and *K. Udluft*, Angew. Chem. *75*, 89 (1963); Angew. Chem. internat. Edit. *2*, 45 (1963).

[76] *G. Wittig* et al., personal communication.

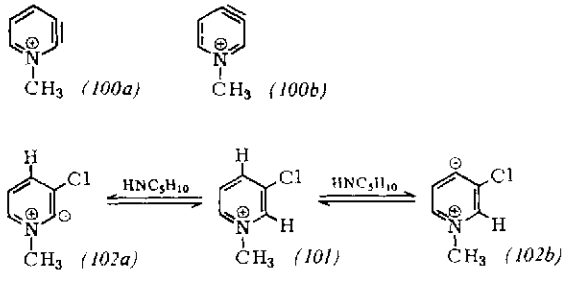
[77] *W. Tochtermann*, *K. Oppenländer*, and *U. Walter*, Chem. Ber. *79*, 1318 (1964).

[78] *Th. Kauffmann* and *H. Marhun*, Chem. Ber. *96*, 2519 (1963).

position of *(98)* leads to the mesomeric hetarynium-carbenium ion *(99a)* ↔ *(99b)* (cf. the thermal decomposition of *(97)* to dehydrobenzene [79]), and that this ion reacts with the hydroxide ion which is also formed, the ultimate product being 2-hydroxypyridine. Under suitable conditions, however, the ion *(99a)* ↔ *(99b)* also reacts with HN_3 (1,3-dipolar cycloaddition) or methanol and loses a proton to form tetrazolopyridine or 2-methoxypyridine. Since our present knowledge [80] indicates that the phenyl cation is less stable than dehydrobenzene, the hetarynium form *(99a)* is presumably more important than the carbenium form *(99b)*.



Besides the hypothetical hetarynium ion *(99)*, other hetarynium ions of the type *(100)* can theoretically be derived from pyridine. So far, no experimental evidence has been found for the occurrence of such an ion. In attempts [67] to react monochloro-1-methylpyridinium halides with anhydrous piperidine at room temperature, the 2- and 4-chloro compounds gave only the corresponding 2- and 4-piperidino compounds, respectively. 3-Chloro-1-methylpyridinium chloride, however was largely recovered unchanged. Neither the 2- nor the 4-piperidino compound was obtained in this case; this was also true of a reaction at 100 °C, which resulted in vigorous resinification. Since it may be assumed that piperidine is capable of removing the highly positive hydrogen atoms on C–2 and C–4 of the cation *(101)*, the EA substitution is evidently prevented by the reluctance of the zwitterions *(102a)* and *(102b)* to lose Cl.



VI. Selectivity and Structure

The higher the energy of an intermediate, the smaller is the activation energy required for further reaction, and the lower is its selectivity when two or more reaction partners are available at the same time.

Huisgen [81] has determined the selectivity of the carbocyclic arynes dehydrobenzene, 1,2-dehydronaphthalene, and 9,10-dehydrophenanthrene in the competitive addition of phenyl-lithium and lithium piperidide. His values show that the fusion of benzene rings to dehydrobenzene leads to an increase in selectivity, *i. e.* has a stabilizing effect. Since the distance between the carbon atoms between which the extra bond is to be formed decreases in the order benzene > naphthalene > phenanthrene (1.39, 1.365, and 1.35 Å respectively), *Huisgen* [81] believes that the increasing selectivity (and hence the increasing stability) is due to an increasing overlap of the extra orbitals.

If this were the only stabilizing effect, 3,4-dehydropyridine should be less selective than dehydrobenzene, since the (C-3)–(C-4) bond of pyridine is slightly longer (1.400 Å [82]) than the C–C bond in benzene (1.39 Å). However, experiments [33, 83] in which piperidine and diethylamine were used as the competing bases (since phenyl-lithium readily adds onto the CN double bond in pyridines [84]) indicated that the opposite is true. Figure 1 shows the results of gas-chromatographic measurements for the competitive addition of piperidine and diethylamine to the arynes dehydrobenzene, 1,2-dehydronaphthalene, and 3,4-dehydropyridine obtained by the action of lithium diethylamide and lithium piperidide [85] on chlorobenzene, 1-chloro-

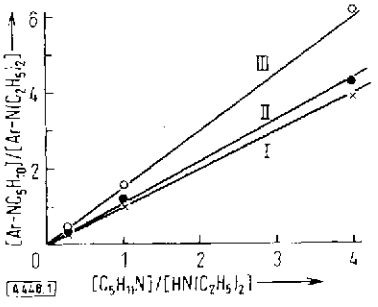


Fig. 1. Results of the competitive addition of piperidine and diethylamine to dehydrobenzene (I), 1,2-dehydronaphthalene (II) and 3,4-dehydropyridine (III) in boiling ether [33, 83].

Abscissa: Ratio of the concentrations of piperidine and diethylamine.

Ordinate: Ratio of the concentrations of aromatic piperidino and diethylamino derivatives in the product.

[79] *G. Wittig* and *R. W. Hoffmann*, Chem. Ber. *95*, 2718 (1962).

[80] For a list of references, see [26], note 25.

[81] *R. Huisgen*, *W. Mack*, and *L. Möbius*, Tetrahedron *1960*, No. 9, p. 29.

[82] *B. Back*, *L. Hansen*, and *J. Rastrup-Andersen*, J. chem. Physics *22*, 2013 (1954); the bond length was determined from microwave measurements.

[83] *M. Daum*, Doctorate Dissertation, Technische Hochschule Darmstadt.

[84] According to *F.-P. Boettcher* (Doctorate Dissertation, Technische Hochschule Darmstadt, 1961), the successive action of phenyl-lithium and acetic anhydride on 3-chloropyridine leads to 1-acetyl-3(or 5)-chloro-2-phenyl-1,2-dihydropyridine; cf. also *K. Ziegler* and *H. Zeiser*, Ber. dtsch. chem. Ges. *63*, 1848 (1930).

[85] The ratio (lithium diethylamide + lithium piperidide): (diethylamine + piperidine) was 1:9. Since the rates of addition of lithium piperidide and piperidine to 9,10-dehydrophenanthrene are roughly equal [26], probably mainly the free bases added onto the arynes in the selectivity determinations.

naphthalene, and 3-chloropyridine. The slopes of the lines joining the experimental points show a 1.0-, 1.1-, and 1.5-fold preference for piperidine.

Thus 3,4-dehydropyridine is more selective than dehydrobenzene and 1,2-dehydronaphthalene [85a].

Since this cannot be plausibly explained by a better overlap of the extra orbitals, it must be assumed that the aromatic π-electron cloud has a considerable influence on the extra bond in arynes; this is supported by the fact that dehydrobenzene is more stable than cyclohexyne [18] and by quantum-mechanical calculations [86]. Since the selectivity is increased by the fusion of a benzene ring to dehydrobenzene or by the substitution of a nitrogen atom for a CH group, it can be expected that 3,4-dehydroquinoline [15] and 4,5-dehydropyrimidine [36] will be more selective in the addition of bases than 3,4-dehydropyridine. 2,3-Dehydropyridine [13] should also be more selective, since the extra orbitals (probably sp^2) in this case can overlap with the orbital (sp^2) of the free electrons on the nitrogen atom (the expected [11] decrease in energy is supported by quantum-mechanical calculations [87]).

Overlapping of this nature could provide the driving force for a rearrangement of 3,4- to 2,3-dehydrothiophene [17] (cf. Section IV).

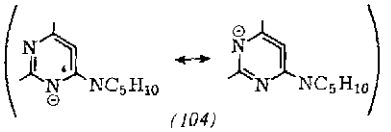
Since hetarynes (apart from those with the extra bond in a carbocyclic ring) contain a nucleophilic center (the heteroatom) and a highly unsaturated electrophilic bond in the same ring, the possibility of stabilization by a transannular reaction to form valence-isomeric forms [*e.g.* formation of *(103)* from *(70)*] must also be considered [24].

(70) *(103)*

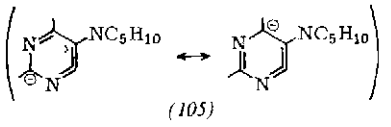
VII. Oriented Addition of Bases to Hetarynes

In the addition of a base to a hetaryne, it is generally possible to predict which of the two isomers formed will predominate, if the energy contents of the anion-hetaryne adducts corresponding to the isomers are estimated from the mesomeric distribution of the negative charge (assuming that similar energy relationships apply in the transition states of the additions) [88].

This can be illustrated by the addition of piperidine to 4,5-dehydropyrimidine. The hypothetical "C-4 adduct" *(104)* of the piperidide ion and 4,5-dehydropyrimidine should have a lower energy than the "C-5 adduct" *(105)*, since according to the resonance structures, the negative charge introduced into the aromatic system can be accommodated by nitrogen atoms only in *(104)*. In agreement with this, the anionic piperidide group appears (cf. Section III.3.b) to add predominantly onto C-4 of 4,5-dehydropyrimidine.



(104)

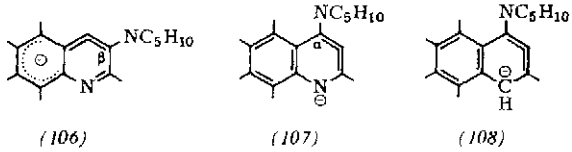


(105)

For similar reasons, the addition of bases to 3,4-dehydropyridine should result in attachment of the anionic group mainly to C-4. In fact, in the addition of NH_3/KNH_2 at −33 °C [12, 22] and in the addition of piperidine at 0 °C [51], the amino and piperidino groups show a pronounced preference for C-4 (ratios of the 3- and 4-isomers = 33:67 and 42:58).

In the addition of piperidine onto 3,4-dehydropyridine, the preference for C–4 is less at 35 °C (ratio of 3- and 4-isomers= 48:52) than at 0 °C. This agrees with the expectation that the selectivity of addition to an asymmetric aryne will decrease as the energy content (which increases with temperature) increases. It is not impossible, however, that the change in the isomer ratio is due to a slight participation of the AE_n mechanism in the reactions giving the ratio 48:52 [11] (cf. Section III.2.a).

It is not possible to decide directly which of the two mesomeric piperidide/3,4-dehydroquinoline adducts represented by *(106)* and *(107)* has the lower energy. The energy relationships in the "α-adduct" *(107)*, however, appear to be more favorable than in the corresponding adduct *(108)* of 1,2-dehydronaphthalene. It was to be expected, therefore, that attachment of the piperidide group in the α-position with respect to the undehydrogenated ring would occur to a greater extent in 3,4-dehydroquinoline than in 1,2-dehydronaphthalene. The ratio of the α- and β-adducts in the former case is, in fact, 49:51 [15], as opposed to 31:69 [26] in the case of 1,2-dehydronaphthalene [89].



(106) *(107)* *(108)*

[85a] Note added in proof: When dehydrobenzene or 3,4-dehydropyridine are treated with lithium piperidide and lithium diethylamide in boiling ether, the diethylamide (!) is added on 1.7- or 2.2-times as fast, respectively, as the piperidide [33]. Thus, 3,4-dehydropyridine here again exhibits a higher selectivity.

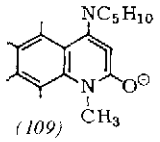
[86] *C. A. Coulson*, Special Publ., Chem. Soc. (London) *12*, 85 (1958).

[87] *H. L. Jones* and *D. L. Beveridge*, Tetrahedron Letters *1964*, 1577.

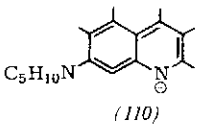
[88] Note that the orientation phenomena in the addition of bases onto substituted dehydrobenzenes has been explained on the basis of the inductive effects of the substituents [26, 46].

[89] It is of interest in connection with the addition of bases onto arynes containing corresponding groups that open-chain alkynes of the type $C_6H_5-C(\alpha)\equiv C(\beta)$-Alk [addition of $NaNH-NH_2$: *S. Sobel*, Doctorate Dissertation, Technische Hochschule Darmstadt; addition of phenylisopropylpotassium (Alk = CH_3): *K. Ziegler* and *H. Dislich*, Chem. Ber. *90*, 1111 (1957)] and $O=C(R)-C(\alpha)\equiv C(\beta)-R$ [*e.g.* addition of piperidine (R=C_6H_5): *E. R. Watson*, J. chem. Soc. (London) *85*, 1319 (1904)] add anionic groups predominantly or exclusively on C-β. Similar behavior is expected with open-chain alkynes $R-N=C(R)-C(\alpha)\equiv C(\beta)-R$.

Whereas the negative charge in *(107)* can be taken over by the nitrogen atom, it can be accommodated by the carbonyl oxygen in "α-adducts" such as *(109)* of hetarynes of the type *(4)*. In agreement with this, the frequency of attachment of the piperidide group to the α-position is greater in the addition of piperidine onto hetarynes of the type *(4)* [cf. *(64a)* to *(66)*] than onto 1,2-dehydronaphthalene. However, this could also be partly due to steric hindrance of the "β-addition" by the carbonyl oxygen.



(109)



(110)

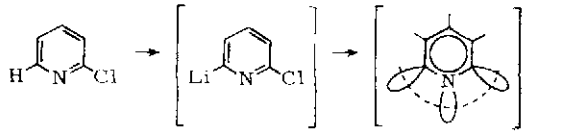
It is not yet clear why the preference for "α-addition" is greater in the addition of piperidide to 7,8-dehydroquinoline *(3)* than to 1,2-dehydronaphthalene [cf. *(3')* and *(10)*], since addition in accordance with formula *(110)* should be more likely in the β-position.

VIII. The 2,6-Dehydropyridine Problem

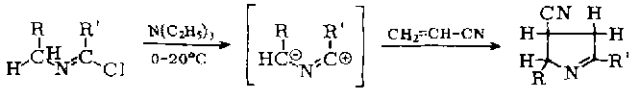
Since all attempts to detect carbocyclic *m*- and *p*-dehydroaromatic compounds have so far been unsuccessful, it must be assumed [26] that *o*-dehydroaromatic compounds can exist only because of the energy-lowering overlap of the orbitals of the extra electrons. Owing to the possibility of overlap between the orbitals of the extra electrons and those of the lone electrons on the nitrogen in hypothetical *m*-dehydroaromatic compounds of the type *(112)*, it appears that such compounds may be capable of existing [87].

Of interest in this connection is the surprising discovery mentioned in Section III.2.a. that the action of lithium piperidide on 2-chloropyridine *(111)* in boiling ether leads to resinification, whereas less than 1 % of the expected 2-piperidinopyridine and none of the 3-piperidino compound are formed [11]. The other 2-halogenopyridines, with the exception of the fluoro compound (Table 1), also yield resins and lithium halide on reaction with lithium piperidide. The same result is obtained if lithium diethylamide or lithium dicyclohexylamide is used instead of lithium piperidide [31].

Since resinification occurs only when the 2-halogenopyridine has a hydrogen on C-6 (and hence does not take place with 2-chloro-6-methylpyridine or 2-chloroquinoline), and since the analogous reaction *(113)* → *(114)* of open-chain compounds proceeds remarkably easily [90], the reactions leading to resin formation may involve 2,6-dehydropyridine *(112)* [formed by the elimination of lithium halide from *(111a)*] as a short-lived intermediate.



(111) *(111a)* *(112)*



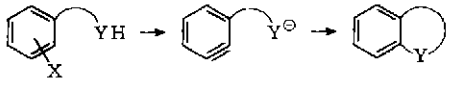
(113), R = C_6H_4-NO_2
R' = C_6H_5

(114)

IX. Outlook

The main method used in future efforts to produce various kinds of hetarynes will still be the reaction of bases with halogenated heteroaromatic compounds, owing to the ease of obtaining the starting materials. A primary aim in future work should be to find rules which allow reliable predictions regarding the mechanisms and products of nucleophilic substitutions in heterocyclic aryl halides.

Since new methods are continuously being found for the production of dehydrobenzene in non-basic media [70, 79, 91–94], it will probably also become possible to produce an ever-widening range of hetarynes in non-basic media, *i.e.* under conditions which will permit the interception of these compounds in good, and possibly even preparative yields with a diene or a 1,3-dipolar compound. The incentive is great, in view of the possible variety in the heterocyclic series. For the same reason, it is possible that the method shown in Scheme 3 for building up ring systems [26, 95] will be modified for the synthesis of heterocyclic aryl halides, in which field it should find many applications.



Scheme 4. Synthesis of ring systems *via* arynes [26, 94].

The "chemistry of transient species", *i.e.* the rapidly expanding chemistry of unstable molecules such as carbenes, nitrenes, arynes, or "hot" 1,3-dipolar compounds, will probably be greatly enriched by future investigations on heterocyclic arynes.

The investigations carried out by my colleagues Dr. F.-P. Boettcher, M. Daum, K. Forberger, J. Hansen, H. Marhan, R. Nürnberg, A. Risberg, J. Schulz, K. Udluft, R. Weber, and R. Wirthwein, were generously supported by the Deutsche Forschungsgemeinschaft, the Fonds der Chemischen Industrie, and the Vereinigung von Freunden der Technischen Hochschule zu Darmstadt, to whom we are sincerely grateful. The author also wishes to thank Prof. C. Schöpf for discussions, Prof. H. J. den Hertog, Prof. R. Huisgen, Dr. W. Tochtermann, and Prof. G. Wittig for making available unpublished results.

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Translated by Express Translation Service, London

[90] *R. Huisgen, H. Stangl, H. J. Sturm*, and *H. Wagenhofer*, Angew. Chem. *74*, 31 (1962); Angew. Chem. internat. Edit. *1*, 50 (1962).

[91] *M. Stiles* and *R. G. Miller*, J. Amer. chem. Soc. *82*, 3802 (1960).

[92] *C. D. Campbell* and *C. W. Rees*, Proc. chem. Soc. (London) *1964*, 296.

[93] *R. F. C. Brown* and *R. K. Solly*, Chem. and Ind. *1965*, 181.

[94] *G. Wittig* and *H. F. Ebel*, Angew. Chem. *72*, 564 (1960).

[95] *J. F. Bunnett*, J. chem. Educat. *38*, 283 (1961).

Anaplerotic Sequences in Microbial Metabolism [1]

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In addition to catabolic and anabolic pathways, which enable nutrients to enter and to be withdrawn from the central routes of metabolism, enzymic sequences operate to ensure that intermediates, removed from these central routes in the course of biosynthesis, are replenished. These obligatory pathways of replenishment are generically designated "anaplerotic sequences". The nature of these sequences, operative in micro-organisms growing on C_3- and C_2-compounds, is discussed in outline, and the mode of regulation of one of them (the glyoxylate cycle) is examined in detail.

Metabolic routes are sequences of chemical steps, catalysed by enzymes, which enable living organisms to obtain from their food both the ingredients required for the synthesis of cell constituents and the energy necessary to effect such and other endergonic processes. The routes whereby this is achieved are generally divided into three distinct types. Catabolic routes serve primarily to promote the entry of individual nutrients into the central, energy-yielding pathways of metabolism (the glycolytic sequence and tricarboxylic acid cycle); anabolic routes utilize the intermediates of these pathways as precursors of the organism's own macromolecules. The central pathways thus play a dual role, and the intermediates which lie upon them are indispensable to the provision both of energy and of the carbon skeletons of the multitudinous components of the cell: by virtue of this dual function, these pathways have been termed amphibolic [2].

However, these three types of metabolic routes are not sufficient to account for the growth of micro-organisms, provided with a single compound as sole carbon source, when the catabolism of that compound cannot directly yield an intermediate of the tricarboxylic acid cycle: some route ancillary to that cycle must operate to ensure that the intermediates of the cycle, which are drained away during growth, are replenished. It is the main purpose of this article to discuss the nature of these obligatory routes of replenishment, which may be generically described as anaplerotic sequences [3].

1. Anaplerotic CO_2-Fixation

The catabolism of hexoses, glycerol, or other precursors of pyruvate yields C_3-compounds which, in aerobic organisms, are totally combusted *via* the tricarboxylic acid cycle. Pyruvate initially loses one of its carbon atoms to form acetyl-coenzyme A, which enters the cycle after condensation with oxaloacetate. Each turn of the cycle then results in the loss of a further two carbon atoms as carbon dioxide and regeneration of the oxaloacetate necessary to accept a further C_2-unit. In the growing cell, however, the operation of anabolic routes for the synthesis of, for example, porphyrins, and amino acids of the glutamate and aspartate "families", removes the intermediates required for this necessary regeneration of oxaloacetate: unless an anaplerotic reaction also occurs, which enables this loss of tricarboxylic acid cycle intermediates to be made good, both energy provision and biosynthesis must cease.

In the example cited, this anaplerotic function is borne by carboxylation reactions (Fig. 1). In *Pseudomonas* [4], oxaloacetate may be formed by the direct carboxylation of pyruvate (Reaction a) but this reaction does not appear to occur in the Enterobacteriaceae [5]. Instead, three other enzymes theoretically capable of effecting the net formation of C_4-acids from the carboxylation of

$$CH_3{-}CO{-}CO_2H + ATP + CO_2 \rightarrow HO_2C{-}CH_2{-}CO{-}CO_2H + ADP + H_3PO_4 \qquad (a)$$

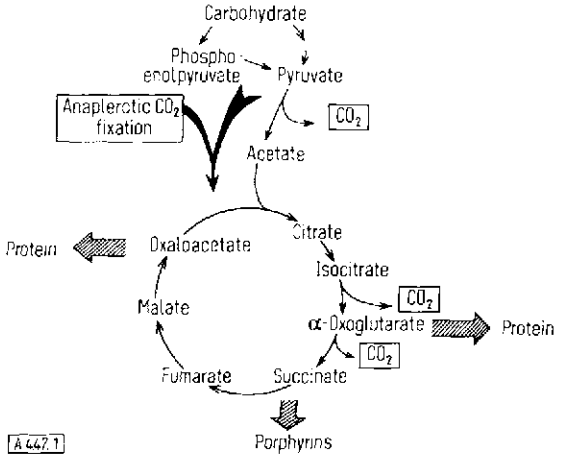

Fig. 1. Anaplerotic fixation of carbon dioxide. The net formation of C_4-compounds through the carboxylation of C_3-acids (indicated by black arrow) is necessary for replenishment of tricarboxylic acid cycle intermediates, removed in the course of growth.

[1] Substance of a plenary lecture, delivered on October 22nd, 1964, at the Herbsttagung der Gesellschaft für Physiologische Chemie, Köln (Germany).

[2] *B. D. Davis*, Cold Spring Harbor Sympos. quantitat. Biol. *26*, 1 (1961).

[3] I am indebted to Professor *A. Wasserstein* who from the wealth of his classical erudition concluded that, if "anaplerotic" did not exist, it ought to be invented. Subsequent investigation showed the word to be respectably enshrined both in the Oxford English Dictionary and in the vocabulary of Pathology.

[4] *W. Seubert* and *V. Remberger*, Biochem. Z. *334*, 401 (1961).

[5] *J. M. Ashworth, H. L. Kornberg*, and *R. L. Ward*, Biochem. J. *94*, 28 P (1965).

C_3-compounds have been found to be present: these are (Reaction b) phosphoenolpyruvate carboxylase [6],

$$CH_2{=}C(CO_2H){-}OPO_3H_2 + CO_2 + H_2O \rightarrow HO_2C{-}CO{\cdot}CH_2{-}CO_2H + H_3PO_4 \quad (b)$$

(Reaction c) "malic enzyme" [7],

$$CH_3{-}CO{-}CO_2H + NADPH_2 + CO_2 \rightleftarrows HO_2C{-}CHOH{-}CH_2{-}CO_2H + NADP \quad (c)$$

and (Reaction d) the ATP-linked oxaloacetate decarboxylase [8]

$$CH_2{=}C(CO_2H){-}OPO_3H_2 + ADP + CO_2 + H_2O \rightleftarrows HO_2C{-}CO{-}CH_2{-}CO_2H + ATP \quad (d)$$

It was possible to distinguish the enzyme bearing the anaplerotic function by studies [5] with a mutant of *Escherichia coli* which, though unable to grow on glucose plus ammonia, grew readily if this medium was supplemented with any intermediate of the tricarboxylic acid cycle able to penetrate the cell. Washed suspensions of this mutant oxidized pyruvate only to the level of acetate, which accumulated; however, pyruvate was totally combusted if catalytic amounts of L-malate were also provided.

Ultrasonic extracts of the mutant contained as much of enzymes for reactions (c) and (d) as did similar extracts of the parent, wild-type organism, but differed from them in being devoid of the ability to catalyse reaction (b). This showed that the enzyme necessary for the net formation of C_4-compounds was a (virtually irreversible) phosphoenolpyruvate carboxylase, and suggested that anaplerotic enzymes are distinguishable from others which, while effecting similar reactions, serve a different function in the cell.

2. Anaplerotic Sequences in Acetate Metabolism

Although mutants of *E. coli* devoid of phosphoenolpyruvate carboxylase are unable to grow on pyruvate or precursors thereof, such mutants grow readily on acetate as sole carbon source [9]. This shows that some other anaplerotic sequence operates under these conditions to effect the net formation of tricarboxylic acid cycle intermediates as these are removed in the course of growth. This sequence has been shown [10] to consist of two enzymes, the concerted action of which serves to bypass the decarboxylative steps of the tricarboxylic acid cycle and to lead to a net increase in the organic carbon content of the cell (Fig. 2).

The first of these enzymes, isocitrate lyase (Reaction e), catalyses the aldol cleavage of *threo*-D_s-isocitrate [11] to

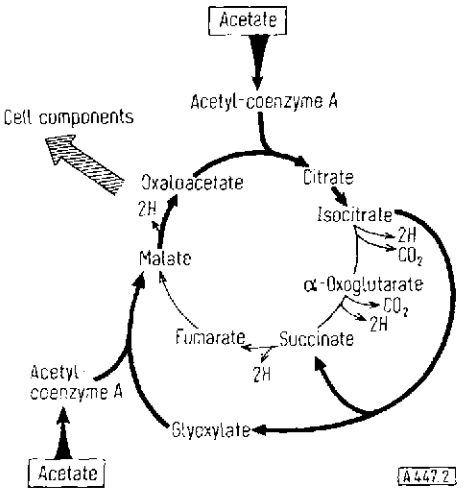

Fig. 2. The tricarboxylic acid cycle and the glyoxylate cycle. The anaplerotic nature of the latter is indicated by heavy arrows.

succinate and glyoxylate [12–14], the second, malate synthase (Reaction f) catalyses the condensation of the glyoxylate thus formed with acetyl-coenzyme A to yield malate [15]. Together with the steps of the tricarboxylic acid cycle (which, of course, provides the energy for growth on acetate) leading from malate to isocitrate, this anaplerotic route serves to maintain the supply of tricarboxylic acid cycle intermediates as they are removed for biosyntheses. The overall effect of this sequence (Reaction g), which has been termed the glyoxylate cycle [16,17], is formally identical with the often-postulated "Thunberg condensation" [18] though the mechanism is quite different.

$$\begin{aligned}
\text{acetyl-coenzyme A} + \text{oxaloacetate} + H_2O &\rightarrow \text{citrate} + \text{coenzyme A} \\
\text{citrate} &\rightleftarrows \text{isocitrate} \\
\text{isocitrate} &\rightleftarrows \text{succinate} + \text{glyoxylate} \quad (e) \\
\text{acetyl-coenzyme A} + \text{glyoxylate} + H_2O &\rightarrow \text{malate} + \text{coenzyme A} \quad (f) \\
\text{malate} + {}^1/_2\,O_2 &\rightarrow \text{oxaloacetate} + H_2O \\
\hline
2\ \text{acetyl-coenzyme A} + {}^1/_2\,O_2 &\rightarrow \text{succinate} + 2\ \text{coenzyme A} + H_2O \quad (g)
\end{aligned}$$

3. Anaplerotic Sequences in Glyoxylate Metabolism

When glyoxylate, or precursors of glyoxylate, serve as carbon source for growth, the tricarboxylic acid cycle still serves to supply biosynthetic intermediates but does not act as the terminal respiratory pathway. Instead, glyoxylate is totally combusted *via* a dicarboxylic acid cycle (Fig. 3), which comprises some but not all of the component reactions of the tricarboxylic acid cycle.

[6] *R. S. Bandurski* and *C. M. Greiner*, J. biol. Chemistry *204*, 781 (1953).

[7] *S. Ochoa, A. H. Mehler*, and *A. Kornberg*, J. biol. Chemistry *174*, 979 (1948).

[8] *M. F. Utter* and *K. Kurahashi*, J. biol. Chemistry *207*, 787 (1954).

[9] *J. M. Ashworth* and *H. L. Kornberg*, Biochim. biophysica Acta *73*, 519 (1963).

[10] For review, see *H. L. Kornberg*, Annual Rev. Microbiol. *13*, 49 (1959); *H. L. Kornberg* and *S. R. Elsden*, Advances in Enzymol. *23*, 401 (1961).

[11] *H. B. Vickery*, J. biol. Chemistry *237*, 1739 (1962).

[12] *J. J. R. Campbell, R. A. Smith*, and *B. A. Eagles*, Biochim. biophysica Acta *11*, 594 (1953).

[13] *J. A. Olson*, Nature (London) *174*, 695 (1954).

[14] *R. A. Smith* and *I. C. Gunsalus*, J. Amer. chem. Soc. *76*, 5002 (1954).

[15] *D. T. O. Wong* and *S. J. Ajl*, J. Amer. chem. Soc. *78*, 3230 (1956).

[16] *H. L. Kornberg* and *N. B. Madsen*, Biochim. biophysica Acta *24*, 651 (1957); Biochem. J. *68*, 549 (1958).

[17] *H. L. Kornberg* and *H. A. Krebs*, Nature (London) *199*, 988 (1957).

[18] *T. Thunberg*, Skand. Arch. Physiol. *40*, 1 (1920).

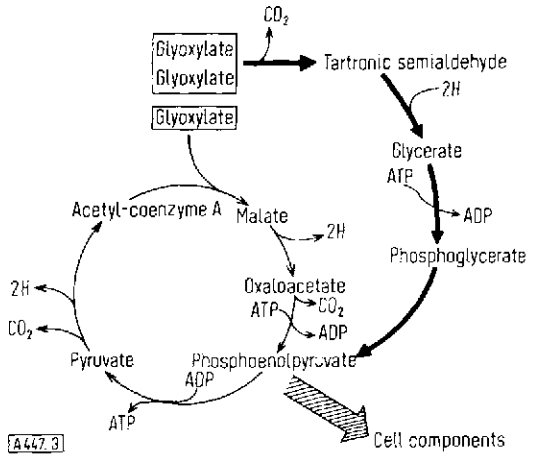

Fig. 3. The dicarboxylic acid cycle for the oxidation of glyoxylate (light arrows) and the glycerate pathway (heavy arrows) which maintains the necessary levels of dicarboxylic acid cycle intermediates.

In this cycle, malate synthetase (Reaction f) plays a respiratory role. The initial condensation of glyoxylate with acetyl-coenzyme A, catalysed by this enzyme, yields malate, which is further oxidized *via* oxaloacetate and pyruvate to regenerate the acetyl-coenzyme A acceptor molecule [19]. The removal of precursors for cellular syntheses from this cycle (and all the intermediates of the cycle can act as such) would cause oxidation to cease: an anaplerotic sequence must therefore operate to effect the net formation of such intermediates from glyoxylate. This sequence has been shown [20] to consist of three enzymes: glyoxylate carboligase [21], which catalyses the formation of tartronic semialdehyde from the condensation of 2 moles of glyoxylate, with elimination of 1 mole of carbon dioxide (Reaction h); tartronic semialdehyde reductase [22] which effects the reduction to glycerate of the tartronic semialdehyde thus formed (Reaction i); and glycerate kinase [23], which enables the glycerate to be transformed into phosphoglycerate (Reaction k), an intermediate of an amphibolic pathway. The overall reaction (l) is that of the glycerate pathway [24] (Fig. 3).

$$2\ \text{glyoxylate} \rightarrow \text{tartronic semialdehyde} + CO_2 \quad \text{(h)}$$

$$\text{tartronic semialdehyde} + 2H \rightarrow \text{glycerate} \quad \text{(i)}$$

$$\text{glycerate} + ATP \rightarrow \text{phosphoglycerate} + ADP \quad \text{(k)}$$

$$2\ \text{glyoxylate} + ATP + 2H \rightarrow \text{phosphoglycerate} + ADP + CO_2 \quad \text{(l)}$$

The phosphoglycerate thus produced is metabolized to acetyl-coenzyme A and, by condensation with a further molecule of the growth substrate, *i.e.* of glyoxylate, enables the dicarboxylic acid cycle to be replenished.

4. Quantitative Aspects of Anaplerosis

The observation that cell-free extracts of micro-organisms catalyse a variety of different chemical reactions is, in itself, not sufficient to show that any particular sequence of such reactions plays an important role in the economy of the cell as an anaplerotic pathway. Such evidence can, however, be readily obtained with auxotrophic mutants. It has already been mentioned that mutants of *E. coli* devoid of phosphoenolpyruvate carboxylase (Reaction b) are unable to grow on glucose, glycerol, or C_3-acids, though they readily grow on these compounds when their media are supplemented with any intermediate of the tricarboxylic acid cycle to which the cells are permeable; such mutants also grow on acetate or glycolate as sole carbon sources, since the anaplerotic sequences necessary under these conditions (Figs. 2 and 3) do not involve the carboxylation of phosphoenolpyruvate. Similarly, mutants of *E. coli* devoid of isocitrate lyase (Reaction e) do not grow on acetate but grow readily on glucose, intermediates of the tricarboxylic acid cycle or glycolate; revertants of such mutants, which regained the ability to grow on acetate, were found concomitantly to have regained isocitrate lyase activity [25]. It is further of interest that *E. coli* has been found [26] to contain two malate synthases with different properties: this may reflect the catabolic role of this enzyme in the dicarboxylic acid cycle and its anaplerotic function in the glyoxylate cycle and glycerate pathway.

A second type of evidence for the intracellular operation as metabolic pathways of the enzymic sequences here described comes from measurement of the amounts of pacemaker enzymes [27] present in extracts of *E. coli* grown on appropriate carbon sources (Table 1): the activities of these enzymes are more than adequate to account for the replenishment of tricarboxylic acid cycle intermediates during growth. It may thus be concluded that the various anaplerotic sequences are both necessary and sufficient for growth.

Table 1. Levels of some anaplerotic enzymes in extracts of *E. coli W* at 30 °C (adapted from [24]).

Growth substrate	Average specific activity [μmoles/mg protein/hour] of			
	Isocitrate lyase (Reacn. e)	Malate synthetase (Reacn. f)	Glyoxylate carboligase (Reacn. h)	Tartronic semialdehyde reductase (Reacn. i)
Lactate	0.5	0.4	1	4
Acetate	15	9	1	4
Glycolate	3	35	28	75

5. Regulation of Anaplerotic Sequences

It is further apparent from the data presented in Table 1 that the pacemaker enzymes of anaplerotic sequences are under metabolic control: the appropriate enzyme is found to be abundant in extracts of cells only when the activity of that enzyme is necessary for growth on the relevant carbon source. This phenomenon, whereby micro-organisms apparently select [24] the correct

[19] *H. L. Kornberg* and *J. R. Sadler*, Nature (London) *185*, 153 (1960); Biochem. J. *81*, 503 (1961).

[20] *H. L. Kornberg* and *A. M. Gotto*, Nature (London) *183*, 1791 (1959); Biochem. J. *78*, 69 (1961).

[21] *G. Krakow, S. S. Barkulis*, and *J. A. Hayashi*, J. Bacteriol. *81*, 509 (1961).

[22] *A. M. Gotto* and *H. L. Kornberg*, Biochem. J. *81*, 273 (1961).

[23] *C. C. Doughty* and *J. A. Hayashi*, Abstr. 6th Internat. Congr. Biochem. 6, 507 (1964).

[24] *H. L. Kornberg*, Cold Spring Harbor Symp. quantitat. Biol. *26*, 257 (1961).

[25] *J. M. Ashworth* and *H. L. Kornberg*, Biochim. biophysica Acta *89*, 383 (1964).

[26] *P. Falmagne, E. Vanderwinkel*, and *J. M. Wiame*, Arch. internat. Physiol. Biochim. *71*, 813 (1963).

[27] *H. A. Krebs* and *H. L. Kornberg*, Ergebn. Physiol., biol. Chem. exp. Pharmakol. *49*, 212 (1957).

metabolic route from the range of routes which they are genetically capable of using, is illustrated by the changes in the ratio of malate synthase to citrate synthase as lactate-grown *E. coli* continue to grow on lactate, or adapt to growth on acetate or glycolate (Fig. 4).

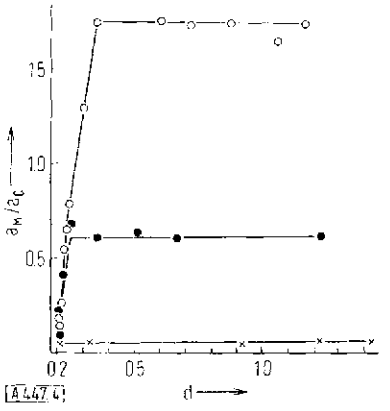

Fig. 4. Variation with growth of the ratio of malate synthase to citrate synthase in lactate-grown *E. coli W* continuing to grow on lactate (×) or adapting to growth on acetate (●) or on glycolate (○).

Ordinate: Activity of malate synthetase/activity of citrate synthetase. Abscissa: Cell density [mg dry weight/ml].

In all of these circumstances, the correct ratio of enzymic activity appears to be achieved before any major increase in the number of cells has occurred: these ratios are then maintained throughout subsequent growth [28]. This suggests that the differential rate of synthesis of pacemaker enzymes of anaplerotic sequences is regulated by variations in the intracellular levels of specific metabolites.

6. "Coarse Control" of the Glyoxylate Cycle

Although the "selection" of a particular metabolic route is a general phenomenon (and is by no means confined to anaplerotic sequences [29]), the mechanisms whereby anaplerotic sequences are regulated have been studied in detail for only one such sequence: the glyoxylate cycle. This study [30] has concentrated largely on analysis of the factors which regulate the formation of isocitrate lyase in *E. coli W*, *E. coli M 22–64* (a mutant of *E. coli W*, devoid of citrate synthase [31]), *E. coli M 191–6* (a mutant of *E. coli W*, devoid of pyruvate oxidase [32]), *E. coli Bm* [33] (a mutant of *E. coli B*, devoid of phosphoenolpyruvate carboxylase [9]), and *Achromobacter d–15* [34].

[28] *J. R. Sadler*, Ph. D. Thesis, University of Oxford, 1961.

[29] For a recent survey, see *H. E. Umbarger*, Science (Washington) *145*, 674 (1964).

[30] *H. L. Kornberg*, Colloq. internat. C.N.R.S., Marseille, 1963.

[31] *C. Gilvarg* and *B. D. Davis*, J. biol. Chemistry *222*, 307 (1956).

[32] *A. D. Gounaris* and *L. P. Hager*, J. biol. Chemistry *236*, 1013 (1961).

[33] A gift from Prof. *L. Gorini* and Mr. *R. E. Lynch* (Harvard Medical School, Boston, Mass., U.S.A.).

[34] A gift from Dr. *R. F. Rosenberger* (Hebrew University - Hadassah Medical School, Jerusalem, Israel).

a) Influence of Growth Substrates on Isocitrate Lyase Levels

The specific activity of isocitrate lyase found in extracts of acetate-grown *E. coli*, strain *W*, was 15.3 μmoles of glyoxylate formed/mg of protein/hour, which was considerably higher than after growth on other carbon sources (Fig. 5).

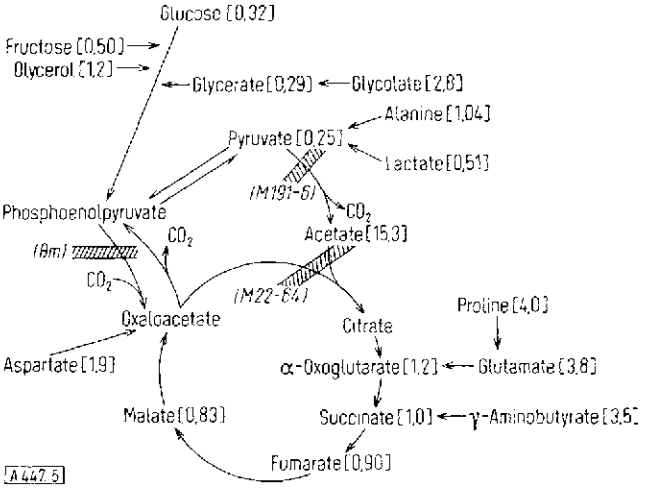

Fig. 5. Influence of growth substrates on isocitrate lyase levels in extracts of *E. coli W*. The observed specific activity of the enzyme is given in square brackets after the name of the growth substrate. The hatched bars indicate the site of the lesions in the mutants used.

However, even the magnitude of these lower specific activities was influenced by the nature of the growth substrate, as the values observed ranged from 0.25, for pyruvate-grown cells, to 4.0, for proline-grown cells. An indication of the probable nature of the phenomena underlying these variations is derived from two correlations:

a) The enzyme levels achieved on any carbon source appear to be related to the place which that carbon source occupies on the "metabolic map" (Fig. 5). Thus, growth on pyruvate and on direct precursors of pyruvate is accompanied by the lowest specific activities of isocitrate lyase, and the interposition of an additional enzymic step before the growth substrate can enter the metabolic pathways leading to C_3-compounds is accompanied by an increased production of the enzyme.

b) The enzyme levels achieved during growth on any carbon source (other than acetate) appear to be inversely related to the growth rate on that carbon source (Fig. 6).

The highest specific activities of isocitrate lyase were found during growth on substrates such as proline, glutamate, γ-aminobutyrate, and glycolate, which require the occurrence of one or more reactions before they can enter the Embden-Meyerhof pathway or the tricarboxylic acid cycle: growth on these substances was slower than on the intermediates of the main metabolic routes to which they are transformed.

These observations support the view that the rate of formation of isocitrate lyase is governed by the intracellular levels of metabolites which act as repressors. Among the factors determining these levels would be the rate of entry of the growth substrate into the main metabolic routes, which would thus influence the rate of growth of the organism.

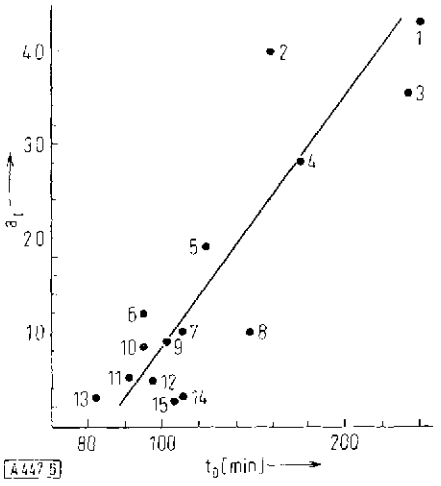

Fig. 6. Relation between mean doubling time and specific activity of isocitrate lyase in *E. coli W*, grown on the following substances as sole carbon sources: 1: Proline, 2: glutamate, 3: γ-aminobutyrate, 4: glycolate, 5: aspartate, 6: glycerol, 7: succinate, 8: alanine, 9: fumarate, 10: malate, 11: lactate, 12: fructose, 13: glucose, 14: glycerate, 15: pyruvate.
Ordinate: Specific activity of isocitrate lyase.
Abscissa: Mean doubling time.

b) The Role of Acetate in Isocitrate Lyase Induction

The high rate of enzyme synthesis during growth on acetate appears to be an exception to these two correlations (a) and (b) and might imply that acetate, or acetyl-coenzyme A, acts as a direct inducer of isocitrate lyase synthesis. There are several lines of evidence against this [35].

Identical specific activities of isocitrate lyase were obtained when *E. coli* were grown on media containing the carbon sources listed in Fig. 6 (with the exception of proline, glutamate, and γ-aminobutyrate) at 20 mM concentration, and in similar media which, in addition, contained 20 mM acetate. This showed that, in the presence of these substances, acetate did not induce isocitrate lyase formation. Only when proline, glutamate, or γ-aminobutyrate were the growth substrates did the inclusion of acetate in the growth medium stimulate the rate of isocitrate lyase synthesis: this "inducer-like" effect of acetate [36] which resulted in isocitrate lyase levels 2–3 times higher than those observed with organisms grown in the absence of acetate, was obtained also when ammonium chloride was omitted from the growth medium and the amino acids thus served as the sole nitrogen as well as the main carbon sources.

However, whereas growth of the wild-type organism *(E. coli*, strain *W)* on proline plus acetate, glutamate plus acetate, or γ-aminobutyrate plus acetate, resulted in higher rates of isocitrate lyase formation than observed during growth on these amino acids alone, the rates of enzyme formation in the mutant *M 22–64* (which lacked the ability to form citrate from oxaloacetate and acetyl-coenzyme A, see Fig. 5) were unaffected by the presence of acetate (Fig. 7).

Since this mutant has been shown to be still capable of activating acetate to acetyl-coenzyme A [31,19], the failure of acetate to stimulate the rate of isocitrate lyase synthesis by *M 22–64* argues against acetate (or acetyl-coenzyme A) as a direct inducer of this enzyme. These observations are, however, those expected if the differential rate of isocitrate lyase formation is governed by the intracellular levels of some repressor substance(s) metabolically close to oxaloacetate: in the wild-type organism, acetate would serve to lower these levels by the formation of citrate but, in the mutant, would be unable to act in this manner.

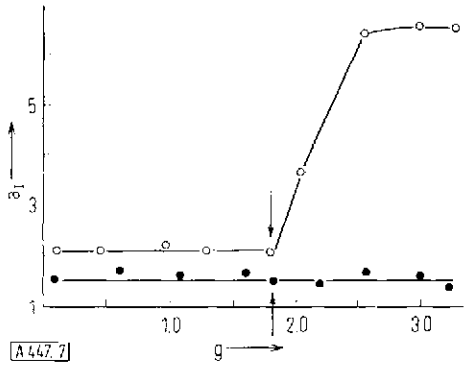

Fig. 7. Effect of 20 mM acetate on isocitrate lyase formation by *E. coli W* (o) and its mutant *M 22–64* (●) during growth on proline. Acetate was added at the points indicated by arrows.
Ordinate: Specific activity of isocitrate lyase.
Abscissa: Number of bacterial generations.

Further evidence for this view was provided from the effect of acetate on *M 22–64* growing on 20 mM glycolate plus 2 mM glutamate. In the absence of acetate, isocitrate lyase was produced at a specific activity of 2,2, which remained constant over nearly 2 generations. The addition of 50 mM acetate after this time not only failed to induce isocitrate lyase formation but caused a sharp decrease in the specific activity of the enzyme without causing any decrease in the growth rate. Similarly, when the glycolate/glutamate-grown mutant was inoculated into a medium containing these carbon sources plus 50 mM acetate, the growth of the organisms was accompanied by an initial decrease in the content of isocitrate lyase to a new level, which was less than 60% of that present in cells growing in the absence of acetate and which was maintained constant during the subsequent growth (Fig. 8).

Since it is known [19] that acetate can enter the metabolic pathways of this mutant during growth on glycolate, by combining with glyoxylate to form malate (cf. Fig. 3),

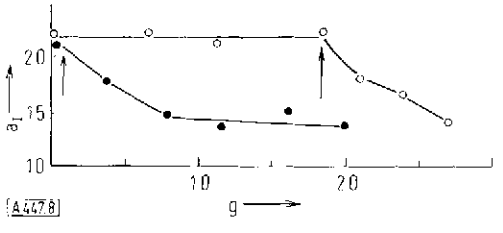

Fig. 8. Effect of acetate on isocitrate lyase formation by *M 22–64* growing on 20 mM glycolate plus 2 mM glutamate (o) or on this medium plus 50 mM acetate (●). The experiments were begun with cells grown on glycolate plus glutamate; acetate was added at the points indicated by arrows.
Ordinate: Specific activity of isocitrate lyase.
Abscissa: Number of generations.

[35] *H. L. Kornberg*, Biochim. biophysica Acta *73*, 517 (1963).
[36] *R. F. Rosenberger*, Biochim. biophysica Acta *64*, 168 (1962).

these observations are consistent with the formation from malate of repressor(s) of isocitrate lyase.

c) Possible Identity of the Metabolite Responsible for Isocitrate Lyase Repression

It was observed that, during growth on glycolate plus acetate, the specific activity of isocitrate lyase in the mutant *M 191–6* (which could not oxidize pyruvate) was less than 30% of that present in *M 22–64* (Fig. 8) and less than 15% of that in the parent wild-type *E. coli* (Fig. 5) under similar growth conditions. This suggested that, if a particular metabolite acted as a specific repressor of isocitrate lyase synthesis, that metabolite is likely to be a C_3-compound rather than an intermediate of the tricarboxylic acid cycle. There are several other lines of evidence in favor of this hypothesis:

(1) The acetate-requiring mutant *M 191-6* was grown on a mixture of 20 mM glycolate plus 10 mM acetate. After an increase in cell density of approximately 0.1 mg dry weight/ml, samples of the cultures were taken for enzyme assay and the volumes of liquid removed were replaced by fresh growth medium. Under these conditions, in which the organism grew at constant rate and remained at relatively constant cell density, they produced isocitrate lyase at constant though unusually low specific activity (0.3 μmoles/mg protein/hour). However, when the liquid removed in the course of sampling was replaced by equivalent volumes of 20 mM glycolate medium from which acetate had been omitted, the exhaustion of the acetate in the growth medium led to a progressive decrease in growth rate and ultimate cessation of growth.

As expected from the known metabolic lesion of this mutant, the decrease in growth rate was also accompanied by the accumulation of pyruvate (identified as the 2,4-dinitrophenylhydrazone) in the medium. The specific activity of isocitrate lyase in successive samples taken from this culture fell sharply to very low levels, which suggested that the overproduction of catabolic products from glycolate raised the concentration of metabolites inside the cells to a level at which isocitrate lyase synthesis was virtually abolished. Since the mutant was unable to oxidize pyruvate to acetate and hence was unable to form malate from glyoxylate in the absence of added acetate, this unusually strong repression of isocitrate lyase synthesis occurred under conditions characterized by an over-production of C_3-compounds without the prior formation of malate.

(2) The addition of pyruvate to a culture of *M 22-64* growing on proline as sole carbon source did not decrease the rate of growth but markedly lowered the rate of isocitrate lyase formation (Fig. 9). In this mutant, the addition of pyruvate could presumably have raised the intracellular levels of C_4-dicarboxylic acids as well as those of C_3-compounds, but could not have raised those of other intermediates of the tricarboxylic acid cycle.

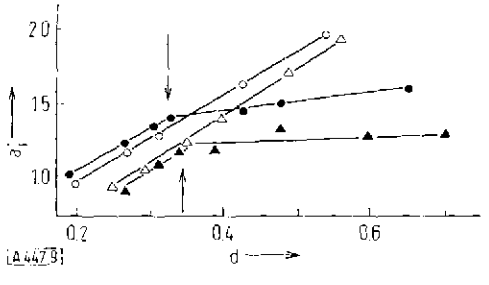

Fig. 9. Effect of pyruvate on isocitrate lyase formation by *M 22–64* (Δ, ▲) and by *Bm* (o, ●) at 30 °C during growth on proline. Pyruvate to 5 mM was added to the cultures marked with closed symbols at the points indicated by arrows.

Ordinate: Specific isocitrate layse activity × cell density.
Abscissa: Cell density [mg dry weight/ml].

(3) The addition of pyruvate to a culture of the mutant *Bm* growing on proline as sole carbon and nitrogen source did not decrease the rate of growth but markedly lowered the rate of isocitrate lyase synthesis (Fig. 9). In this mutant, pyruvate could be oxidized but could not give rise to the net formation of C_4-dicarboxylic acids.

(4) The addition of pyruvate to a culture of *Bm* growing on 50 mM acetate plus 5 mM glutamate, added as sole nitrogen source, did not decrease the rate of growth of the organism but led to a decrease of over 85 % in the high rate of isocitrate lyase synthesis; this effect persisted until the added pyruvate had been used up (Fig. 10). Since glutamate had been added as sole nitrogen source, and since no α-oxo acids were detected in the medium, the amino acid must have been utilized for growth but without causing the intracellular accumulation of repressor substances; such substances were, however, formed from pyruvate, although no net formation of C_4-dicarboxylic acids from pyruvate could occur in this mutant.

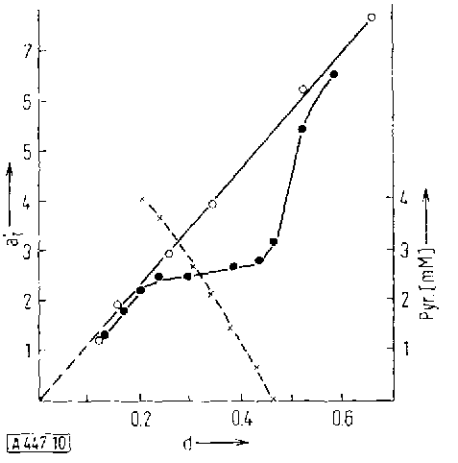

Fig. 10. Effect of pyruvate on isocitrate lyase formation by *Bm* during growth on 50 mM acetate plus 5 mM glutamate, in the absence of other nitrogen sources. Pyruvate to 5 mM was added to the culture marked (●); the decrease in the pyruvate content of the medium is indicated by (×). The culture marked (o) received no pyruvate.

Ordinates: left: Specific activity of isocitrate lyase × cell density.
right: Pyruvate concentration [mM].

Abscissa: Cell density [mg dry weight/ml].

(5) The addition of pyruvate to a culture of *Bm* growing on 50 mM acetate plus 5 mM aspartate, added as sole nitrogen source, did not decrease the rate of growth but caused a sharp decrease in the high rate of isocitrate lyase synthesis (Fig. 11). Again, the amino acid must have been utilized for growth and must therefore have provided oxaloacetate to the organism, but at a rate insufficient to lower significantly the high rate of isocitrate lyase formation: again, the enzyme was repressed by the addition of pyruvate although, in this mutant, this C_3-compound could not give rise to the net formation of C_4-compounds.

These findings suggest that, if any single metabolite may be regarded as a specific repressor of isocitrate lyase, that metabolite cannot be a C_4-dicarboxylic acid (results with *Bm*), cannot be another intermediate of the tricarboxylic acid cycle (results with *M 22–64*), and cannot be an oxidation product of pyruvate (results with *M 191–6*): the metabolite must be either pyruvate itself or some product metabolically close to both pyruvate and oxaloacetate.

If it can be assumed that the factors which regulate isocitrate lyase synthesis in *E. coli* are similar to those which regulate it in other micro-organisms (and data obtained

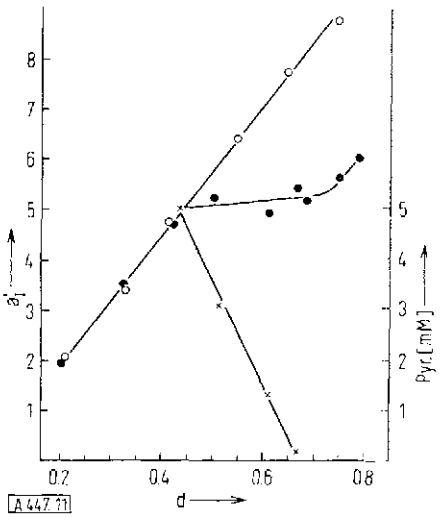

Fig. 11. Effect of pyruvate on isocitrate lyase formation by *Bm* during growth on 50 mM acetate plus 5 mM aspartate, in the absence of other nitrogen sources. Pyruvate to 5 mM was added to the culture marked (●); the decrease in the pyruvate content of the medium is indicated by (×). The culture marked (○) received no pyruvate.

Ordinates: left: Specific activity of isocitrate lyase × cell density.
right: Pyruvate concentration [mM].
Abscissa: Cell density [mg dry weight/ml].

with bacteria [10], fungi [37,38], algae [39,40], and protozoa [41] suggest that this assumption is justified), then pyruvate itself is not likely to act as a repressor metabolite. Evidence for this belief stems from results obtained with *Achromobacter d–15*. This organism is unusual in that cell-free extracts contain isocitrate lyase of high specific activity (6–8 μmoles/mg protein/hour) after growth on pyruvate, lactate, or alanine as sole carbon sources, though, as observed with other organisms, the enzyme is synthesized to only a small extent during growth on intermediates of the tricarboxylic acid cycle. A second unusual feature of *Achromobacter d–15* is that it is unable to grow on glucose, glycerol, or glycolate; this disability may be ascribed [42] to the absence of pyruvate kinase (Reaction m) activity, with

$$CH_3{-}CO{-}CO_2H + ATP \rightleftharpoons CH_2{=}C(CO_2H)O{-}PO_3H_2 + ADP \quad (m)$$

consequent inability to gain entry into the tricarboxylic acid cycle for catabolites which must traverse this essential step of the Embden-Meyerhof sequence to do so. It is thus probable that the high levels of isocitrate lyase found in extracts of pyruvate-grown *Achromobacter d–15* are similarly symptomatic of the inability of this organism directly to form phosphoenolpyruvate from pyruvate[*]; since this substance can still be formed from oxaloacetate (*via* Reaction d), and since growth on intermediates of the tricarboxylic acid cycle yields only low levels of isocitrate lyase, it is tempting to conclude that one of the repressor metabolites responsible for regulating the synthesis of isocitrate lyase is phosphoenolpyruvate.

It is probable that more than one metabolite exerts a regulatory function over isocitrate lyase. Evidence for this view stems from studies with a mutant, *BmR*, which, though derived from *Bm*, differs from it in being able to grow on glycerol, glucose, or pyruvate. This growth pattern is, however, not due to a reversion, with consequent restoration of phosphoenolpyruvate carboxylase activity, but (as has also been reported [43] for a similar mutant of *E. coli K 12*) is the result of a second mutational change affecting a regulator gene for isocitrate lyase synthesis (Table 2).

Table 2. Effect of growth substrates on isocitrate lyase levels in wild-type *E. coli* and the mutant *BmR* at 30 °C.

Growth substrate	Specific activity [μmoles/mg protein/hour] of isocitrate lyase in	
	Wild-type *E. coli*	Mutant *BmR*
Glucose	0.3	10
Lactate	0.5	20
Malate	0.8	27
Succinate	1.0	34
Acetate	15	50

Thus, even during growth on glucose, the differential rate of isocitrate lyase synthesis is over thirtyfold that observed in wild-type *E. coli*, and the necessary net formation of C_4-acids can, in *BmR*, be effected *via* the glyoxylate cycle despite the presence of substrates which strongly repress this enzyme in wild-type organisms and in *Bm*. It is, however, remarkable that extracts of *BmR* obtained from cells, grown on a variety of substrates, exhibit a pattern of variation of isocitrate lyase activity with the mean doubling time on that substrate which is qualitatively similar to that observed with wild-type cells (*cf.* Fig. 6): to adapt the famous slogan of *George Orwell*'s "Animal Farm", it is clear that, although isocitrate lyase production in *BmR* is constitutive, it is under some circumstances more constitutive than under others. These observations suggest that *BmR* has escaped from the repression exerted by one metabolite but remains subject to repression by another [44].

7. "Fine Control" of the Glyoxylate Cycle

Although the variations in the differential rate of synthesis of isocitrate lyase described represent one type of control of the glyoxylate cycle, such a regulatory process must be relatively "coarse". Studies with *E. coli*, strain *B*, and its mutant *Bm* suggest that, in addition, a "fine" control of the cycle may be exerted by variations in the intracellular levels of phosphoenolpyruvate, which has been found to be a powerful non-competitive inhibitor of isocitrate lyase [9].

[37] *J. F. Collins* and *H. L. Kornberg*, Biochem. J. *77*, 430 (1960).

[38] *W. S. Wegener* and *A. H. Romano*, J. Bacteriol. *87*, 156 (1964).

[39] *L. C. Harrop* and *H. L. Kornberg*, Biochem. J. *88*, 42P (1963).

[40] *A. G. Callely* and *D. Lloyd*, Biochem. J. *90*, 483 (1964).

[41] *J. F. Hogg* and *H. L. Kornberg*, Biochem. J. *86*, 461 (1963).

[42] *H. L. Kornberg, J. Dennis*, and *E. M. Wilson*, Biochem. J. *92*, 55P (1964).

[*] Note added in proof: It is unlikely that phosphoenolpyruvate can be formed from pyruvate by Reaction (m) since *E. coli* contains a PEP-synthase system for this purpose distinct from pyruvate kinase. – Cf. *R. Cooper* and *H. L. Kornberg*, Biochim. biophysica Acta *104*, 618 (1965).

[43] *E. Vanderwinkel, P. Liard, F. Ramos*, and *J. M. Wiame*, Biochem. biophysic. Res. Commun. *12*, 157 (1963).

[44] These observations are analogous to the finding that mutants lacking the *i* gene for β-galactosidase are still subject to catabolite repression: see *J. Mandelstam*, Biochem. J. *82*, 489 (1962); *W. F. Loomis* and *B. Magasanik*, J. molecular Biol. *8*, 417 (1964).

Although the addition of pyruvate to cultures of *E. coli B* growing on acetate, or of *Bm* growing on acetate in the presence of glutamate or aspartate, did not decrease the rate of growth, the addition of this C_3-compound to a culture of the mutant growing on acetate in the absence of these amino acids speedily arrested its growth, which was resumed when the added pyruvate had been utilized (Fig. 12).

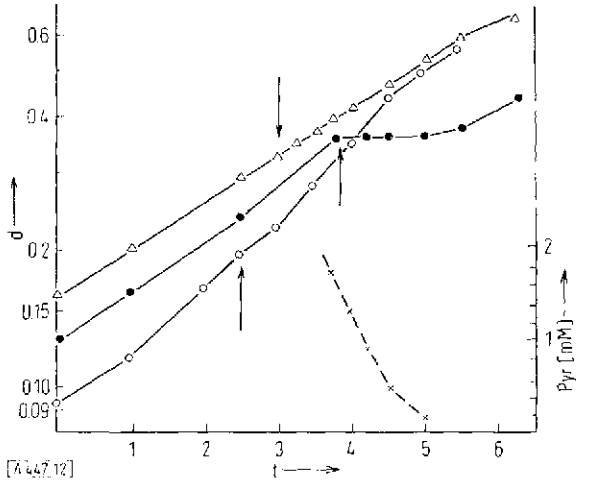

Fig. 12. Effect of pyruvate at 30 °C on the growth of *E. coli B*, (Δ) on 50 mM acetate, and on the growth of its mutant *Bm* in media containing 50 mM acetate (●), or 50 mM acetate plus 5 mM glutamate (○). Sodium pyruvate was added where indicated by arrows. The inset (×) records the decrease in the pyruvate concentration (mM) after its addition to *Bm* growing on acetate (●).

Ordinates: left: Cell density [mg dry weight/ml].
right: Pyruvate concentration [mM].
Abscissa: Time [hours].

This observation indicated that pyruvate, or a product of pyruvate metabolism, inhibited the net formation of C_4-compounds from acetate: as an alternative mode of formation of such compounds, *e. g.* by carboxylation of phosphoenolpyruvate, was not possible in this mutant, its growth ceased. (The failure of pyruvate to inhibit the growth of *Bm* on acetate plus aspartate or glutamate is thus further indication that these amino acids were indeed utilized as sources of intracellular C_4-dicarboxylic acids: cf. Figs. 10 and 11). Since pyruvate was utilized by *Bm* though its growth had ceased, and since washed suspensions of the acetate-grown mutant readily oxidized pyruvate, it was evident that pyruvate did not inhibit a component reaction of the tricarboxylic acid cycle but probably acted on a key enzyme of the glyoxylate cycle.

An indication of the mechanism of this effect was provided by the finding that, whereas neither 0.1 mM nor 1 mM pyruvate inhibited significantly the activity of isocitrate lyase in cell-free extracts of acetate-grown *Bm*, phosphoenolpyruvate was a powerful inhibitor of this enzyme. At a concentration of 1×10^{-4} M, phosphoenolpyruvate reduced the quantity of glyoxylate formed from the cleavage of 2 mM isocitrate to 58%, and at 1×10^{-3} M to 11% of that observed in its absence. Quantitative spectrophotometric assay [45] showed that neither malate synthase nor citrate synthase was inhibited by 0.1 mM phosphoenolpyruvate, but that isocitrate lyase was inhibited non-competitively, with K_i 1.3×10^{-4} M. Other intermediates of the Embden-Meyerhof pathway (such as 2-phosphoglycerate, 3-phosphoglycerate and hexose mono- and di-phosphates) exerted no inhibitory action at 1 mM concentration. Similar results have been obtained with the isocitrate lyase in extracts of *E. coli W*, *Chlorella vulgaris*, Brannon No. 1 strain, and *Achromobacter d–15*.

[45] *G. H. Dixon* and *H. L. Kornberg*, Biochem. J. 72, 3P (1959).

Concluding Remarks

It has been the main purpose of this communication to summarize the evidence for the belief that, for a proper description of the flow of nutrients associated with the release of energy and its utilization for biosyntheses, a special type of metabolic pathway must operate inside the cell which may be regarded as serving solely to maintain the functioning of the tricarboxylic acid cycle and other amphibolic routes. It has been proposed to generically designate this type of ancillary pathway as an anaplerotic sequence. Key enzymes of anaplerotic sequences may be recognized as distinct biological entities, even when other enzymes exist in the cell which catalyse a closely similar or the same chemical reaction; their action is necessary for growth on C_3- and C_2-compounds to occur (Table 3).

Table 3. Catabolic and anaplerotic sequences in *E. coli*.

Carbon source	Catabolic route	Anaplerotic sequence
Glucose, glycerol or C_3-compounds	Tricarboxylic acid cycle	Phosphoenolpyruvate carboxylase
Acetate	Tricarboxylic acid cycle	Glyoxylate cycle
Glycolate	Dicarboxylic acid cycle	Glycerate pathway

Although little is known in detail of the factors which regulate the operation of the various anaplerotic sequences, studies on the glyoxylate cycle suggest that they act at least at two levels: *via* a "fine control" mechanism, achieved through inhibition of the activity of a pacemaker enzyme, and a "coarse control" mechanism, achieved through inhibition of the synthesis of that enzyme. The data obtained further suggest that both modes of control may be exerted, at least in part, through variations in the intracellular levels of the same metabolite – phosphoenolpyruvate. Since phosphoenolpyruvate can be regarded both as the precursor of many cell components (such as aromatic amino acids, the pentose moieties of nucleic acids, and other carbohydrates) in their formation from acetate and as the major product of the glyoxylate cycle, these types of control are further examples of feedback mechanisms [29], which enable micro-organisms sensitively and efficiently to adjust to changes in their environment.

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Chemiluminescence in Organic Compounds

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Dedicated to Professor Fritz Micheel on the occasion of his 65th birthday

As a result of the development of very sensitive equipment, it is now possible to show that the chemiluminescence of organic compounds in solution is quite a common phenomenon. Notable advances have been made during recent years in the investigation of the chemiluminescence of substituted phthalic acid hydrazides and related compounds. A new and probably generally applicable method of producing chemiluminescence has recently been discovered in the reaction of aromatic free-radical anions with appropriate free-radical cations.

1. Introduction

Chemiluminescence reactions are processes in which a molecule capable of fluorescing is raised to an excited electronic state by chemical energy [1]. If the reaction is to be accompanied by the emission of visible light, it must supply an energy of at least 40–70 kcal/mole. This is the case, for example, in free-radical chain oxidations. There should consequently be a large number of chemiluminescence reactions, and many examples are in fact to be found in the literature (reviews: [2–7]). Only a few reactions are known, however, in which a really brilliant light is emitted. Owing to advances in the construction of equipment, it is now possible to measure accurately light intensities of some 10^3 photons cm^{-3} sec^{-1} [8,9], so that even weak chemiluminescence in organic reactions can be detected (cf. also the earlie workby *Audubert* [10]).

The relationships between the constitution of organic compounds and their ability to exhibit chemiluminescence are roughly parallel to the relationships between constitution and ability to fluoresce [11–15]. However, just as the fluorescence of organic compounds in solution is affected by many parameters relating to the medium, such as concentration, pH, solvent, quenching action of foreign substances present (cf. [15]), chemiluminescence is further complicated by the fact that the processes yielding the radiant energy may be accompanied by other chemical reactions (cf. Section 8).

Bioluminescence reactions are enzyme-catalyzed chemiluminescence processes in which oxygen acts as an electron acceptor. According to *McElroy* and *Seliger* [17], these oxidation processes are controlled by the enzyme so efficiently that the quantum yields are about unity [16], in contrast to organic chemiluminescence reactions in solution, which give quantum yields of at most 0.05.

2. Chemiluminescence in the Slow Autoxidation of Hydrocarbons, Aldehydes, Ketones, and Unsaturated Acids and their Esters

The very weak chemiluminescence in the autoxidation of hydrocarbons such as ethylbenzene, cumene, diphenylethane, cyclohexane, or tetralin can be measured with the aid of very sensitive photoelectric measuring devices[8,9,18,18a]. In the cases of cumene, cyclohexane, and tetralin, the emitted light has a maximum in the blue-green region of the spectrum, corresponding to a reaction enthalpy of approximately 55 kcal/mole [9].

[1] Definition by: *E. J. Bowen*, Angew. Chem. *77*, 47 (1965); Angew. Chem. internat. Edit. *4*, 81 (1965).

[2] *E. H. White* and *M. M. Bursey*, J. Amer. chem. Soc. *86*, 941 (1964).

[2a] *T. I. Quickenden*, J. New Zealand Inst. Chem. *28*, 10 (1964).

[2b] *J. Stauff* and *H. Schmidkunz*, Z. physikal. Chem. N.F. *33*, 273 (1962).

[3] *H. Stork*, Chemiker-Ztg. *85*, 467 (1961).

[4] *E. N. Harvey*: A History of Luminescence. The American Philosophical Society, Philadelphia 1957.

[5] *A. Bernanose*, Bull. Soc. chim. France *1952*, 39 D.

[6] *W. Vaughan*, Chem. Reviews *43*, 447 (1948).

[7] *R. S. Anderson*, Ann. New York Acad. Sci. *49*, 337 (1947).

[8] *V. Y. Shlyapintokh, R. F. Vassil'ev, O. N. Kharpukhin, L. M. Postnikov*, and *L. A. Kibalko*, J. Chim. physique *57*, 1113 (1960).

[8a] *J. Stauff* and *G. Rümler*, Z. physik. Chem. N.F. *34*, 67 (1962).

[9] *M. Höfert*, Angew. Chem. *76*, 826 (1964).

[10] *R. Audubert*, Angew. Chem. *51*, 153 (1938); Trans. Faraday Soc. *35*, 197 (1939).

[11] *Th. Förster*: Fluoreszenz organischer Verbindungen. Vandenhoek & Ruprecht, Göttingen 1951.

[12] *Th. Förster* in Houben-Weyl: Methoden der organischen Chemie. Thieme, Stuttgart 1955, Vol. 3/2, p. 481.

[13] *W. C. Price*, Annual Rev. physic. Chem. *11*, 133 (1960).

[14] *H. Meier*: Die Photochemie der organischen Farbstoffe. Springer, Berlin 1963, p. 65.

[15] *B. J. van Duuren*, Chem. Reviews *63*, 325 (1963).

[16] *E. N. Harvey*: Bioluminescence. Academic Press, New York 1952.

[17] *W. D. McElroy* and *H. H. Seliger* in *W. D. McElroy* and *B. Glass*: A Symposium on Light and Life. The Johns Hopkins Press, Baltimore 1961, p. 219.

[18] *R. F. Vassil'ev* and *A. A. Vichutinskii*, Nature (London) *194*, 1276 (1962); *R. F. Vassil'ev* and *I. F. Rusina*, Dokl. Akad. Nauk SSSR *156*, 1402 (1964).

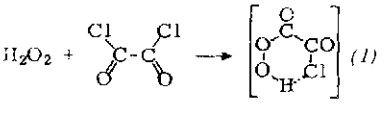
End products containing oxygen (alcohols, aldehydes, and ketones) are particularly capable of emitting visible light [18]. Kinetic studies show that the intensity of the light is in most cases proportional to the oxygen consumption [19]. The lifetime of the excited state in the oxidation of ethylbenzene (10^{-7} to 10^{-6} sec) agrees well [18] with that of the triplet state of acetophenone [18b]. The chemiluminescence accompanying the autoxidation of hydrocarbons is intensified by free-radical formers such as azobisisobutyronitrile [18] or by X-rays [9], and weakened by free-radical scavengers such as 2,6-di-butyl-*p*-cresol [9,20]. This fact offers a possible method of determining the efficiencies of antioxidants [21] and oxidation initiators [22] with the aid of chemiluminescence reactions.

The extremely weak light emission (quantum yields $\approx 10^{-8}$ to 10^{-10}) accompanying these autoxidations becomes stronger if the reaction medium contains fluorescent molecules, such as anthracene, oxazole, or pyrazole derivatives (sensitized or "activated" chemiluminescence). Thus the chemiluminescence in the oxidation of cyclohexane is intensified by a factor of almost 50 by 9,10-dibromoanthracene. The spectrum of the "activated" chemiluminescence corresponds to the fluorescence spectrum of the activator [18].

Other examples of autoxidative chain reactions exhibiting very weak chemiluminescence are the oxidation of acetaldehyde [23], oleic or linoleic acid [9], methyl oleate [18], and n-butyl oleate [9].

3. Chemiluminescence in the Reactions of Oxalyl Chloride or Nitriles with Hydrogen Peroxide

Chandross [24] observed a weak bluish-white chemiluminescence during the reaction of oxalyl chloride with hydrogen peroxide. He postulated the intermediate



(1)

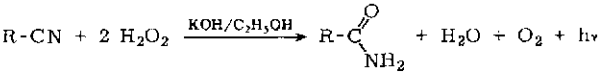
$\longrightarrow$ HCl + 2 CO + O_2 + hν

formation of monoperoxyoxalic acid monochloride *(1)*, which was then assumed to decompose into oxygen, carbon monoxide, and hydrogen chloride, with simultaneous liberation of the excitation energy required for the chemiluminescence. The luminescent species has not yet been established. The energy levels of HCl, CO, or CO_2 are too high, and the energy of an excited oxygen singlet (38 kcal/mole) is too low to cause the observed chemiluminescence.

It is interesting that the vapors escaping during the reaction of oxalyl chloride with hydrogen peroxide can excite fluorescence. One possible explanation according to *Chandross* is that the excitation energy is first absorbed by oxalyl chloride to give molecules in the triplet state; these are then carried out of the liquid phase with the reaction gases and pass on their excitation energy to a fluorescent molecule.

Acetyl chloride exhibits no luminescence under identical conditions. *Rauhut* et al. found that other derivatives of monoperoxyoxalic acid also decompose in the presence of sensitizers with light emission [24a], *e.g.* t-BuOOCO · CO · Cl [24b]. The simultaneous cleavage of all bonds involved ("concerted multiple bond cleavage") is decisive for the occurrence of chemiluminescence. Extremely weak chemiluminescence (quantum yields of 10^{-13} to 10^{-15}) has been observed in the reaction of adipyl chloride or benzoyl chloride with hexamethylenediamine or aniline [8,25].

A blue luminescence, which persists for a relatively long time and which is visible in the dark with the naked eye, occurs during the reaction of certain nitriles such as benzyl cyanide, acrylonitrile, or benzonitrile with hydrogen peroxide in alkaline solution [26]. The chemiluminescence observed with benzonitrile, however, is very



R = $C_6H_5CH_2$-; H_2C=CH-; C_6H_5-.

weak. Since the reactions proceed by a heterolytic mechanism [26], molecular oxygen can initially be formed only in an excited singlet state (cf. the investigations by *Bowen* et al. [27,28] on the chemiluminescence of dissolved oxygen; see also the next section).

4. Grignard Compounds and Polyphenols

The chemiluminescence accompanying the autoxidation of Grignard compounds was studied in detail as early as 1925 [29], together with the relationships between structure and chemiluminescence. It has been shown by a preparative method that the reaction proceeds *via* the

[18a] *G. Lundeen* and *R. Livingston*: Symposium on Chemiluminescence. Durham N.C. 1965. Preprints p. 281.

[18b] *F. Wilkinson* and *J. Dubois*, J. chem. Physics *39*, 377 (1963).

[19] *R. F. Vassil'ev*, Nature (London) *196*, 668 (1962); *R. F. Vassil'ev*, *A. A. Vichutinskii*, and *A. S. Tcherkassov*, Dokl. Akad. Nauk SSSR *149*, 124 (1962).

[20] *R. F. Vassil'ev*, Dokl. Akad. Nauk SSSR *144*, 143 (1962).

[21] *V. Ya. Shlyapintokh*, *O. N. Kharpukhin*, and *I. F. Russina*, Zh. obshch. Khim. *33 (95)*, 3110 (1963).

[22] *A. A. Vichutinskii*, Zh. Fiz. Khim. *38*, 1668 (1964).

[23] *L. M. Possnikow*, *W. F. Schuwalow*, and *V. Ya. Shlyapintokh*, Izv. Akad. Nauk SSSR, Ser. Fiz. *27*, 735 (1963); Chem. Zbl. *1965*, No. 5, 0759.

[24] *E. A. Chandross*, Tetrahedron Letters *1963*, 761.

[24a] *M. M. Rauhut* et al. in: Symposium on Chemiluminescence. Durham N.C. 1965. Preprints p. 347.

[24b] *P. D. Bartlett* and *R. E. Pincock*, J. Amer. chem. Soc. *82*, 1769 (1960).

[25] *Ss. G. Enteliss*, *V. Ya. Shlyapintokh*, *O. N. Kharpukhin*, and *O. V. Nessterow*, Zh. Fiz. Khim. *34*, 1651 (1960).

[26] *E. McKeown* and *W. A. Waters*, Nature (London) *203*, 1063 A (1964).

[27] *E. J. Bowen* and *R. A. Lloyd*, Proc. chem. Soc. (London) *1963*, 305 (1963).

[28] *E. J. Bowen*, Nature (London) *201*, 180 B (1964).

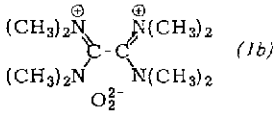
[29] *W. V. Evans* and *E. M. Diepenhorst*, J. Amer. chem. Soc. *48*, 715 (1926); *R. T. Dufford*, *D. Nightingale*, and *S. Calvert*, ibid. *47*, 95 (1925), and earlier papers.

intermediate R–O–O– MgBr [30]. Kinetic studies on the autoxidation of phenylmagnesium bromide confirmed the relationship between chemiluminescence and the free-radical chain mechanism [31].

The intense red chemiluminescence observed during the reaction of pyrogallol with formaldehyde, hydrogen peroxide, and alkali has an emission band at 630 mμ due to excited oxygen molecules [27]. *Stauff* et al. [31a] found that the chemiluminescence spectra of the oxidation of formaldehyde with H_2O_2, and of other organic and inorganic oxidation reactions, correspond to the absorption bands of $(O_2)_2$ molecules, which should therefore be considered as the emitting species. The chemiluminescence that accompanies the oxidation of pyrocatechol, resorcinol, and other polyfunctional phenols with ozone can be sensitized by fluorescent dyes such as rhodamine B. Quantitative investigations have recently been carried out of the dependence of this sensitized chemiluminescence on the structure of the polyphenol [32].

5. Tetrakis(dimethylamino)ethylene

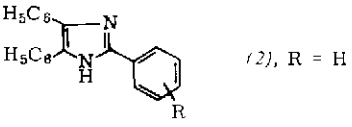
The autoxidation of the powerful electron donor tetrakis-(dimethylamino)ethylene, $[(CH_3)_2N]_2C{-}C[N(CH_3)_2]_2$ *(1a)*, and its reaction with bromine, occur with emission of green light [32a, b], the spectrum of which agrees with the fluorescence spectrum of *(1a)* [32c]. The products include tetramethylurea, tetramethyloxamide, and bis-(dimethylamino)methane [32b, d], which are formed, as shown by NMR-spectroscopy [32d], from the primary product *(1b)*, which can be isolated under suitable conditions. According to kinetic studies by *Paris* [32e], the carbene $[(CH_3)_2N]_2C{:}$ is an important intermediate.



(1b)

6. 2,4,5-Triphenylimidazole ("Lophine") and Related Compounds

The blue-green chemiluminescence accompanying the oxidation of lophine *(2)* with oxygen in alkaline solution [3] is one of the strongest known prior to the discovery of the chemiluminescence of "lucigenin" *(6)* and "luminol" *(11)*, which will be discussed in the next section.



(2), R = H

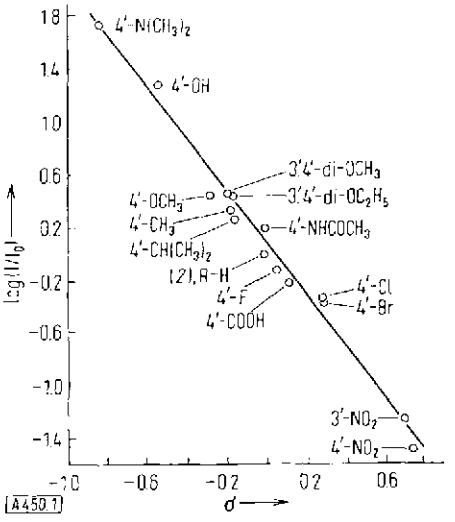
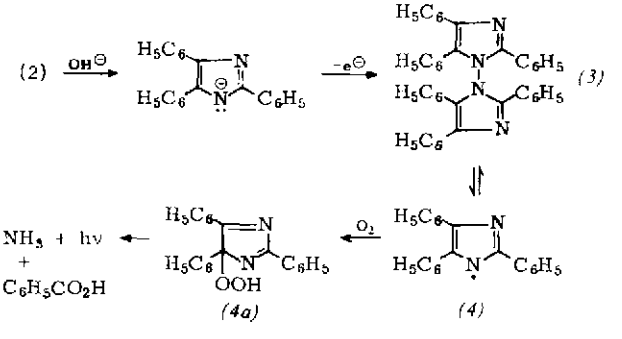


Fig. 1. Relative intensities of the chemiluminescence of substituted lophines *(2)* [35].
I_0: maximum intensity of lophine *(2)*.
I: maximum intensity of the substituted lophine.
Abscissa: σ constants according to *J. Hine* [33a].

The chemiluminescence intensities of a number of lophine derivatives containing substituents in positions 3' or 4' of the 2-phenyl group [33] have recently been compared. It can be seen from Fig. 1 that the substituent effects follow the Hammett equation. All the substituted lophines were found to have a chemiluminescence emission maximum at 530 mμ, irrespective of whether the oxidation is carried out with oxygen or with hydrogen peroxide. Recent investigations [34] indicate that the oxidation of *(2)* in alkaline media leads *via* the anion to the diimidazolyl derivative *(3)*, which exists in equilibrium with the radical *(4)*. This radical can react with



[30] Cf. the review by *H. Hock, H. Kropf*, and *F. Ernst*, Angew. Chem. *71*, 541 (1959).

[31] *Th. Bremer* and *H. Friedmann*, Bull. Soc. chim. Belges *63*, 415 (1954).

[31a] *J. Stauff* and *F. Lohmann*, Z. physik. Chem. N. F. *40*, 123 (1964).

[32] *D. S. Bersis*, Z. physik. Chem. *26*, 359 (1960).

[32a] *R. L. Pruett* et al., J. Amer. chem. Soc. *72*, 3646 (1950).

[32b] *N. Wiberg* and *J. W. Buchler*, Angew. Chem. *74*, 490 (1962); Angew. Chem. internat. Edit. *1*, 406 (1962); Chem. Ber. *96*, 3223 (1963).

[32c] *H. E. Winberg, J. R. Downing*, and *D. D. Coffman*, J. Amer. chem. Soc., in press.

[32d] *W. H. Urry* and *J. Sheeto*: Symposium on Chemiluminescence. Durham, N.C. 1965. Preprints p. 223.

[32e] *J. P. Paris*, in [32d], p. 243

[33] *G. E. Philbrook* and *M. A. Maxwell*, Tetrahedron Letters *1964*, 1111.

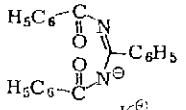
[33a] *J. Hine*: Physical Organic Chemistry. McGraw-Hill, New York 1962, p. 87.

[34] *T. Hayashi* and *K. Maeda*, Bull. Soc. chem. Japan *35*, 2057 (1962); *36*, 1052 (1963).

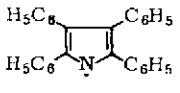
[35] *T. Hayashi* and *K. Maeda*, Bull. chem. Soc. Japan *35*, 2058 (1962).

oxygen to form the peroxide *(4a)* [35a], which decomposes into benzoic acid, ammonia, and other products, with simultaneous emission of light. *(4a)* is relatively stable; it can be isolated, and it chemiluminesces in warm oxygen-free alkaline solutions or when heated to 110 °C [35a].

Since the chemiluminescence spectra of *(2)* and its derivatives are identical with the fluorescence spectra of diaroylarylamidine salts of the type *(4b)*, these salts are regarded as the emitting species [35b]. A similar reaction sequence is also postulated for the weakly chemiluminescent oxidation of 2,3,4,5-tetraphenylpyrrole [35], *i.e.* the radical *(5)* is an important intermediate in this case.



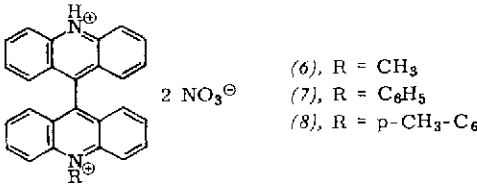
(4b)



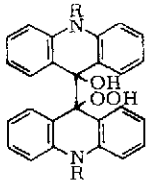
(5)

7. 9,9′-Diacridinium Salts ("Lucigenin" and Related Compounds)

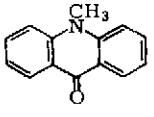
The intense green chemiluminescence observed during the oxidation of "lucigenin" *(6)* with H_2O_2 in alkaline solution was first described by *Gleu* and *Petsch* [36] (cf. [7]). The observation [37] that the color of the chemiluminescence changes from green to blue when the *N*-alkyl groups in compounds of the type *(6)* are replaced by phenyl groups to form *(7)*, was confirmed for the *N,N′*-di-*p*-tolyl compound *(8)* [38]. Recent spectroscopic and kinetic studies [39–46] corroborate the finding [47] that the radiating species in the "lucigenin" chemiluminescence is *N*-methylacridone *(10)*; this is probably formed in a free-radical chain reaction involving the hydroperoxide *(9)* [43,47a]. The peroxyacid derivative *(10a)* shows strong chemiluminescence with water.



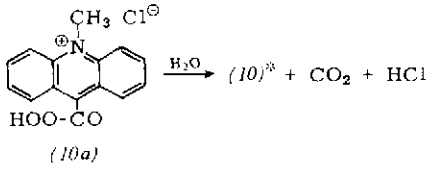
(6), R = CH_3
(7), R = C_6H_5
(8), R = p-CH_3-C_6H_4



(9)



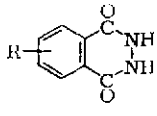
(10)



(10a)

8. 3-Aminophthalhydrazide ("Luminol") and Other Hydrazides

Since the first publication [48] describing the intense blue chemiluminescence accompanying the alkaline oxidation of 3-aminophthalhydrazide (5-amino-1,2,3,4-tetrahydrophthalazine-1,4-dione) *(11)*, these and similar chemiluminescence reactions have been studied in great detail [2–6,46,48]. The reader is referred in particular to *Anderson's* review [7], which presents an excellent analysis of the position regarding the luminol problem at the beginning of the second phase of these investigations (after 1945).



(11), R = 3-NH_2
(12), R = 4-NH_2

a) Constitution and Luminescence in Carbohydrazides

Albrecht [48] had referred as early as 1928 to the chemilumescence of *N,N′*-diacylhydrazines on oxidation in alkaline media; his investigations, however, were mainly confined to substituted phthalhydrazides, since these give by far the most intense effects. The chemiluminescence of acyclic diacylhydrazines was confirmed by *Kautsky* and *Kaiser* [49], who postulated that acyclic hydrazides are in principle capable of chemiluminescing, provided they are fluorescent (see also [50]). *Ojima* investigated *inter alia* the emission of light by monoacyl-

[35a] *J. Sonnenberg* and *D. M. White*, J. Amer. chem. Soc. *86*, 5685 (1964).

[35b] *E. H. White* and *M. J. C. Harding*, J. Amer. chem. Soc. *86*, 5686 (1964).

[36] *K. Gleu* and *W. Petsch*, Angew. Chem. *48*, 57 (1935).

[37] *K. Gleu* and *R. Schaarschmidt*, Ber. dtsch. chem. Ges. *73 B*, 909 (1940).

[38] *A. Chrzaszczewska*, *A. Braun*, and *M. Nowaczyk*, Soc. Sci. Lodziensis, Acta chim. *3*, 93 (1958); Chem. Abstr. *53*, 13148 (1959).

[39] *B. D. Ryzhikov*, Dokl. Akad. Nauk SSSR, Ser. Fiz. *20*, 533 (1956).

[40] *J. Kroh* and *Z. Czernik*, Roczniki Chem. *31*, 915 (1957); Chem. Abstr. *52*, 6928 (1958).

[41] *A. V. Karyakin*, Opt. i Spektroskopiya *7*, 122 (1959); Chem. Abstr. *54*, 23816 (1960).

[42] *A. Dorabialska* and *K. Kolodziejczak*, Soc. Sci. Lodziensis, Acta chim. *7*, 5 (1961); Chem. Zbl. *1965*, Nr. 2, 0886.

[43] *J. R. Totter*, *V. J. Medina*, and *J. L. Scoseria*, J. biol. Chemistry *235*, 238 (1960).

[44] *J. R. Totter*, Photochem. Photobiol. *3*, 231 (1964).

[45] *L. Greenlee*, *I. Fridovich*, and *P. Handler*, Biochemistry *1*, 779 (1962).

[46] *E. H. White* in *W. D. McElroy* and *B. Glass* [17], p. 183.

[47] *H. Kautsky* and *K. H. Kaiser*, Naturwissenschaften *31*, 505 (1943).

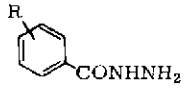
[47a] *F. McCapra* and *D. G. Richardson*, Tetrahedron Letters *1964*, 3167.

[48] *H. O. Albrecht*, Z. physik. Chem. *136*, 321 (1928).

[49] *H. Kautsky* and *H. Kaiser*, Z. Naturforsch. *5b*, 353 (1950).

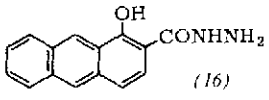
[50] *J. Kroh* and *J. Luczszczewski*, Roczniki Chem. *30*, 647 (1956).

hydrazines on uncatalysed oxidation with hydrogen peroxide in alkaline solution. He found that the luminescence of anthranilhydrazide *(13)* is 5 orders of magnitude weaker than that of luminol; chemiluminescence is also observed with *m*-aminobenzhydrazide *(14)*, but not with the *p*-isomer *(15)* [2,51]. As explained in Section 8b, the deciding factor is whether the carboxylic acid on which the hydrazide is based, or its anion, is capable of fluorescing, as is the case with *(13)* and *(14)*,



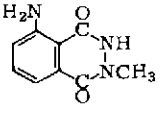
(13), R = o-NH_2
(14), R = m-NH_2
(15), R = p-NH_2

but not with *(15)*. Similar behavior is found with the isomeric hydroxybenzhydrazides [51], although the luminescence in this case is about ten times weaker. If, however, the hydrazinocarbonyl group is attached to a strongly fluorescent aromatic hydrocarbon residue, as in *(16)*, the quantum yield of the chemiluminescence is about 1/3 of that of Luminol [2].

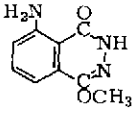


(16)

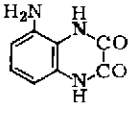
An extremely important point with regard to chemiluminescence is that the hydrazide group remains unaltered; thus *(17)*, *(18)*, and *(19)* do not chemiluminesce [52,53]. It is evidently essential that the molecule contains a bond system from which elementary nitrogen can be readily split off.



(17)



(18)



(19)

Drew et al. [54] have studied how substituents in the benzene ring affect the chemiluminescence of the phthalhydrazide, and have listed the intensities of the chemiluminescence of a number of substituted phthalhydrazides [55], which have been largely confirmed by subsequent measurements [56–58]. These investigations led to the formulation of two main rules:

1. The chemiluminescence is strengthened by electron-releasing substituents in the benzene nucleus of the phthalhydrazide system, and weakened by electron-attracting substituents, analogously to the substituted lophines (Section 6).

2. The effects of substituents in position 3 of the phthalhydrazide system are more pronounced than those of substituents in position 4; this is particularly obvious on comparing luminol *(11)* with the isomeric 4-aminophthalhydrazide *(12)*, the luminescence of which is an order of magnitude weaker than that of *(11)*.

α) Steric Hindrance of Resonance

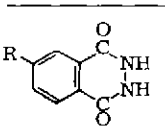
Deviations from Rule 1 are observed in the cases of 3-methylamino- and 3-dimethylaminophthalhydrazide; the emission of the former is only about 60%, and that of the latter only 2%, of that of luminol, although the alkylamino and dialkylamino groups are stronger electron donors than the amino group [58]. This anomaly is due to steric hindrance of resonance. Thus the dimethylamino group in position 3 cannot lie in the same plane as the aromatic system, owing to the adjacent carboxyl group. The compound therefore behaves essentially as the parent phthalhydrazide system, which is only very faintly chemiluminescent. In 3-methylaminophthalhydrazide, on the other hand, the methylamino group can lie in the same plane as the benzene nucleus, but only in the configuration in which the *N*-methyl group is turned away from the carbonyl group. However, the steric hindrance of resonance in the phthalhydrazides is probably less important than in the corresponding phthalate dianions (which are the radiating particles; cf. Section 8b).

The chemiluminescence of 3-methylphthalhydrazide [52] is weaker than that of phthalhydrazide, although the methyl group acts as an electron donor; this is probably again due to steric hindrance.

β) 4-Dialkylaminophthalhydrazides

Dialkylamino groups in position 4 of the phthalhydrazide or of the phthalate dianion are not sterically hindered, and the luminescence in this case is an order of magnitude stronger than that of 4-aminophthalhydrazide. The maximum chemiluminescence intensity of 4-diethylaminophthalhydrazide (in the hemin-catalysed oxidation) is equal to that of luminol, and the total emission exceeds that of luminol by 20–30% [58]; this was the first hydrazide found to have a greater chemiluminescent power than luminol. Other 4-dialkylaminophthalhydrazides exhibit chemiluminescence as strong as that of luminol [58,59] (Table 1).

Table 1. Relative emissions of 4-dialkylaminophthalhydrazides [58,59] (luminol = 100).

	Chemiluminescence (relative emission)
(20), R = $-N(CH_3)_2$	87
(21), R = $-N(C_2H_5)_2$	120
(22), R = 1-Pyrrolidinyl	105
(23), R = 1-Piperidinyl	80

[51] *H. Ojima*, Naturwissenschaften *48*, 600 (1961).

[52] *H. D. K. Drew* and *R. F. Garwood*, J. chem. Soc. (London) *1937*, 1841.

[53] *E. H. Huntress* and *J. V. K. Gladding*, J. Amer. chem. Soc. *64*, 2644 (1942).

[54] *B. E. Cross* and *H. D. K. Drew*, J. chem. Soc. (London) *1949*, 1532, and earlier papers.

[55] *H. D. K. Drew* and *F. H. Pearman*, J. chem. Soc. (London) *1937*, 586.

[56] *A. Spruit van der Burg*, Recueil Trav. chim. Pays-Bas *69*, 1525 (1950).

[57] *A. A. Ponomarenko*, *N. A. Murkar'yan*, and *A. I. Komlev*, Dokl. Akad. Nauk SSSR *89*, 1061 (1953); cited by [3].

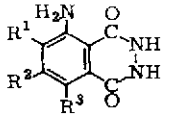
[58] *K.-D. Gundermann* and *M. Drawert*, Chem. Ber. *95*, 2018 (1962).

[59] *K.-D. Gundermann*, *W. Horstmann*, and *G. Bergmann*, Liebigs Ann. Chem. *684*, 127 (1965); Angew. Chem. *76*, 686 (1964); Angew. Chem. internat. Edit. *3*, 637 (1964).

The chemiluminescence of the hydrazides *(20)*–*(23)* is much less sensitive to alkali than that of luminol. In the system aqueous alkali/hydrogen peroxide/hemin, the emission of luminol reaches its optimum value at an alkali concentration of 0.03 N, and falls off as the pH is raised further; the emission of the 4-dialkylaminophthalhydrazides, on the other hand, reaches its optimum value at an alkali concentration of 0.1 N, and shows no appreciable decrease between this concentration and 1.0 N (cf. [60–62]).

γ) Polysubstituted Phthalhydrazides

According to Rule 1 above, strong chemiluminescence should be observed above all with phthalhydrazides having several electron-releasing substituents in the benzene nucleus. Although such compounds often exhibit very strong fluorescence, however, their ability to chemiluminesce is by no means always equally pronounced. It is obvious, therefore, that strong fluorescent power is not necessarily synonymous with strong chemiluminescent power, and that chemical stability in oxidizing media is also an important factor. Thus 3,6-diaminophthalhydrazide exhibits extremely weak chemiluminescence [55] because, being a *p*-phenylenediamine derivative, it is very rapidly oxidized to a red quinone dye. The chemiluminescence of 3,5-diaminophthalhydrazide *(24)*, however, which cannot be oxidized directly to a quinone, is also very weak [58].



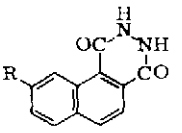
(24), R^1 = H, R^2 = NH_2, R^3 = H
(25), R^1 = R^2 = H, R^3 = OCH_3
(26), R^1 = H, R^2 = R^3 = OCH_3
(27), R^1 = R^2 = R^3 = OCH_3

The compound *(25)* fluoresces strongly in neutral solution and gives an initially intense chemiluminescence on hemin-catalyzed oxidation in aqueous solution; however, the intensity of the chemiluminescence falls off very rapidly. On the other hand, the quantum yields of the chemiluminescence of *(26)* and *(27)* in the system dimethyl sulfoxide/tert-butoxide/oxygen exceed the quantum yield of luminol by 13 and 30% respectively [2].

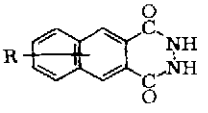
For a discussion of the partly sterically hindered 3,4-dimethoxyphthalhydrazide and of 3,4-methylenedioxyphthalhydrazide, both of which exhibit only weak chemiluminescence, see [61].

δ) Naphthalenedicarbohydrazides

As would be expected from the larger π-electron system, the isomeric naphthalenedicarbohydrazides *(28)* and *(29)* exhibit stronger chemiluminescence than phthalhydrazide [52, 54]. Nevertheless, the aminonaphthalenedicarbohydrazides *(30)* and *(31)* fall far short of luminol in intensity [52, 54].



(28), R = H
(32), R = $N(CH_3)_2$
(33), R = $N(C_2H_5)_2$
(34), R = $N(n\text{-}C_3H_7)_2$
(35), R = 1-Pyrrolidinyl



(29), R = H
(30), R = 1-NH_2
(31), R = 8-NH_2

The intense green chemiluminescence of 7-dialkylaminonaphthalene-1,2-dicarbohydrazides of the type *(32)*, however, is two to three times as strong as that of luminol (Table 2) [59] These hydrazides may be regarded as vinylogues of the 3-dialkylaminonaphthalhydrazides, in which the dialkylamino groups, as we have seen, cannot exert their chemiluminescence-promoting effect, owing to steric hindrance of resonance. The effect of the alkali concentration on the chemiluminescence of 7-substituted naphthalene-1,2-dicarbohydrazides is very similar to that observed in the case of the 4-dialkylaminophthalbydrazides. Since compounds *(32)*–*(35)* are yellow, autoabsorption of the chemiluminescence becomes noticeable at lower hydrazide concentrations than in the case of the colorless luminol.

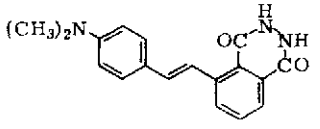
Table 2. Chemiluminescence, fluorescence, and relative emission of naphthalene-1,2-dicarbohydrazides (luminol = 100) [59].

	Chemiluminescence		Fluorescence [*] λ_{max} [mμ]	
	λ_{max} [mμ]	Relative emission	A	B
(32)	514	2.28	529	514
(33)	514–518	2.54	529	516
(34)	515	3.00	529	515
(35)	515	2.07	529	515

[*] Chemiluminescence under optimum conditions [59].
A: fluorescence of the hydrazide in 0.2 N NaOH.
B: fluorescence after chemiluminescence has ceased.

ε) 4′-Dialkylaminostilbene-2,3-dicarbohydrazides [63,63a]

The *trans*-isomers of compounds of the type *(36)* are also sterically unhindered vinylogues or phenylogues of 3-dialkylaminophthalhydrazides. In this case, however,



(36)

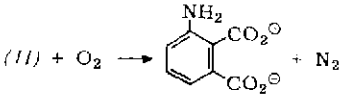
the transmission of the electron-donating effect of the dialkylamino group requires even greater "de-aromatization" than in the 7-dialkylaminonaphthalene-1,2-dicarbohydrazides [64]; consequently, the chemiluminescence emissions of these stilbene derivatives are lower than those of the naphthalene derivatives. Thus the

[60] *K. Weber, A. Režek*, and *V. Vouk*, Ber. dtsch. chem. Ges. *75*, 1141 (1942).
[61] *W. Horstmann*, Doctorate Dissertation, Universität Münster, 1964.
[62] *H. H. Seliger* in *W. D. McElroy* and *B. Glass* [17], p. 204.
[63] *G. Wellhausen*, Diploma Thesis, Universität Münster, 1964.
[63a] *K.-D. Gundermann*: Symposium on Chemiluminescence Durham N.C. 1965. Preprints p. 305.
[64] *R. Wizinger*, Chimia *15*, 89 (1961).

chemiluminescence of *(36)*, although considerably stronger than that of the sterically hindered 3-dimethylaminophthalhydrazide, is only about 2/3 as strong under optimum conditions as that of luminol. The optimum chemiluminescence is obtained by the addition of about 40 vol-% of dimethyl sulfoxide to the aqueous alkaline oxidation solution (H_2O_2/hemin). This promoting effect of dimethyl sulfoxide (which is also shown to a lesser extent by dimethylformamide and by *N*-methylpyrrolidone) on the chemiluminescence of hemin-catalysed oxidations has so far been observed only with stilbene derivatives of the type *(36)*. The chemiluminescence accompanying the oxidation of luminol in aqueous alkali with H_2O_2/hemin is greatly reduced by even small quantities of dimethyl sulfoxide (cf. the entirely different relationships observed in the chemiluminescence of luminol in the system dimethyl sulfoxide/tert-butoxide/oxygen [46]).

b) The Mechanism of the Chemiluminescence Reaction of Luminol

Albrecht [48] had assumed as early as 1928 that the oxidation of luminol led to 3-aminophthalic acid and nitrogen. Since, however, he could isolate only unchanged luminol from the reaction mixture after the chemiluminescence had ceased, he thought that luminol itself was the emitting species. This view was also shared by other authors (for a review see [52]).



(11) *(37)*

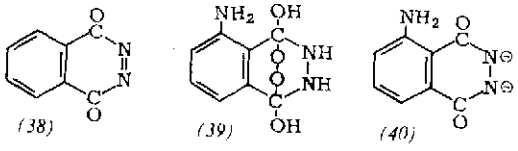
All earlier investigations on the course of the chemiluminescence reaction of luminol were impeded by the fact that the initial products of the reaction in aqueous alkaline media very rapidly undergo further oxidation and secondary reactions; for a long time, therefore, no definite breakdown product of luminol could be isolated. It was only by the use of polar organic solvents such as dimethyl sulfoxide, with oxygen as the oxidizing agent and tert-butoxide as the base [46], that it became possible to isolate 3-aminophthalic acid as a product; the yield (as the dimethyl ester) was such as to show, on comparison with the quantum yield of the chemiluminescence, that the dianion *(37)* is the product and the emitting particle of the luminol reaction, and does not result from a "dark reaction" that accompanies the chemiluminescence reaction. The consumption of alkali and oxygen and the quantity of nitrogen produced lead to the overall equation:

(11) + 2 NaOH + O_2 → N_2 + 2 H_2O + *(37)* (as the di-Na salt).

Comparison of the chemiluminescence spectrum of the luminol reaction with the fluorescence spectra of luminol and of *(37)* also shows that the radiating species is not luminol, but *(37)* [2].

The emitting particles in the chemiluminescence of the 7-dialkylaminonaphthalene-1,2-dicarbohydrazides (Section 8a) are again probably not the hydrazides themselves, but the substituted naphthalene-1,2-dicarboxylate dianions (cf. Table 2). The same applies to the stilbene derivatives *(36)* [64a].

The intermediate steps involved in the chemiluminescence reactions of hydrazides of the luminol type are still not known with certainty. The intermediate formation of an azodiacyl compound of the type *(38)* [48,49] is unlikely, since *e.g.* dihydrophthalazinedione *(38)* prepared by another route [65, 66] does not chemiluminesce under conditions in which distinct chemiluminescence is observed with the phthalhydrazide [2,46]. The endoperoxide *(39)* described by *Drew* and *Garwood* [67] is apparently a luminol salt containing H_2O_2 of crystallization [2] [*].



(38) *(39)* *(40)*

The mesomeric dianion *(40)* could be an intermediate in the chemiluminescence reaction of luminol with oxygen. If the oxygen used is enriched in ^{18}O, more than 85% of the latter is found in the 3-aminophthalic acid after the reaction [68].

No free-radical intermediates could be detected in the luminol reaction by electron spin resonance measurements [68]. A free-radical chain mechanism may nevertheless be assumed, at least in other oxidizing systems, for the chemiluminescence reaction of luminol also [69–71]. Thus chemiluminescence has been brought about in aqueous solutions of luminol by the action of X-rays, and this effect can be blocked by the introduction of cysteine, which acts as a free-radical interceptor [72].

Further evidence in favor of a free-radical mechanism is to be found in the recent extensive literature on the influence of catalysts on the chemiluminescence reaction of luminol (cf. the reviews [73,74]; also [74a]).

[64a] *K.-D. Gundermann*, unpublished work.

[65] *T. J. Kealy*, J. Amer. chem. Soc. *84*, 966 (1962).

[66] *R. A. Clement*, J. org. Chemistry *25*, 1724 (1960).

[67] *H. D. K. Drew* and *R. F. Garwood*, J. chem. Soc. (London) *1938*, 791.

[*] Note added in proof: *W. S. Metcalf* and *T. J. Quickenden*, Nature (London) *206*, 507 (1965) recently found that luminol chemiluminesces in alkaline solutions of hydroxylamine-*O*-sulfonic acid, *p*-toluenesulfonylhydrazide, and other substances which give rise to diimine, HC=NH, under these conditions. The Albrecht-Kautsky mechanism is thus provided with new experimental support.

[68] *E. H. White, O. Zafiriou, H. M. Kägi*, and *J. H. Hill*, J. Amer. chem. Soc. *86*, 940 (1964).

[69] *J. R. Totter, W. Stevenson*, and *G. E. Philbrook*, J. physic. Chem. *68*, 752 (1964).

[70] *H. Behrens, J. R. Totter*, and *G. E. Philbrook*, Nature (London) *199*, 595 (1963).

[71] *H. Ojima*, J. chem. Soc. Japan, pure Chem. Sect. *80*, 1375 (1959) (formation of *O*-radicals from *syn*-diazotates).

[72] *H. Bergstermann*, Strahlentherapie *98*, 474 (1955).

[73] *L. Erdey, W. F. Pickering*, and *C. L. Wilson*, Talanta *9*, 653 (1962).

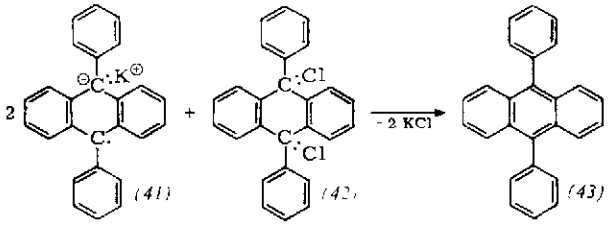
[74] *H. Linschitz* in *W. D. McElroy* and *B. Glass* [17], p. 173.

[74a] *A. K. Babko* and *L. I. Dubovenko*, Z. analyt. Chem. *200*, 428 (1964).

9. Chemiluminescence of Aromatic Free-Radical Ion Pairs

When anthracene, chrysene, pyrene, and other highly condensed aromatic hydrocarbons are electrolysed in dimethylformamide or acetonitrile with tetraethylammonium salts as electrolytes, chemiluminescence occurs in the neighborhood of the cathode, provided that atmospheric oxygen (which has a quenching effect in this case) is excluded. This chemiluminescence is due to an excited singlet state of the hydrocarbon [75]; this presumably results from the formation at the electrodes of hydrocarbon radical ions. $\cdot Ar^{\oplus}$ and $\cdot Ar^{\ominus}$, which then react with each other in solution by a one-electron transfer.

This new type of chemiluminescence reaction can also be brought about by purely chemical means. Thus the compound *(41)* obtained by the reaction of potassium metal with 9,10-diphenylanthracene *(43)* reacts with 9,10-dichloro - 9,10-diphenyl - 9,10 - dihydroanthracene *(42)*, emitting a bright chemiluminescence that has been identified as the fluorescence of 9,10-diphenylanthracene [76]. Basically this reaction again involves the



transfer of an electron from the free-radical anion of the potassium compound *(41)* to the acceptor *(42)*, which is a potential 9,10-diphenylanthracenium dication; *(43)* is then formed, partly in the excited singlet state (recombination luminescence; cf. [76]).

The investigations carried out so far have indicated that this type of chemiluminescence reaction is of general importance; thus the free-radical anion *(41)* may be replaced by another donor, such as the sodium compound of naphthalene or of *N*-methylacridone. Other electron acceptors that can be used are diacylperoxides or even aluminum chloride. The only essential point seems to be that the free-radical anion must be derived from a molecule that fluoresces in the visible region of the spectrum, and that the acceptor molecule has no quenching action.

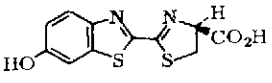
According to *Chandross*, one-electron transfers of this type are probably much faster than chemical reactions in which covalent bonds are formed or broken. The faster the release of chemical energy in the smallest possible volume of the reaction solution, the smaller should be the losses due to radiationless energy transformations (into heat, *etc.*), and the greater the proportion of the chemical energy transformed into excited electronic states. It is likely, therefore, that this new type of chemiluminescence reaction comes closer than most other types to the ideal conditions of bioluminescence reactions.

[75] *D. M. Hercules*, Science (Washington) *145*, 808 (1964); *R. E. Visco* and *E. A. Chandross*, J. Amer. chem. Soc. *86*, 5350 (1964); *K. S. V. Santhanam* and *A. J. Bard*, ibid. *87*, 139 (1965).

[76] *E. A. Chandross* and *F. I. Sonntag*, J. Amer. chem. Soc. *86*, 3179 (1964).

10. Firefly Luciferin

The bioluminescence of the American firefly *(Photinus pyralis)* is probably the most widely studied of the biological luminescence reactions (for a review, see [17]). The structure elucidation and synthesis of the substrate of this reaction, *i.e.* firefly luciferin *(44)* is due to *White* et al. [77]. *In vivo*, *(44)* is converted to the dehydro compound *(45)*, with simultaneous emission of light, by the action of the enzyme luciferase together with adenosine triphosphate [*], Mg^{2+} ions, and oxygen. It has been possible to study these processes *in vitro*, since both the luciferin and the luciferase have been isolated in the crystalline state [17].



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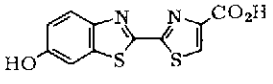

(45)

The light emitted on dehydrogenation of firefly luciferin has a maximum at 562 mμ (cf. also [78]), corresponding to an energy of at least 57 kcal/mole. *(44)* can also be made to luminesce (although only very weakly) in the absence of the enzyme by the use of powerful oxidizing agents [79].

11. Closing Remarks

Notable progress has been made during recent years in the investigation of the chemiluminescence of organic compounds. Nevertheless, many questions, such as that of the quantitative relationship between chemiluminescence and structure, have not yet been answered. The mechanisms of many chemiluminescence reactions also require further clarification. A possible additional advantage of knowing these mechanisms is that they may suggest methods of obtaining higher quantum yields than are possible at present.

I am grateful to Dr. Bergmann for many helpful discussions and for his collaboration in the experimental work.

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Translated by Express Translation Service, London

[77] *E. H. White* et al., J. Amer. chem. Soc. *83*, 2402 (1961); *85*, 337 (1963).

[*] This bioluminescence provides a method of following the formation of ATP in biological phosphorylation reactions: *B. L. Strehler* and *D. D. Hendley* in *W. D. McElroy* and *B. Glass*, ref. [17], p. 601.

[78] *H. H. Seliger* et al., J. gen. Physiol. *48*, 95 (1964).

[79] *H. H. Seliger* and *W. D. McElroy*, Science (Washington) *138*, 683 (1962).

The Structure of Sugar Phenylosazones

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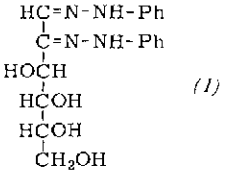
Dedicated to Professor Fritz Micheel on the occasion of his 65th birthday

The open-chain chelate structure of sugar osazones, first proposed by Fieser and Fieser, has now been confirmed by chemical methods, X-ray analysis, and NMR spectroscopy. These investigations showed that the properties of sugar osazones are best described by a formula containing a quasi-aromatic chelate ring.

Introduction

Although the first sugar phenylosazones were prepared 80 years ago, the problem of the structure of this group of compounds has continued to intrigue many carbohydrate chemists up to the present day. When *Emil Fischer* [1,2] first prepared the sugar phenylosazones,



(1)

he represented them as open-chain compounds *(1)*. But as our knowledge of the nature and reactions of sugar osazones has increased, it has become evident that this structure does not fulfil all the requirements necessary. *Fischer*'s open-chain structure does not explain:

1. Why osazone formation stops at the second carbon atom, instead of continuing to the third and further carbon atoms.

2. Why the two phenylhydrazone groups in the sugar osazones behave differently in most of their reactions. These differences are manifested:

a) on methylation [3–6], when only one of the two imino groups is methylated;

b) on transosazonization [7]: the phenylhydrazine attached to C–1 is always more easily substituted by another molecule of phenylhydrazine than that on C–2;

c) by formation of osone-hydrazones [8]: the phenylhydrazone group on C–2 is always hydrolysed first, while that on C–1 displays increased stability;

d) by formation of osotriazoles [7,9]: it is the phenylhydrazone group on C–1 which furnishes most of the aniline liberated in the course of the reaction;

e) by the different behaviour of the two phenylhydrazone groups on reduction [10–13]: the phenylhydrazone group on C–1 is reduced to the amine, while that on C–2 is eliminated (except under extreme conditions [14]).

3. Why there is a distinct difference between the phenylosazones and the 1-(methylphenyl)-2-phenylosazones, on the one hand, and the bis(methylphenyl)osazones, on the other. The difference is shown:

a) in the ultraviolet spectra [15–20];

b) in the formation of anhydro-osazones [21,22] which are readily obtained from the first group of compounds and not at all from the second;

c) in the formation of dehydro-osazones [23]: the second group of compounds does not give these derivatives;

d) in the mutarotation [24,25]: this phenomenon is peculiar to the phenylosazones and to mixed osazones;

[1] *E. Fischer*, Ber. dtsch. chem. Ges. *17*, 579 (1884).

[2] *E. Fischer*, Ber. dtsch. chem. Ges. *20*, 821 (1887).

[3] *S. Akiya* and *S. Tejima*, J. pharmac. Soc. Japan *72*, 1574 (1952); Chem. Abstr. *47*, 9275 (1953).

[4] *S. Akiya* and *S. Tejima*, J. pharmac. Soc. Japan *72*, 894 (1952); Chem. Abstr. *47*, 6351 (1953).

[5] *E. E. Percival* and *E. G. V. Percival*, J. chem. Soc. (London) *137*, 1398 (1935).

[6] *E. G. V. Percival*, J. chem. Soc. (London) *1936*, 1770.

[7] *F. Weygand, H. Grisebach, K. D. Kirchner*, and *M. Haselhorst*, Chem. Ber. *88*, 487 (1955).

[8] *G. Henseke*, Acta chim. Acad. Sci. hung. *12*, 173 (1957).

[9] *G. Henseke* and *M. Winter*, Chem. Ber. *93*, 45 (1960).

[10] *E. Fischer*, Ber. dtsch. chem. Ges. *19*, 1920 (1886).

[11] *K. Maurer* and *B. Schiedt*, Ber. dtsch. chem. Ges. *68*, 2187 (1935).

[12] *T. Neilson* and *H. C. S. Wood*, J. chem. Soc. (London) *1962*, 44.

[13] *R. Kuhn, G. Krüger, H. J. Haas*, and *A. Seelinger*, Liebigs Ann. Chem. *644*, 122 (1961).

[14] *M. L. Wolfrom, F. Shafizadeh, J. O. Wehrmüller*, and *R. K. Armstrong*, J. org. Chemistry *23*, 571 (1958).

[15] *E. C. C. Baly, W. B. Tuck, E. G. Marsden*, and *M. Gazdar*, J. chem. Soc. (London) *109*, 1572 (1907).

[16] *L. L. Engel*, J. Amer. chem. Soc. *57*, 2419 (1935).

[17] *G. Henseke* and *H. J. Binte*, Liebigs Ann. Chem. *612*, 205 (1958).

[18] *P. Grammaticakis*, C. R. hebd. Séances Acad. Sci. *223*, 1139 (1946).

[19] *G. Henseke* and *H. J. Binte*, Chimia *12*, 103 (1958).

[20] *G. Henseke, G. Hanisch*, and *H. Fischer*, Liebigs Ann. Chem. *643*, 161 (1961).

[21] *O. Diels* and *R. Meyer*, Liebigs Ann. Chem. *519*, 157 (1935).

[22] *G. Henseke* and *H. Hantschel*, Chem. Ber. *87*, 477 (1954).

[23] *O. Diels, E. Cluss, H. J. Stephan*, and *R. König*, Ber. dtsch. chem. Ges. *71*, 1189 (1938).

[24] *L. Mester* and *A. Major*, J. Amer. chem. Soc. *79*, 3232 (1957).

[25] *G. Henseke* and *H. Köhler*, Liebigs Ann. Chem. *614*, 105 (1958).

the bis-(methylphenyl)-osazones do not change their rotation except as a result of a change in temperature [26].

4. Why the behavior of sugar osazones is entirely different from that of non-sugar osazones. Here, the differences are shown:

a) in the spectra of the two groups of products [15–20];

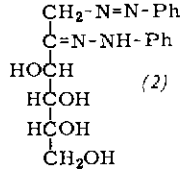
b) in the formation of osotriazoles [7,9]: with sugar osazones, the aniline is liberated mainly from the phenylhydrazone group on C–1, while in the case of non-sugar phenylhydrazones the aniline comes equally from the phenylhydrazone groups on C–1 and C–2;

c) on reaction with diazotized aniline [27,28]: sugar osazones yield osazone formazans, while non-sugar osazones react with substitution of the phenyl ring of the aniline on C–1 or do not react at all.

5. Why it is impossible to tritylate the primary hydroxy group of sugar osazones [23,29] under the usual conditions.

Early Attempts to Define the Structure of Sugar Osazones

Many investigators have tried to find the answers to these questions, which explains the surprising abundance of work in this field. Several tautomeric structures have been proposed, some cyclic, some non-cyclic, but none of these formulae explains all the properties of osazones.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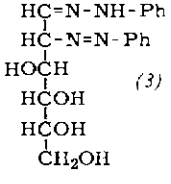
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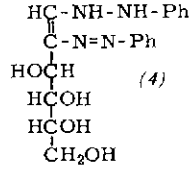
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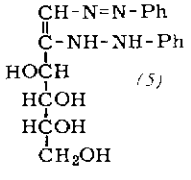
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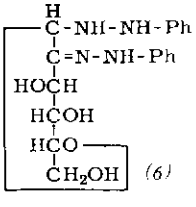
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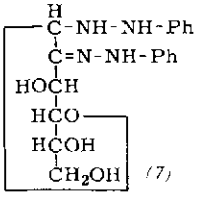
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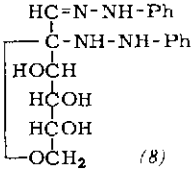
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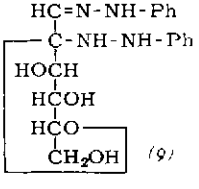

(9)

[26] *G. Henseke* and *H. J. Binte*, Chem. Ber. *88*, 1167 (1955).

[27] *L. Mester*, J. Amer. chem. Soc. *77*, 4301 (1955).

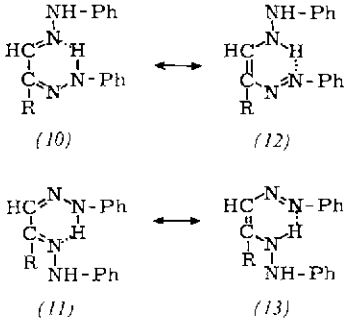
[28] *W. Ried* and *K. Sommer*, Liebigs Ann. Chem. *611*, 108 (1958).

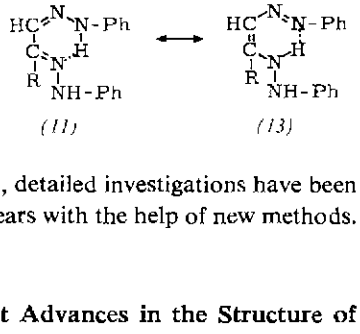
[29] *E. G. V. Percival*, J. chem. Soc. (London) *1945*, 783.

In 1907, *Baly* et. al. [15] put forward the open-chain structures *(2)* and *(3)*, in which the two phenylhydrazines are differently bound: one as a phenylhydrazone and the other in the azo form. *Zerner* and *Waltuck* [30] proposed the open-chain phenylhydrazino-phenylazo structures *(4)* and *(5)* with a double bond between C–1 and C–2, while *Haworth* [31] and *Percival* and *Percival* [5] preferred cyclic structures *(6)* or *(7)* and *(8)* or *(9)*.

As an explanation of the properties of osazones, *Baly* and his collaborators [15] already advanced the idea that in the osazones the two hydrazone groups could form a "condensed system" containing an intramolecular linkage.

Fieser and *Fieser* [32] revived and developed this idea in proposing, on purely theoretical grounds, two alternate chelate structures *(10)* and *(11)* for sugar osazones, these being stabilized by resonance with the forms *(12)* and *(13)*. They considered that the formation of a chelate ring between C–1 and C–2 prevented further electron displacement necessary to osazone formation, and thus explained why the reaction stops at C–2. In 1948, in the absence of experimental proof, *Percival* [33], in his detailed study on the sugar osazones, did not accept this hypothesis and in 1952 *Hardegger* and *Schreier* [34] also considered any attempt to define the structure of osazones as being premature.


(10) (12)


(11) (13)

To solve this problem, detailed investigations have been made in the last ten years with the help of new methods.

Recent Advances in the Structure of Sugar Osazones

1. The Formazan Reaction

Mester [27] in 1955 studied the structure of sugar osazones by means of the formazan reaction. By the action of diazotized aniline on D-glucosazone *(14)* in alkaline ethanolic solution, the osazone formazan *(15)* of D-glucose is obtained as dark violet needles. Mild acetylation produces a black tetra-*O*-acetate.

[30] *E. Zerner* and *R. Waltuch*, Mh. Chem. *35*, 1025 (1914).

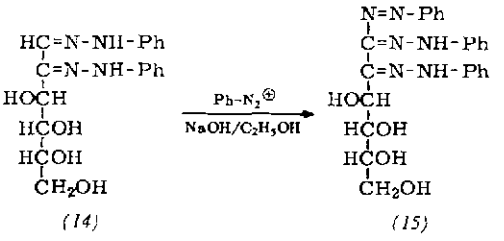
[31] *W. N. Haworth*: The Constitution of Sugars. Edward Arnold & Co., London 1929, p. 7.

[32] *L. F. Fieser* and *Mary Fieser*: Organic Chemistry. Heath and Co., Boston, Mass. 1944, p. 351.

[33] *E. G. V. Percival*, Adv. Carbohydrate Chem. *3*, 23 (1948).

[34] *E. Hardegger* and *E. Schreier*, Helv. chim. Acta *35*, 232 (1952).

This reaction confirmed, first of all, that the osazones have an open-chain structure, since a cyclization involving C–1 [formulae *(6)* and *(7)*], as proposed by



(14) *(15)*

Haworth [31], excludes the possibility of formazan formation. Cyclization involving C 2 [formulae *(8)* and *(9)*], suggested by *Percival* and *Percival* [5], is also excluded since study of the ultraviolet spectra of the osazone formazan obtained in the course of the reaction shows, in addition to the formazan group, the presence of a further chromophore. Moreover, the ultraviolet spectra of the osazone formazans of D-glucose and pyruvaldehyde are very similar (Fig. 1), and in the latter compound such a cyclization is quite impossible.

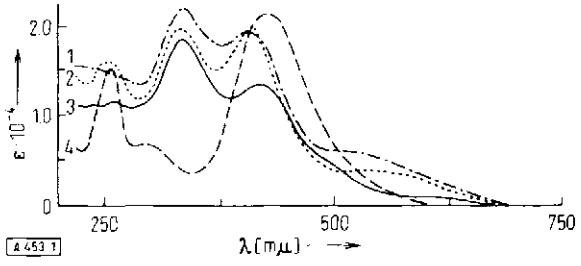
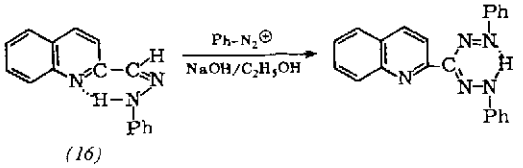


Fig. 1. Ultraviolet spectra in ethanol.
Curve 1: D-Glucose phenylosazone formazan.
Curve 2: Tetra-*O*-acetyl-D-glucose phenylosazone formazan.
Curve 3: Pyruvaldehyde phenylosazone formazan.
Curve 4: D-Glucose diphenylformazan.

On the other hand, the fact that formazan formation from sugar osazones requires a medium more basic than pyridine, indicates the occurrence of chelation, since this prevents the formation of formazans in pyridine [35]. Mention may be made of quinoline-2-carboxaldehyde phenylhydrazone *(16)* as a model compound. Here, too



(16)

chelation prevents the formazan reaction in pyridine, whereas the formazan is produced in an alkaline alcoholic solution.

Thus the formazan reaction constituted the first experimental proof in favour of the formulae proposed by *Fieser* and *Fieser* for the sugar osazones: chelated, open-chain structures.

[35] *G. Zemplén, L. Mester, A. Messmer*, and *A. Major*, Acta chim. Acad. Sci. hung. *7*, 455 (1955).

[36] *B. Jambor* and *L. Mester*, Acta chim. Acad. Sci. hung. *9*, 485 (1956).

2. Polarographic Behavior of Sugar Osazones

The chelate structure of sugar osazones and mixed osazones has been confirmed by *Jambor* and *Mester* [36] with the aid of polarography. D-Glucosazone, 1-(methylphenyl)-2-phenyl-D-glucosazone, and bis(methylphenyl)-D-glucosazone exhibit a four-electron reduction wave, which for the third compound is 200 mV more positive than for the first two.

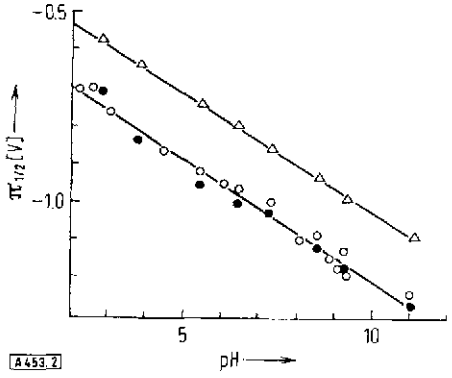


Fig. 2. Polarographic reduction potentials of sugar osazones.
o –o D-Glucose phenylosazone.
●—● D-Glucose-1-methylphenyl-2-phenylosazone.
Δ—Δ D-Glucose bis(methylphenyl)osazone.
Ordinate: Half-wave potential [V].

This difference between D-glucosazone and 1-(methylphenyl)-2-phenyl-D-glucosazone, on the one hand, and bis(methylphenyl)-D-glucosazone, on the other, is a further manifestation of the structural difference which characterizes these two groups of compounds. The fact that the first two are less readily reduced (their reduction potential is more negative) is explained by the increased stability conferred by their chelate structures, in contrast with the bis(methylphenyl)hydrazone structure which cannot be stabilized by chelation.

3. Ultraviolet Spectra of Osazones

Figure 3 shows the spectra of D-glucose phenylosazone, 1-(methylphenyl)-2-phenyl-D-glucosazone, bis(methylphenyl)-D-glucosazone, and benzil phenylosazone. It will be seen that the spectra of the first two compounds are

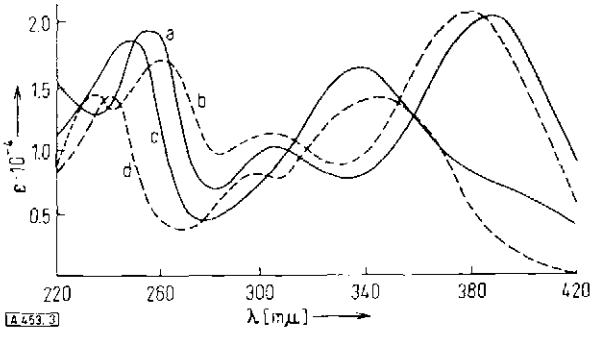
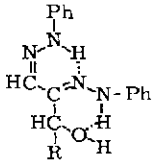


Fig. 3. Ultraviolet spectra in ethanol of (a) D-glucose phenylosazone, (b) D-glucose 1-(methylphenyl)-2-phenylosazone, (c) D-glucose bis-(methylphenyl)osazone and (d) benzil phenylosazone.

very similar and differ from the spectra of the bis(methylphenyl)-D-glucosazone and of the non-sugar osazone. By comparison with the spectra of diphenylpolyenes and diphenylpolyenazines, *Henseke* et al. [19] concluded that osazones form a mesomeric bond system conjugated with the two benzene rings, in which the two NH-groups correspond in absorption to a double bond. Taking into account the often evoked role played by the hydroxy group on C–3 in these molecules [16,24,37], they proposed the formulae *(17)* and *(18)* for sugar osazones.



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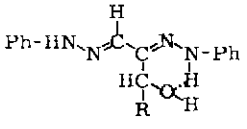


(18)

The existence of a hydrogen bond of the type N–H···O in the osazones is considered to be supported by the fact that it is more stable (2 kcal/mole) than a bond of the type N–H···N– (1.3 kcal/mole). In formula *(18)* the N–H···N– type of chelation, proposed by *Fieser* and *Fieser*, is abandoned because 1-(methylphenyl)-2-phenyl-osazones exhibit the same behavior as unsubstituted osazones.

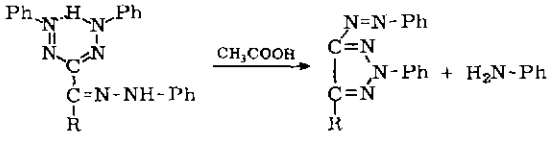
4. Infrared Spectra of Osazones

Ottig [38] was the first to publish infrared spectra of a number of sugar osazones and to compare them with the spectrum of glyoxal phenylosazone. The bands characteristic of osazones are situated between 1550 and 1600 cm^{-1}, especially at 1495–1500, 1530, 1570, and 1600 cm^{-1} for sugar osazones. For glyoxal phenylosazone the same bands were found, except for the weakest osazone band at 1530 cm^{-1} which was replaced by a strong band at 1510 cm^{-1}.

Although the infrared spectra can be used to identify osazones, they do not shed further light on the structure of osazones.

5. Formation of Osotriazoles from Osazone Formazans

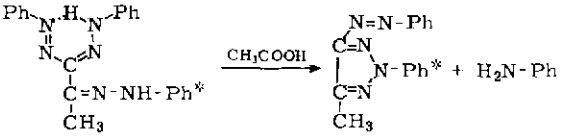
If a solution of an osazone formazan *(19)* is refluxed in acetic acid for a few minutes, a 1-phenylazoosotriazole derivative *(19a)* is formed with the elimination of aniline [39].



(19) *(19a)*

Applying this reaction to osazone formazans labelled with ^{14}C, *Mester* and *Weygand* [40] provided additional confirmation of the chelated structure of the sugar osazones.

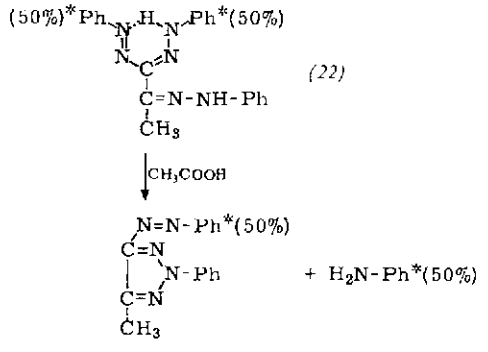
They synthesized the osazone formazan *(20)* of methylglyoxal labelled in the phenylhydrazone group on C–2 by the reaction of [^{14}C]-phenylhydrazine with pyruvaldehyde formazan. The osotriazole *(21)* formed from it contained the same radioactivity, which means that the



(20) *(21)*

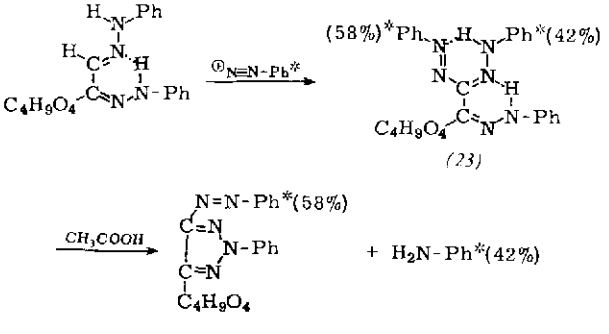
aniline liberated arises exclusively from the substituent on C–1 of the osazone formazan. The same result is obtained with a D-glucosazone formazan labelled in the phenylhydrazone group on C–2.

If the radioactivity is introduced into the substituent on C–1 of the methylglyoxal osazone formazan *(22)* by coupling pyruvaldehyde phenylhydrazone with diazotized [^{14}C]-aniline, followed by condensation with non-radioactive phenylhydrazine, then exactly half the radioactivity is lost with the aniline in the osotriazole reaction.



(22)

In contrast, if D-glucosazone is coupled with diazotized [^{14}C]-aniline and the D-glucosazone formazan *(23)* obtained submitted to the osotriazole reaction, 58% of the total radioactivity is found in the osotriazole and only 42% in the liberated aniline. This difference is a direct proof of the presence of chelation in D-glucosazone, which disturbs the usual equilibration of the radioactivity between the substituents on C–1 in the osazone formazan.



(23)

[37] *H. El Khadem, E. Schreier, G. Stöhr,* and *E. Hardegger,* Helv. chim. Acta *35,* 993 (1952).

[38] *W. Ottig,* Liebigs Ann. Chem. *640,* 44 (1961).

[39] *E. Bamberger* and *J. Lorenzen,* Ber. dtsch. chem. Ges. *25,* 3542 (1892).

[40] *L. Mester* and *F. Weygand,* Bull. Soc. Chim. France *1960,* 350.

6. Sugar Dehydro-Osazones

The structure of dehydro-D-glucosazone was studied by *Mester* and *Moczar* [41,42]. This compound, very similar in appearance to the initial osazone, was obtained first by *Diels* et al. [23] in 1938 by oxidation of D-glucosazone in alkaline solution with air. The loss of two hydrogen atoms stabilizes the osazone structure which can therefore be conveniently investigated using dehydro-osazones.

The ultraviolet spectra of dehydro-osazones are similar to those of the osazones, with maxima at 255, 315, and 386 mμ. The only difference is that the maximum at 315 mμ is more accentuated in the spectra of dehydro-osazones (Fig. 4).

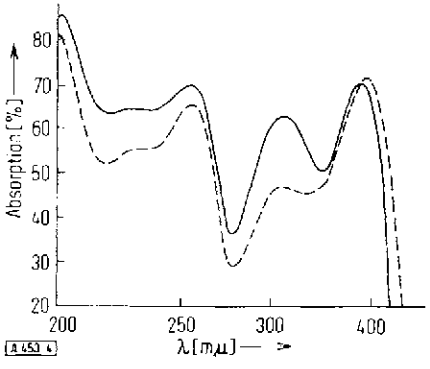
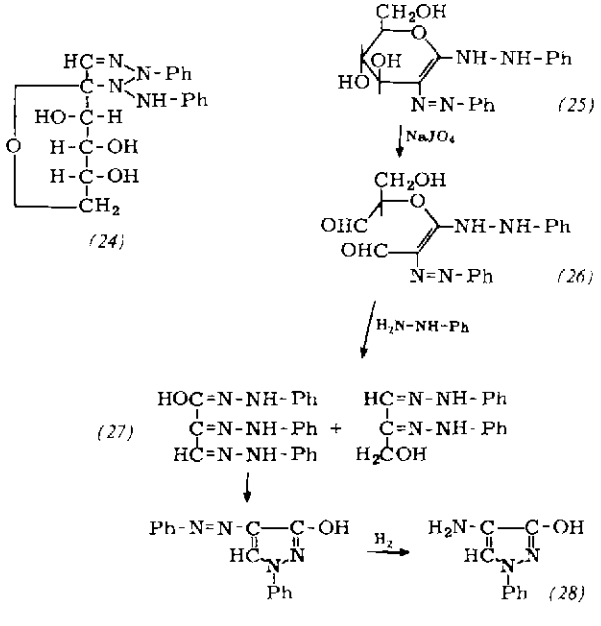


Fig. 4. Ultraviolet spectra in ethanol of (— ·) dehydro-D-glucose phenylosazone and (- - -) D-glucose phenylosazone.
Ordinate: Absorption [%].

Diels et al. have proposed the structure *(24)* for dehydro-D-glucosazone. Results of investigations carried out by *Mester* and *Moczar* [41] did not confirm this structure. On oxidation of the compound with periodic acid, only one mole of reagent is consumed instead of two moles, and there is no formation of formic acid, as would be expected on the basis of structure *(24)*. Moreover, no formazan is formed, even in alkaline solution. These observations together with the infrared spectrum of the compound suggest the structure *(25)*, which has been confirmed by the phenylhydrazinolysis [41] of the product *(26)* of periodate oxidation.



Degradation of the oxidation product *(26)* by refluxing it with phenylhydrazine in ethanol, water, and acetic acid gave D-glyceraldehyde phenylosazone and the phenylhydrazide *(27)* of formylglyoxalic acid phenylosazone. The latter compound was transformed by acid hydrolysis with elimination of phenylhydrazine into 3-hydroxy-1-phenyl-4-phenylazopyrazole, which on catalytic hydrogenation gave 4-amino-3-hydroxy-1-phenylpyrazole *(28)*.

To confirm the proposed structure, the NMR spectrum of tri-*O*-acetyldehydro-D-glucosazone was determined at 60 Mc in deuterated chloroform [42] (Fig. 5).

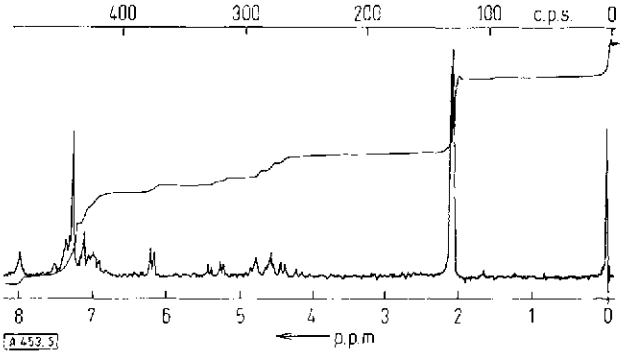


Fig. 5. NMR spectrum of tri-*O*-acetyldehydro-D-glucose phenylosazone at 60 Mc in $CDCl_3$ (internal standard: tetramethylsilane).

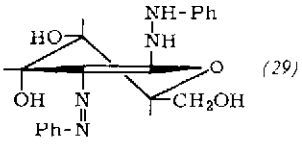
The integrated curve shows the presence of three *O*-acetyl groups, five hydrogens attached to the sugar carbon chain, two hydrogens on nitrogen, and two phenyl groups. The sharp doublet at 6.2 p.p.m., well separated from other signals, requires the presence of a hydrogen atom coupled with only one neighboring hydrogen atom. The spacing for this signal (3 c.p.s.) recurs in the quartet of intensity one centered at 5.3 p.p.m. The position of the latter signal is characteristic of hydrogen atoms on secondary carbon atoms in carbohydrate structures which at the same time carry an acetoxy group each. This signal can therefore be assigned to the hydrogen atom on C -4 and the broad spacing of the quartet (10 c.p.s.) requires the hydrogen to be axially oriented and coupled with two hydrogen atoms, one of which is axial in orientation and must be the hydrogen at C–5. The other hydrogen atom must be quasi-equatorially oriented in view of the weak coupling; it must give rise to the doublet at 6.2 p.p.m. and must be located at C–3 because of the chemical shift. That this shift is 0.9 p.p.m. less than normal can be ascribed to the decreased diamagnetic shielding of equatorial over axial hydrogens together with paramagnetic deshielding arising from the neighboring double bond.

The multiplet from 4.60 to 5.32 p.p.m. corresponds to three hydrogen atoms. It can be assigned to the hydrogen atoms on C–5 and C–6. Similar splitting in this region was observed in the spectra of acetylated sugar osazones; it is characteristic of a *C*-methylene group which carries an acetate function. Signals at this position are not

[41] *L. Mester* and *E. Moczar*, Chem. and Ind. *1962*, 554.
[42] *L. Mester* and *E. Moczar*, J. org. Chemistry *29*, 247 (1964).

present in the spectrum of di-*O*-acetyldehydro-L-rhamnosazone, hut instead a doublet centered around 1.44 p.p.m. occurs, which is typical for a methyl group.

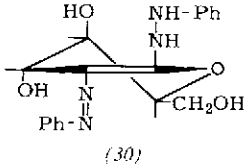
The group of lines centered around 2.10 p.p.m. can be assigned to the three acetate methyl groups. Finally, there are two peaks at 7.97 and 12.50 p.p.m. which seem to correspond to the two N–H bonds. Therefore, the structure *(29)* is assigned to dehydro-D-glucose phenylosazone (without regard to chelation).



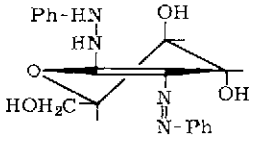
(29)

This is the same structure which was found for dehydro-D-glucosazone on the basis of chemical investigations *(25)* [41], except that the hydroxy group on C–3 is not equatorially oriented as in the original D-glucose configuration, but has the axial position (D-allose configuration). This transposition is certainly due to steric hidrance of this hydroxy group in the equatorial position by the vicinal azo group, and occurs during dehydrogenation in an alkaline medium.

The structure *(29)* was supported by further chemical evidences. In the D-scries of hexoses, four dehydro-osazones (derived from D-glucose, D-galactose, D-allose, and D-gulose) may be expected if no transposition of the OH-group on C–3 occurs. If, however, the 3-hydroxy group does undergo a transposition to the axial position, then D-glucose should give the same dehydro-osazone as D-allose, and D-galactose should give the same as D-gulose. Furthermore dehydro-D-glucosazone and dehydro-L-allosazone, on the one hand, and dehydro-D-galactosazone *(30)* and dehydro-L-gulosazone *(31)*, on the other, must be optical antipodes (enantiomers).



(30)



(31)

The experimental data are in accord with these expectations. It was found that dehydro-D-glucosazone (m.p. 202–203 °C, $[\alpha]_D^{24}$ + 346 °, c = 0.5 in pyridine/ethanol 1:1) is identical with dehydro-D-allosazone (m.p. 203 °C, no depression with dehydro-D-glucosazone, identical infrared spectrum and optical rotatory power), while dehydro-D-galactosazone (m.p. 212 °C, $[\alpha]_D^{24}$ + 300 °, c = 1 in pyridine/ethanol 1:1) and dehydro-L-gulosazone (m.p. 212–213 °C, identical infrared spectrum, but $[\alpha]_D^{24}$ −298 °) are enantiomers.

The establishment of the steric structure of dehydro-D-glucosazone permitted a more exact delineation of the chelated structure of sugar osazones by NMR spectroscopy (see Section 8).

7. X-Ray Analysis

A very important contribution to the problem of the structure of sugar osazones has been the X-ray analysis made by *Furberg* et al. [43]. The *p*-bromophenylosazones of D-glucose, D-xylose, and D-ribose all have the same crystal structure (Fig. 6).

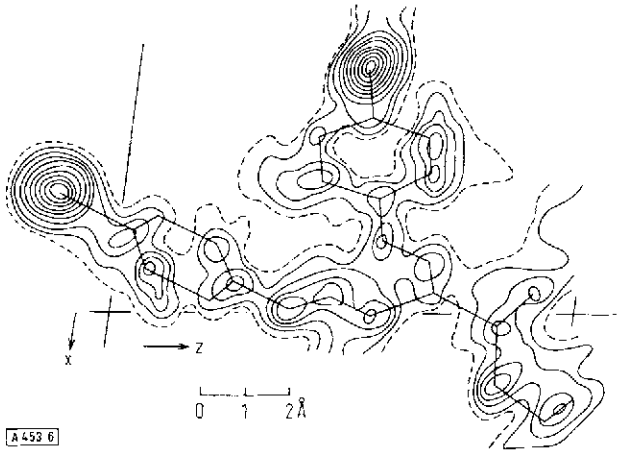
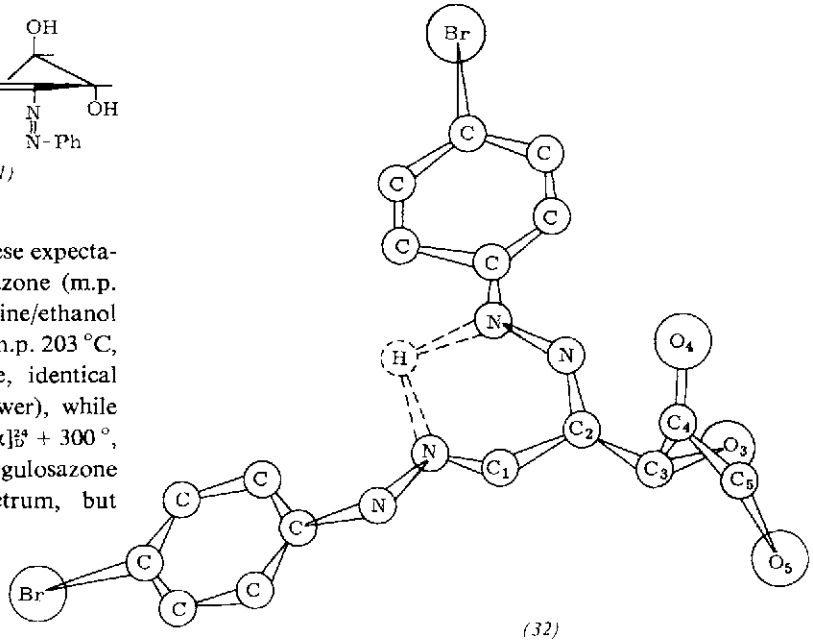


Fig. 6. Electron-density projection in the direction of the b axis of xylose *p*-bromophenylosazone. The distances between lines of equal density are arbitrary.

The electron-density projection in the direction of the b axis of these crystals has confirmed the open-chain structure of the sugar osazones and has also revealed the presence of chelation between the two phenylhydrazone groups. The two benzene rings and the chelate ring are almost coplanar. Hydrogen bonding between the hydroxy group on C–3 and the phenylhydrazone group on C–2, as suggested by *Henseke* [19], is unlikely because of the distance separating both groups.



(32)

[43] *K. Bjamer, S. Dahm, S. Furberg*, and *C. S. Petersen*, Acta chem. scand. *17*, 559 (1963).

From the electron-density projection, formula *(32)* can be derived for *p*-bromophenyl-D-xylosazone which agrees exactly with the formula proposed by *Mester* for sugar osazones on the basis of chemical studies.

8. NMR Spectra of Osazones

Final confirmation of the structure of sugar osazones has been obtained by the examination of their NMR spectra. On the basis of NMR studies, *Wolfrom* et al. [44] put forward the chelate structure *(11)*, while *Mester*, *Moczar*, and *Parello* [45–47] have confirmed structure *(10)*.

The chemical shifts of the signals corresponding to the protons on C–1 and on the nitrogen atoms in sugar osazones, dehydroosazones, and a number of related compounds are given in Table 1. In the spectra of compounds *(33)*–*(37)* a signal corresponding to a chelated N–H proton is present between 12 and 13 p.p.m. It is absent in the spectrum of compound *(38)*, whose aldehydophenylhydrazone structure has been proved. It is also absent from the spectrum of the symmetrical bisphenylhydrazone *(39)*.

Table 1. NMR signals of the protons on C-1 and on the nitrogen atoms of sugar osazones, dehydro-osazones, and related compounds. The data are chemical shifts [p.p.m.] relative to the signal of tetramethylsilane (internal standard).

		in dimethyl sulfoxide			in deuteriopyridine		
		N–H (chelated)	N–H	C(1)–H	N–H (chelated)	N–H	C(1)–H
(33)	Dehydro-D-glucose phenylosazone	12.45	9.35	–	12.95	9.61	–
(34)	Tetra-*O*-acetyl-dehydro-D-glucose phenylosazone	12.48	9.55	–	12.90	10.05	–
(35)	D-Glucose phenylosazone	12.20	10.66	7.89	12.65	11.20	8.68
(36)	Tetra-*O*-acetyl-D-Galactose phenylosazone	12.20	10.80	7.73	12.86	11.49	8.05
(37)	D-Glycerosazone	12.05	10.70	7.79	12.63	11.27	8.23
(38)	Tetra-*O*-acetyl-D-Galactose phenylhydrazone	–	10.12	[*]	–	11.00	7.58
(39)	Glyoxal bisphenylhydrazone	–	10.33	7.69	–	11.10	8.12

[*] Signal included in the benzene peaks.

The signal of the non-chelated imino proton in *(38)* at 11 p.p.m. in deuteriopyridine (at 10.12 p.p.m. in dimethyl sulfoxide) is also present in the spectra of compounds *(33)*–*(37)*. A strong signal in the same region corresponding to two protons was found in the spectrum of *(39)*. Furthermore a signal between 7 and 8 p.p.m., corresponding to the C–1 proton, occurs in the spectra of the compounds *(35)*–*(37)*, but is absent in the spectra of the cyclic compounds *(33)* and *(34)*. The identity of the signals corresponding to the NH protons in the spectra of dehydro-D-glucosazone and of the sugar osazones suggests a great similarity of the chelate structures of both types of compounds.

Since the hydroxy group on C–3 is axially oriented in dehydro-D-glucosazone [42], it cannot form a chelate ring with the phenylhydrazine residue on C–2, as was proposed by *Henseke* [19] for the sugar osazones. Moreover, such a chelation in sugar osazones was excluded also by X-ray analysis (see Section 7) [48]. Thus the chelate ring must be formed by the two phenylhydrazine residues in the dehydroosazones as well as in the sugar osazones according to the structure proposed by *Fieser* and *Fieser*.

A more exact delineation of these chelate structures has been made possible by exchange of the hydrogens bonded to nitrogen with deuterium oxide: In deuteriochloroform the NMR signal of the free imino proton is located between 7 and 8 p.p.m. (Table 2). It disappears instantaneously on shaking of the compound with deuterium oxide. The signal at 12–13 p.p.m., corresponding to the proton involved in the chelation, disappears somewhat less rapidly; here shaking and heating are needed. The signal of the C–1 proton is located at 7.56 p.p.m. in compounds *(36)* and *(41)*, while in the spectra of compounds *(37)* and *(40)* it is overlapped by the signals of the protons of the aromatic rings. In compound *(34)* there is no C–1 proton.

The fact that replacement of the α-imino hydrogen in the phenylhydrazine residue on C–1 by a methyl group [compound *(40)*] has practically no influence on the position of the signal of the chelated NH group, while the signal of the non-chelated NH group disappears, proves that the position of the non-chelated proton in the sugar osazones is the same as the position of the methyl group in the 1-methylphenyl-2-phenylosazones. This position is chemically well defined [22, 27]. Thus the sugar osazones must have the structures *(10)* and *(12)* rather than *(11)* and *(13)*.

Table 2. NMR signals of the protons on C-1 and on the nitrogen atoms of some osazones in deuteriochloroform. The data are chemical shifts [p.p.m.] relative to the signal of tetramethylsilane (internal standard).

		N–H (chelated)	N–H	C(1)-H
(34)	Tetra-*O*-acetyl-dehydro-D-glucose phenylosazone	12.50	7.97	–
(36)	Tetra-*O*-acetyl-D-Galactose phenylosazone	12.34	7.89	7.54
(37)	D-Glycerosazone	12.16	7.78	[*]
(40)	Tetra-*O*-acetyl-D-Glucose 1-methylphenyl-2-phenyl-osazone	12.54	–	[*]
(41)	Tetra-*O*-acetyl-D-arabinose phenylosazone	12.42	7.88	7.56

[*] Signal included in the benzene peaks.

[44] *M. L. Wolfrom, G. Fraenkel, D. R. Lieneback*, and *F. Komitsky*, J. org. Chemistry *29*, 457 (1964).

[45] *L. Mester*, International Carbohydrate Symposium, July 1964, Münster (Germany); Angew. Chem. *77*, 137 (1965); Angew. Chem. internat. Edit. *4*, 166 (1965).

[46] *L. Mester, E. Moczar*, and *J. Parello*, Tetrahedron Letters *1964*, 3223.

[47] *L. Mester, E. Moczar*, and *J. Parello*, J. Amer. chem. Soc. *87*, 596 (1965).

[48] *S. Furberg*, personal communication.

Recent work of *Chapman* et al. [49] and of *El Khadem* et al. [50], based on NMR spectral data, also favors the chelate structure *(10)*.

Moreover, a long-range spin-spin coupling between the C–1 proton and the non-chelated NH proton (Fig. 7) [45–47] supports the structures *(10)* and *(12)*. The weak splitting (J ≈ 1 c.p.s.) of the signal of the C–1 proton at 7.56 p.p.m. in the spectra of compounds *(36)* and *(41)*

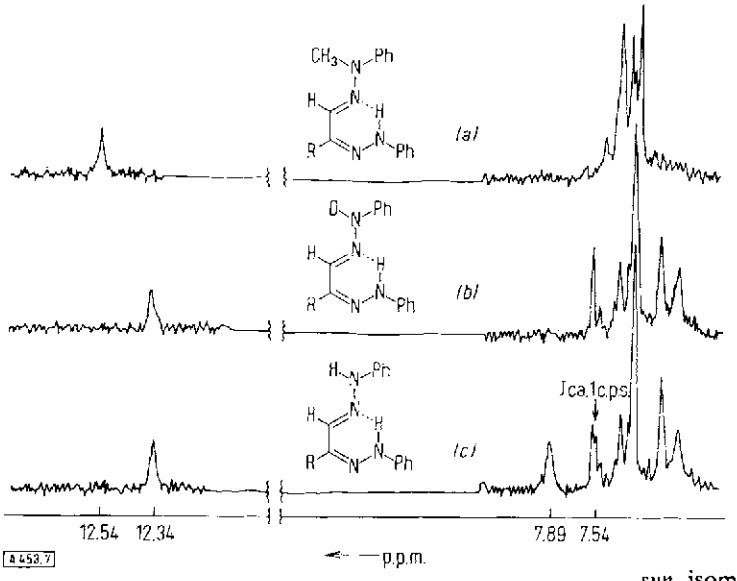


Fig. 7. NMR spectra of (a) tetra-*O*-acetyl-D-glucose 1-methylphenyl-2-phenylosazone *(40)*, (b) tetra-*O*-acetyl-D-galactose phenylosazone after partial deuteration, and of (c) non-deuterated tetra-*O*-acetyl-D-galactose phenylosazone *(36)*. The spectra were recorded at 60 Mc in $CDCl_3$ (internal standard: tetramethylsilane).

disappears during exchange of the non-chelated NH proton for deuterium, giving place to a singular but more accentuated peak (Fig. 7b).

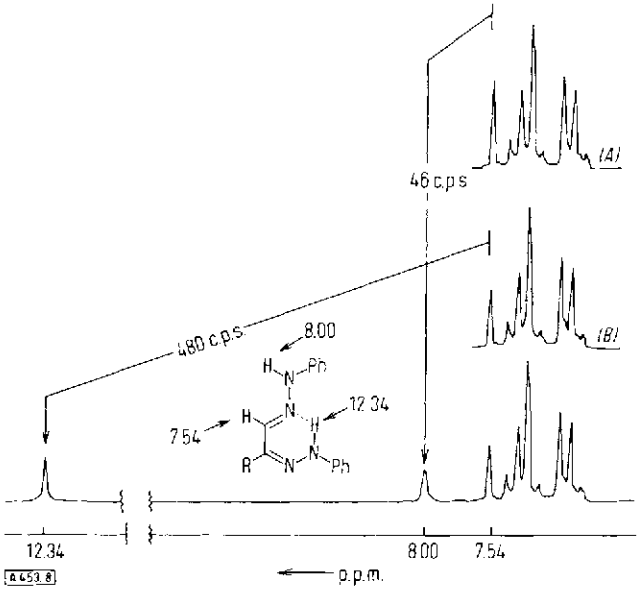
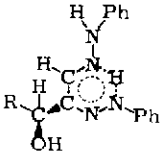


Fig. 8. High-resolution NMR spectrum (100 Mc) of tetra-*O*-acetyl-D-galactose phenylosazone in deuteriochloroform. Decoupling of the C-1 proton (7.54 p.p.m.): *(A)* Decoupling by irradiation of the non-chelated NH proton (8.00 p.p.m.). *(B)* Decoupling showing no coupling with the chelated NH proton (12.34 p.p.m.). — Internal standard: tetramethylsilane.

High-resolution NMR spectroscopy (100 Mc) using the double-resonance method (Fig. 8) also confirmed that the C–1 proton is coupled with the non-chelated NH proton (signal at 8.0 p.p.m.) and not with the chelated NH proton whose signal is at 12.34 p.p.m.

A similar long-range spin-spin coupling between the C–1 proton and the α-imino proton was reported for the *syn* isomers of aldehyde 2,4-dinitrophenylhydrazones [51]. The positions of both protons in these compounds and in the sugar osazones *(10)* and *(12)* are very similar. A comparable coupling between the C–1 proton and the distant free NH proton in structures *(11)* and *(13)*of the sugar osazones is highly improbable.

Considering the behavior of the sugar osazones and their ultraviolet, infrared, and NMR spectra, it seems probable that the structures *(10)* and *(12)* are limiting forms of a quasi-aromatic structure *(42)*. This would be


(42)

supported by the results of X-ray analysis [43,48] which show (cf. Section 7) that the six-membered chelate ring is approximately planar, and that its bond angles are about 120°. Moreover, polarographic analysis [36] indicates that the chelated sugar phenylosazones are more stable by about 10 kcal/mole, than the non-chelated sugar 2-methylphenyl-1-phenylosazones. This difference in stability is much larger than the normal chelation energy.

Conclusions

The quasi-aromatic structure *(42)* is proposed for the sugar osazones. It allows a satisfactory interpretation of most of their properties:

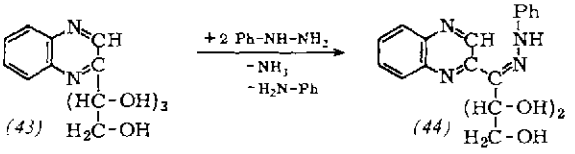
[49] *O. L. Chapman, R. W. King, W. J. Welstead*, Jr., and *T. J. Murphy*, J. Amer. chem. Soc. *86*, 4968 (1964).

[50] *H. El Khadem, M. L. Wolfrom*, and *D. Horton*, J. org. Chemistry *30*, 858 (1965).

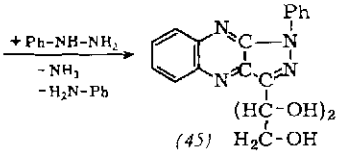
[51] *G. J. Karabatsos, B. L. Shapiro, F. M. Vane, J. S. Fleming*, and *J. S. Ratka*, J. Amer. chem. Soc. *85*, 2784 (1963).

1. Osazone formation must stop at the second carbon atom, since the phenylhydrazone attached to C–2 is engaged in the formation of the quasiaromatic chelate ring and thus cannot initiate further osazone formation.

If, however, the first two carbon atoms of a sugar are part of a quinoxaline system *(43)* having a double



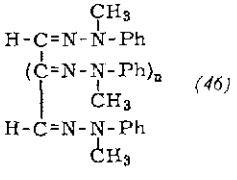
(43) *(44)*



(45)

Schiff-base structure, then the hydroxy group on C–3 undergoes a reaction analogous to osazone formation [52]: it is first oxidized by phenylhydrazine to a keto group which then condenses with a second molecule of phenylhydrazine *(44)*. In this particular case, the reaction goes further, yielding the tricyclic derivative *(45)* by oxidation with a third molecule of phenylhydrazine.

The hypothesis that the chelate ring stops the osazone reaction after C–2 has been reached was recently confirmed by *Champan* et al. [53]. They succeeded in oxidizing sugars completely by means of 1-(methylphenyl)hydrazine, thus synthesizing a new type of sugar derivative, the alkazones *(46)*, which are nothing else than sugars completely converted into osazones. Taking



(46)

into account that the methylphenylosazones cannot form chelate rings, it is readily understood that in this case osazone formation can proceed right through the entire carbohydrate chain.

2. The difference between phenylosazones and mixed osazones, on the one hand, and the bis(methylphenyl)-osazones, on the other, can also be explained by structure *(42)*: compounds of the latter group cannot give rise to chelate rings.

3. Formula *(42)* shows the difference between the two phenylhydrazone groups in the sugar osazones and thus explains their different behavior on methylation, reduction, transosazonization, osonehydrazone formation, and osotriazole formation.

The abnormal behavior of the primary hydroxy group of sugar osazones on tritylation has not yet been satisfactorily interpreted. The special character of this group is also shown in the NMR spectra [42,44] and in the fact that a benzoyl group attached to it is readily hydrolysed [54,55]. *Wolfrom* et al. [44] attribute the irregularities observed in the NMR spectra to the non-equivalence of the two protons on C-6 which is caused by the asymmetry of C-5. Possibly, however, this phenomenon is due rather to steric hindrance between the hydroxy group on C-6 and the rest of the molecule, in particular the hydroxy groups on C-3.

4. The presence of a hydroxy group (free or substituted) on C–3 favors the stabilization of the chelate ring in the quasi-aromatic structure *(42)*. At the same time the electron-attracting effect of the quasi-aromatic system influences the behavior of this hydroxy group in many of its reactions [16,37,42].

The absence of a hydroxy group on C–3 in the case of non-sugar osazones makes the formation of a chelate structure similar to *(42)* more difficult. This is the reason why both groups of osazones behave so differently. However, in some cases, the size of a substituent on C–2 in non-sugar osazones may favor the formation of a chelate ring [49], which then differs in nature from that present in sugar osazones [28,56].

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[52] *H. Ohle* and *G. A. Melkonian*, Chem. Ber. *74*, 279, 398 (1941).

[53] *O. L. Chapman*, *W. J. Welstead*, Jr., *T. J. Murphy*, and *R. V. King*, J. Amer. chem. Soc. *86*, 732 (1964).

[54] *H. Zinner*, *W. Bock*, and *H. P. Klöcking*, Chem. Ber. *92*, 1313 (1959).

[55] *E. Fischer* and *H. Noth*, Ber. dtsch. chem. Ges. *51*, 321 (1918).

[56] *L. Mester*, *E. Moczar*, and *G. Vass*, unpublished results.

New Methods in Preparative Organic Chemistry IV [*]

New Reactions of Alkylidenephosphoranes and their Preparative Uses

Part I: The Acid-Base Character of Phosphonium Salts and Alkylidenephosphoranes [**]

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Phosphonium salts may be regarded as Bronsted acids, and alkylidenephosphoranes as the conjugate bases. Compounds of the two classes exist in equilibrium with each other. Phosphonium salts and alkylidenephosphoranes can be obtained by this "transylidation". Other methods are also given for the preparation of members of both classes.

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A. Introduction

The discovery by *Wittig* and co-workers [1] that alkylidenetriphenylphosphoranes react with aldehydes and ketones to form olefins and triphenylphosphine oxide has supplied the incentive to a large number of investigations. The Wittig reaction has already been discussed by *Schöllkopf* [2] and by *Trippett* [3], as well as by *Bergelson* and *Schemjakin* [4].

[*] The contributions in the previous three series have been published collectively in three volumes by Verlag Chemie, Weinheim/Bergstr.; English edition: Academic Press, New York-London.

[**] Parts II and III will appear shortly in this journal.

[1a] *G. Wittig* and *G. Geissler*, Liebigs Ann. Chem. *580*, 44 (1953).

[1b] *G. Wittig* and *U. Schöllkopf*, Chem. Ber. *87*, 1318 (1954).

[1c] *G. Wittig* and *W. Haag*, Chem. Ber. *88*, 1654 (1955).

[2] *U. Schöllkopf*, Angew. Chem. *71*, 260 (1959).

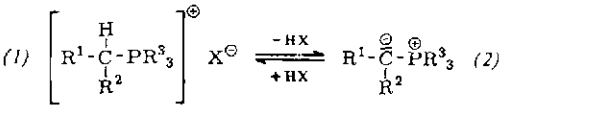
[3] *S. Trippett* in: Advances in Organic Chemistry. Vol. 1, Interscience, New York 1960; Quart. Rev. *17*, 406 (1963).

The aim of the present series of articles is to show that the recently discovered reactions of alkylidenephosphoranes with polar compounds are also of interest in preparative chemistry.

B. Phosphonium Salts and Alkylidenephosphoranes as Conjugate Acid-Base Pairs

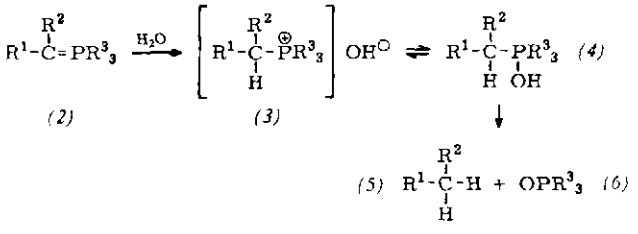
Strong bases eliminate HX from phosphonium salts *(1)* to form alkylidenephosphoranes *(2)*. *Staudinger* [5] found that the latter in turn can add HX, with re-formation of the phosphonium salts *(1)*.

Thus phosphonium salts can be regarded as Bronsted acids, and alkylidenephosphoranes as the conjugate bases.



(1) *(2)*

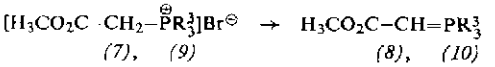
The basicity of the ylides *(2)* is also apparent in their reaction with water [1b, 1c, 2, 6, 7], in which addition of a proton to the free electron pair of the open C–P double bond leads to formation of the phosphonium hydroxide *(3)*.



(2) *(3)* *(4)* *(5)* *(6)*

The hydroxides *(3)* decompose *via* the compounds *(4)* of pentavalent phosphorus into a hydrocarbon *(5)* and a phosphine oxide *(6)* [8, 9]. The ligand eliminated from the phosphorus atom of *(3)* as a hydrocarbon is always the most strongly electronegative or the most highly resonance stabilized of the four [9, 10].

The acid-base strength of the phosphonium salts *(1)* and the alkylidenephosphoranes *(2)* depends mainly on R^1 and R^2. Electron-attracting groups increase the acidity of the phosphonium salt *(1)* and lower the basicity of the corresponding ylide *(2)*. Thus dilute sodium carbonate solution is sufficient to precipitate the ylide *(8)* from an aqueous solution of triphenylmethoxycarbonylmethylphosphonium bromide *(7)*, which is a very strong acid owing to the presence of the ester group [11, 12]. Compound *(8)* is stable towards cold water, since the ester group lowers the basicity and so hinders the attack of a proton on the lone electron pair of the open C–P double bond. The alkylidenephosphorane *(8)* decomposes with water into methyl acetate and triphenylphosphine oxide only on boiling.



(7), *(9)* *(8)*, *(10)*

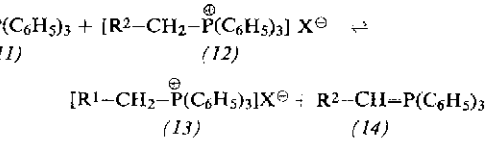
(7), *(8)*: $R^3 = C_6H_5$; *(9)*, *(10)*: R_3 = Cyclohexyl

The acid and base strengths of *(1)* and *(2)* are also determined by R^3. The electron-attracting inductive effect of the three phenyl groups in *(7)* loosens the H atoms of the CH_2 group. If the triphenylphosphine residue in *(7)* is replaced by a tricyclohexylphosphine residue, the (–I) effect of the three cyclohexyl residues in the phosphonium bromide *(9)* strengthens the CH bonds of the methylene group. The deprotonation of *(9)* can no longer be effected with sodium carbonate solution, but requires the use of dilute sodium hydroxide solution [12].

Methoxycarbonylmethylidenetricyclohexylphosphorane *(10)* is more strongly basic than the triphenyl compound *(8)*. In contrast to *(8)*, *(10)* decomposes simply on standing for a short time in cold water.

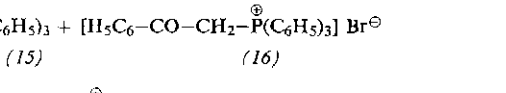
C. Transylidation

Since phosphonium salts and alkylidenephosphoranes are related as an acid-base pair, and since the strength of these acids and bases is governed by R^1 and R^2, an acid-base equilibrium is set up between alkylidenetriphenylphosphoranes *(11)* and triphenylphosphonium salts *(12)* [13].



(11) *(12)* *(13)* *(14)*

The position of the equilibrium is governed by the residues R^1 and R^2. If the basicities of *(11)* and *(14)* or the acid strengths of *(12)* and *(13)* are very different, the equilibrium always favors the formation of the more weakly basic alkylidenephosphorane and the more weakly acidic phosphonium salt. Thus the reaction of methylidenetriphenylphosphorane *(15)* with triphenylphenacylphosphonium bromide *(16)* yields triphenylmethylphosphonium bromide *(17)* and benzoylmethylidenetriphenylphosphorane *(18)* in almost 90% yield. This is an example of a reaction which we shall refer to as transylidation.



(15) *(16)* *(17)* *(18)*

Transylidation provides a method of comparing the strengths of the mesomeric or inductive effects of the substituents on the acidity of the methylene group α to

[4] *L. D. Bergelson* and *M. M. Schemjakin*, Angew. Chem. *76*, 113 (1964); Angew. Chem. internat. Edit. *3*, 250 (1964).

[5] *H. Staudinger* and *J. Meyer*, Helv. chim. Acta *2*, 635 (1919).

[6a] *G. Lüscher*, Doctorate Thesis, E.T.H. Zürich 1922.

[6b] *H. Issler*, Doctorate Thesis, E.T.H. Zürich 1924.

[7] *D. D. Coffman* and *C. S. Marvel*, J. Amer. chem. Soc. *51*, 3496 (1929).

[8] *J. Meisenheimer*, *J. Casper*, *M. Höring*, *W. Lauter*, *L. Lichtenstadt*, and *W. Samuel*, Liebigs Ann. Chem. *449*, 213 (1926).

[9] *G. W. Fenton* and *C. K. Ingold*, J. chem. Soc. (London) *1929*, 2342.

[10] *L. Hey* and *C. K. Ingold*, J. chem. Soc. (London) *1933*, 531; *L. Horner*, *H. Hoffmann*, *H. G. Wippel*, and *G. Hassel*, Chem. Ber. *91*, 52 (1958).

[11] *O. Isler*, *H. Gutmann*, *M. Montavon*, *R. Rüegg*, *G. Ryser*, and *P. Zeller*, Helv. chim. Acta *40*, 1242 (1957).

[12] *H. J. Bestmann* and *O. Kratzer*, Chem. Ber. *95*, 1894 (1962).

[13] *H. J. Bestmann*, Chem. Ber. *95*, 58 (1962).

the P atom in the phosphonium salt or on the basicity of the alkylidenephosphorane. Such a comparison gives the sequence:

$C_6H_5{-}CO > CO_2CH_3 > C_6H_5 >$ alkyl

The reaction of phosphonium salts

$[R^1{-}CH_2{-}P^{\oplus}(C_6H_5)_3]X^{\ominus}$

with alkylidenephosphoranes $R^2{-}CH{=}P(C_6H_5)_3$ in which R^2 lies to the right of R^1 in the above series leads to transylidation.

Experiments with phosphonium salts labelled with tritium have shown that transylidation also takes place if R^1 and R^2 in *(11)* and *(12)* are identical, or if the inductive or mesomeric effects of R^1 and R^2 differ only slightly [13].

Procedure:

Preparation of Benzoylmethylidenetriphenylphosphorane by Transylidation [13]

Finely powdered triphenylphenacylphosphonium bromide *(16)* (9.24 g), which has been dried in vacuum over P_2O_5, is added to a salt-free solution (see Section D2 for preparation) of 0.02 mole of methylidenetriphenylphosphorane *(15)* in 100 ml of anhydrous toluene [14], and the mixture is refluxed for 24 h in the absence of moisture and oxygen. The benzoylmethylidenetriphenylphosphorane *(18)* is filtered off, the precipitate is washed with toluene, and the solution is evaporated in vacuum. The crystalline residue is mixed with 15 to 20 ml of ethyl acetate and filtered. A small second fraction is obtained by slow evaporation of the filtrate. Total yield 6.65 g (87.5 %); m.p. and mixed m.p. with benzoylmethylidenetriphenylphosphorane 180 °C.

The salt filtered off from the solution in ethyl acetate weighs 7.8 g. It is dissolved in 60 ml of water by warming, and the pH of the solution is adjusted to 13–14 with dilute sodium hydroxide solution, whereupon 0.65 g of *(18)*, formed from unchanged triphenylphenacylphosphonium bromide *(16)*, precipitates. This is filtered off, and the aqueous solution is acidified with acetic acid, heated to boiling, and a solution of 3 g of NaI in 10 ml of water is added. Triphenylmethylphosphonium iodide crystallizes on cooling; yield 4.9 g (60.8 %), m.p. and mixed m.p. 182 °C (from isopropanol).

D. Preparation of Phosphonium Salts and Alkylidenephosphoranes

1. Phosphonium Salts

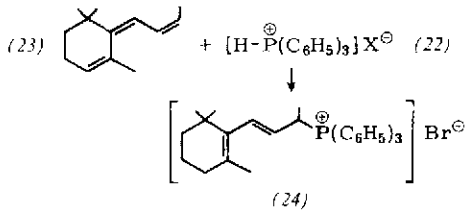
Phosphonium salts *(21)* are generally prepared from alkyl halides *(19)* and triphenylphosphine *(20)* [2].

$$\underset{(19)}{R{-}X} + \underset{(20)}{P(C_6H_5)_3} \rightarrow \underset{(21)}{[R{-}\overset{\oplus}{P}(C_6H_5)_3]\,X^{\ominus}}$$

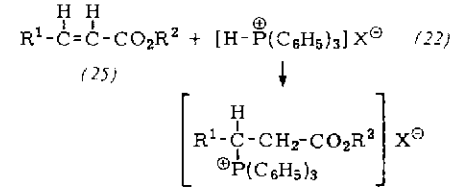
The following method is of great preparative interest [15, 16]:

$$R{-}OH + \underset{(22)}{[H{-}\overset{\oplus}{P}(C_6H_5)_3]X^{\ominus}} \rightarrow \underset{(21)}{[R{-}\overset{\oplus}{P}(C_6H_5)_3]X^{\ominus}} + H_2O$$

A phosphonium salt *(21)* is obtained from an alcohol by reaction with triphenylphosphonium halides *(22)* (preferably the bromide). Triphenylphosphonium bromide *(22)*, X = Br, adds onto the ends of many polyene chains by ω,ω'-addition. Thus 1,6-addition of the bromide *(22)*, X = Br, to the triene *(23)* leads to the phosphonium salt *(24)* [16].



Phosphonium salts can also be obtained from compounds containing polarized C–C double bonds (*e.g.* α,β-unsaturated nitriles, esters of carboxylic acids *(25)*, and nitro compounds) by reaction with the bromide *(22)*, X = Br [17].



The reaction of quaternary ammonium salts of Mannich bases *(26)* with triphenylphosphine also allows the preparation of phosphonium salts *(27)* which are difficult or impossible to obtain by other methods [18].

$$\underset{(26)}{[R{-}CH_2{-}\overset{\oplus}{N}(CH_3)_3]X^{\ominus}} + P(C_6H_5)_3 \rightarrow \underset{(27)}{[R{-}CH_2{-}\overset{\oplus}{P}(C_6H_5)_3]X^{\ominus}} + N(CH_3)_3$$

New possibilities in the preparative field are opened up by additions to vinylphosphonium salts *(28)* [19] and to phenylethynylphosphonium salts *(29)* [20].

$$3\,\underset{(28)}{[(C_4H_9)_3\overset{\oplus}{P}{-}CH{=}CH_2]\,Br^{\ominus}} + H_3C{-}CO{-}C_6H_5 \rightarrow \{[(C_4H_9)_3\overset{\oplus}{P}{-}CH_2{-}CH_2]_3C{-}CO{-}C_6H_5\}\,3\,Br^{\ominus}$$

$$\underset{(29)}{[(C_6H_5)_3\overset{\oplus}{P}{-}C{\equiv}C{-}C_6H_5]\,Br^{\ominus}} + H_2N{-}C_6H_5 \rightarrow [(C_6H_5)_3\overset{\oplus}{P}{-}CH_2{-}\overset{N{-}C_6H_5}{\overset{\|}{C}}{-}C_6H_5]\,Br^{\ominus}$$

The possibility of synthesizing phosphonium salts from alkylidenephosphoranes and halogen compounds is discussed in Part II.

[14] *F. Ramirez* and *S. Dershowitz*, J.org.Chemistry *22*, 41 (1957).

[15] German Patent 1046046 (Dec. 11th, 1958), BASF, inventors: *W. Sarnecki* and *H. Pommer*.

[16] *H. Pommer*, Angew. Chem. *72*, 811 (1960).

[17] *H. Hoffmann*, Chem. Ber. *94*, 1331 (1961).

[18] *H. Hellmann* and *O. Schumacher*, Liebigs Ann. Chem. *640*, 79 (1961).

[19] *P.T. Keough* and *M.Grayson*, J.org.Chemistry *29*, 631 (1964).

[20] *H.Hoffmann* and *H.Förster*, Tetrahedron Letters *1964*, 983.

Procedures:

β-Methoxyethyltriphenylphosphonium Bromide [15]

A mixture of 34 g of triphenylphosphonium bromide *(22)*, X = Br, and 8 g of glycol monomethyl ether is refluxed for 7 h with 50 g of anhydrous tetrahydrofuran. When the reaction mixture is cooled, 17 g of β-methoxyethyltriphenylphosphonium bromide *(21)*, R = $H_3C-O-CH_2CH_2$, m.p. 216 °C, separates out. A further 7 g is obtained by concentration of the mother liquor.

Phosphonium Salts from Compounds Containing Activated Double Bonds and Triphenylphosphonium Bromide [17]

Method a: 2.62 g (10 mmole) of triphenylphosphine *(20)* and 10 mmole of the component containing an activated double bond are heated with stirring at 100 °C with 5 ml of 48 % aqueous HBr for 5–15 min. The mixture is then diluted with about 10 ml of water, extracted with ether to remove any unchanged starting material, and the phosphonium salt is allowed to crystallize or is extracted with chloroform, depending on its solubility. Iodides can be precipitated by addition of excess NaI.

Method b: 3.4 g (10 mmole) of triphenylphosphonium bromide *(22)*, X = Br, and 10 mmole of the component containing an activated double bond are heated in 5 ml of acetonitrile for 5–15 min on a boiling water bath. The phosphonium salt is then precipitated with ethyl acetate or ether, and purified as described under a.

Skatyltriphenylphosphonium Methylsulfate [18]

Three grams of gramine methylsulfate is boiled with 15 mmole of triphenylphosphine *(20)* in 30 ml of methanol for 90 min under nitrogen (trimethylamine is liberated). The precipitate formed on cooling is washed with methanol, and can be recrystallized from water to give a pale pink salt, m.p. = 185–186 °C.

2. Alkylidenephosphoranes

The best method of preparing alkylidenephosphoranes is the action of bases on phosphonium salts *[(1)→(2)]* (see Section B). The strength of the base necessary for deprotonation depends on the acidity of the phosphonium salt. A base recently found to be particularly useful is the methylsulfinyl carbanion obtained from dimethyl sulfoxide and sodium hydride and used in dimethyl sulfoxide as solvent [21a].

In many of the reactions described below, it is important that the ylide solutions used should be free from lithium salts, since these react with the ylide to form complexes which strongly interfere with the reaction. The most suitable method for the preparation of such solutions is the sodamide method [21b] described below.

Schöllkopf [2] has made reference to elimination reactions which can hinder ylide formation. The action of bases on phosphonium salts containing activated hydrogen β to the phosphorus atom can lead to decomposition of the initially formed ylide into an olefin and triphenylphosphine by intermolecular proton migration [22] (cf. also Part II, Section C 1, on the Hofmann degradation of quaternary phosphonium salts). In such cases, sodium alkoxides should not be used as bases, since these compounds strongly favor the Hofmann degradation [22].

Ylides are also formed from triphenylphosphine and carbenes *(30)*. Alkylidenephosphoranes with halogen atoms on the C-atom α to the C–P double bond have become available by this method [23,24].

$$(C_6H_5)_3P + :C\begin{matrix}X\\Y\end{matrix} \longrightarrow (C_6H_5)_3P{=}C\begin{matrix}X\\Y\end{matrix}$$

(30)

Aliphatic diazo compounds can also be used as sources of carbenes for the preparation of ylides. However, they must be decomposed in the presence of copper salts [25], since the reaction of diazo compounds with triphenylphosphine generally leads to phosphazines *(31)* [26].

$$(C_6H_5)_3P + |N{\equiv}\overset{\oplus}{N}\text{–}\overset{\ominus}{C}R_2 \xrightarrow{Cu^{2+}} (C_6H_5)_3P{=}CR_2 + N_2$$

$$\rightarrow (C_6H_5)_3P{=}N{-}N{=}CR_2$$

(31)

The dihalogenomethylidenephosphoranes *(32)* are also readily obtainable by the reaction of triphenylphosphine with carbon tetrachloride or carbon tetrabromide [27].

$$2\ P(C_6H_5)_3 + CX_4 \rightarrow (C_6H_5)_3P{=}CX_2 + (C_6H_5)_3PX_2$$

X = Cl, Br *(32)*

The reaction of acrylic acid derivatives *(33)* with triphenylphosphine leads to ylides *(34)* which can be intercepted with carbonyl compounds by a Wittig reaction [28], and which are difficult to obtain by other methods owing to the ease with which the Hofmann degradation takes place.

$$(C_6H_5)_3P + H_2C{=}CHR \rightarrow (C_6H_5)_3P{=}CH{-}CH_2R$$

(33) *(34)*

R = $-CO_2R^1$; $-CONH_2$; $-C{\equiv}N$

[21a] *R. Greenwald, M. Chaykovsky,* and *E. J. Corey,* J. org. Chemistry *28*, 1128 (1963).

[21b] *G. Wittig, H. Eggers,* and *P. Duffner,* Liebigs Ann. Chem. *619*, 10 (1958).

[22] *H. J. Bestmann, H. Häberlein,* and *I. Pils,* Tetrahedron *20*, 2079 (1964).

[23a] *A. J. Speziale, G. J. Marco,* and *K. W. Ratts,* J. Amer. chem. Soc. *82*, 1260 (1960); *A. J. Speziale* and *K. W. Ratts,* ibid. *84*, 854 (1962).

[23b] *D. Seyferth, S. O. Grim,* and *T. O. Read,* J. Amer. chem. Soc. *82*, 1510 (1960); *D. Seyferth* and *S. O. Grim,* ibid. *83*, 1610 (1961).

[24] *G. Wittig* and *M. Schlosser,* Angew. Chem. *72*, 324 (1960); Chem. Ber. *94*, 1373 (1961).

[25] *G. Wittig* and *M. Schlosser,* Tetrahedron *18*, 1023 (1962).

[26a] *H. Staudinger* and *J. Meyer,* Helv. chim. Acta *2*, 619 (1919).

[26b] *H. Staudinger* and *G. Lüscher,* Helv. chim. Acta *5*, 75 (1922).

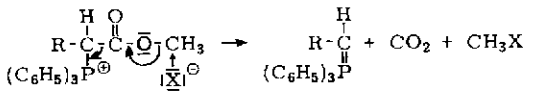
[26c] *G. Wittig* and *W. Haag,* Chem. Ber. *88*, 1654 (1955).

[26d] *H. J. Bestmann, H. Buckschewski,* and *H. Leube,* Chem. Ber. *92*, 1345 (1959).

[27] *R. Rabinowitz* and *R. Marcus,* J. Amer. chem. Soc. *84*, 1312 (1962); *F. Ramirez, N. B. Desai,* and *N. McKelvie,* ibid. *84*, 1745 (1962).

[28] *R. Oda, T. Kawabata,* and *S. Tanimoto,* Tetrahedron Letters *1964*, 1653. Cf. also the analogous formation of ylide from triphenylphosphine and maleic anhydride: *R. F. Hudson* and *P. A. Chopard,* Helv. chim. Acta *46*, 2178 (1963).

Alkylidenephosphoranes are also formed on thermal decomposition of triphenyl-α-methoxycarbonylalkylphosphonium salts *(35)* [29].



(35)

The ylides formed can be isolated if they are stable. They can also be intercepted by various reagents, or undergo intramolecular reactions.

Procedures:

Salt-free Alkylidenephosphorane Solutions

All operations are carried out under nitrogen or argon. Ammonia is condensed in a trap cooled with liquid air and containing sodium. The resulting dry ammonia is distilled into a second tube (75–100 ml), and the required quantity of finely chopped sodium (up to 25 % excess) and a few grains of ferric nitrate are added. When the blue sodium solution has turned grey, the absolutely dry and finely powdered phosphonium salt is added, stirred for a short time with a glass rod, and the ammonia is then evaporated off through a mercury valve. The evaporation is accelerated by heating the tube with hot air. To the residue is added 100 ml of an inert, anhydrous solvent, *e.g.* benzene, toluene, ether, or tetrahydrofuran, and the solution is boiled for about 10 min to remove residual gas, the reflux condenser being sealed with mercury. The solid residue is then filtered off using a G-3 frit. The filtration can be dispensed with if the subsequent reactions are not affected by excess sodamide and undissolved sodium halide.

Preparation of Ylide Solutions by the Dimethylsulfinate Method

The preparation must be carried out under nitrogen and in the strict absence of moisture. The stoichiometric quantity of sodium hydride (as a 50 % suspension in mineral oil) is freed from mineral oil by repeated washing on a sintered glass filter with anhydrous petroleum ether, and placed in the reaction vessel. Dimethyl sulfoxide (dried over calcium hydride) is added (50 ml of dimethyl sulfoxide per 100 mmole of NaH), a reflux condenser with a mercury valve is fitted to the vessel, and the mixture is slowly heated to 70–80 °C, with stirring (magnetic stirrer). The evolution of hydrogen stops after about 45 min. The resulting solution of the dimethyl sulfoxide anion is cooled in ice and the solution or suspension of the phosphonium salt in dimethyl sulfoxide (50 mmole of salt in about 100 ml of dimethyl sulfoxide) is added. The mixture is stirred for a further 10–20 min at room temperature before being used for further reactions.

Chloromethylidenetriphenylphosphorane Solution [24b]

A solution of 40 mmole of butyl-lithium in about 25 ml of anhydrous ether is added dropwise, over a period of 40 min, to a well-stirred solution of 35 mmole of triphenylphosphine in 45 ml of absolute methylene chloride at −60 °C. The resulting solution of the chloromethylidenetriphenylphosphorane is then used for further reactions.

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[29] *H. J. Bestmann, H. Hartung*, and *I. Pils*, unpublished work.

Melting and Crystal Structure – Some Current Problems

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The "classical" definition of liquid and solid phases acording to mechanical criteria is unsatisfactory. It is now known that "premelting" effects occur in crystals, and in many liquids the formation of clusters is observed near the melting point, with structures which can correspond to the short-range order of the crystals from which the melt is derived. – In particular, the implications of the theories of Lennard-Jones and Devonshire and of Mizushima and Ookawa are discussed.

As is now well known, many melts have structures which resemble the crystals from which they are formed more or less closely. This is shown, for example, by the similarity of density. X-ray diffraction shows, too, that the interatomic or intermolecular distance in many melts is quite close to that in the crystals. However, the conventional radial distribution function of melts gives data which are far too condensed to be really informative. Methods are required which give a three-dimensional representation of regions or domains in the liquid, as a counterpart to the elaborate three-dimensional information usually available about the crystals.

This gap in our direct structural knowledge about the molecular arrangements in melts is a serious obstacle to systematic development of theories of the liquid state. It has tended to direct mathematical theories to the discussion of liquids whose units of structure are extremely simple, such as atoms or diatomic molecules [1]. Actually, such melts form only a minute fraction of the range of known liquids; their

[1] *K. Furukawa*, Rep. Progr. Physics *25*, 396 (1950).

behaviour is not necessarily representative of melting in general. Alternatively, statistical theories of liquids may be developed on a quasi-gaseous analogy [2]. Whilst this approach is rather more broadly based, it is applicable most generally near the critical temperature of the liquids, and does not yield particularly refined structural information about the solid-liquid transformation at the melting point. This consideration makes it convenient to refer to liquids at temperatures around their freezing point as *melts*, to distinguish them in broad terms from quasi-gaseous fluids near the critical temperature.

The primary distinction between solid and liquid, regarded as condensed states of matter, is mechanical. But at the present time, for these as for other states of matter, the most general approach to theories of transitions between them has to be based on thermodynamic and statistical considerations. With reference to the role of structural features in melting, some of the concepts from which new lines of experimentation may originate will be briefly reviewed here.

Two principal thermodynamic parameters of general interest in discussing structural aspects of melting are the entropy of fusion S_f and the fractional change in molar volume $\Delta V_f/V_s$, where V_s is the molar volume of the crystal at the melting point T_f. These are related by the Clausius-Clapeyron equation

$$dP/dT = S_f/\Delta V_f.$$

Subsidiary thermodynamic properties, of great interest for particular structures, are derived parameters such as the compressibility, the thermal expansion coefficient and the heat capacities. It can be very informative to known what is the change in these quantities at the melting point, but very often the data are not available. Also of great importance are any premonitory changes in these subsidiary parameters, in premelting or prefreezing effects. The entropy of fusion is particularly useful in its correlation with the melting of different kinds of crystal structures by virtue of the Boltzmann relationship

$$S_f/R = \ln (W_L/W_S)$$

where W_L and W_S are the number of independent ways of contriving the liquid and solid states respectively.

For all known cases of melting, S_f is positive, *i.e.* the fluid condensed state has a higher entropy than any state with rigidity. In general the higher entropy of the melt can be attributed to its greater disorder. More specifically, various types of crystal structure can be disordered in different ways. Each distinguishable mode of disordering constitutes a mechanism of melting. Some crystal structures exhibit a single mechanism of melting, whereas others combine more than one mechanism of disordering on passing from the crystal to the melt.

A representative but not exhaustive discussion of mechanisms of disordering may be conveniently given, with emphasis on directions in which research is currently particularly active, or where problems seem ripe for attack.

[2] Cf. *R. Fowler* and *E. A. Guggenheim*: Statistical Thermodynamics. University Press, Cambridge 1939.

I. Positional Melting

As is apparent for example from X-ray diffraction studies, all crystals undergo loss of long-range order on melting. What is not quite as well established is the extent of the disordering of local packing. Current diffraction methods [1] establish a smooth average, but for some theories of the structures of melts, particularly in the temperature range around T_f, it is important to know to what extent cooperative fluctuations about the smoothed average lead to clusters of any kind. Some types of cluster can act as crystal nuclei; other types of assembly may have an enthalpy lower than the average, but lack 3-dimensional lattice ordering and thus are non-crystallizable. This kind of information about domains or cooperative fluctuations in the melt is only beginning to receive attention by the use of diffraction methods [3]. Other aspects will be referred to later in connection with prefreezing phenomena.

Numerical values of the entropy of positional disordering may be given a kind of norm from data for crystals of the rare gases. Where quantum effects, *i.e.* contributions from zero-point energy, can be neglected, the entropy of positional disordering on melting of these crystals is about 3.3 e.u. [4]. This value can be built into a particularly straightforward statistical thermodynamic model of positional melting, first discussed in mathematical details by *Lennard-Jones* and *Devonshire* in 1939 [5]. In their model, positional disordering is restricted to the insertion of atoms in interstitial sites, in the so-called Frenkel positional defects. According to this theory, equilibrium can be established at T_f between a slightly defective crystal (the solid) and a highly defective crystal (the liquid). Changes of vibrational entropy are neglected, and the cooperative influence of crystal defects upon neighboring crystal sites is allowed for in terms of the expansion on melting by a Bragg-Williams type of volume-dependent interaction. Despite its obvious oversimplifications, this well-known model helps to clarify the main features of positional melting. It is one of the simplest ways of describing the structure of a quasi-crystalline liquid.

Amongst current developments of this simple version of positional melting, the following may he noted:

1. Dislocation Melting

Any crystal defect whose energy of creation is lowered by virtue of defects on neighboring lattice sites may be termed cooperative to distinguish it from an isolated or point defect. As an alternative or an addition to Frenkel defects the intervention of cooperative defects in mechanisms of melting has been proposed on qualitative

[3] *V. K. Prokhorenko* and *J. Z. Fisher*, Zh. Fiz. Khim. *33*, 1852 (1959).

[4] *A. R. Ubbelohde*, Quart. Rev. (Chem. Soc., London) *4*, 356 (1950).

[5] *J. E. Lennard-Jones* and *A. F. Devonshire*, Proc. Roy. Soc. (London) A *169*, 317 (1939); ibid. *170*, 464 (1939).

grounds [6], but a quantitative theory has proved difficult to elaborate. Recently, an attempt has been followed through to describe the positional melting of metals on a dislocation theory [7,8].

In its present form, this theory still involves some harsh simplifications. However, this development of a cooperative defect model appears to be significant for at least two aspects of the behavior of melts.

a) It points to the kinds of positional disordering in a quasi-crystalline liquid on a more realistic basis than the interstitial defect model of *Lennard-Jones* and *Devonshire*. A dislocation type of approach can be of importance for describing thermodynamic behaviour, and may also be more readily applicable when dealing with any transport processes that show some chain-mechanism character in the melt. Thus the Lennard-Jones model harmonises most readily with the theory that transport processes in liquids all occur by the activated hopping discussed by *Eyring* [9], according to which momentum transfer is the outcome of mass transfer. Dislocation models suggest that in addition to any hopping of units, momentum transfer may occur by dislocation movement, in a kind of zip fastener action.

b) In calculating the total entropy of fusion, a particular dislocation model gives [7]:

$$S_f = \Delta S_{vib.}\ (0.69\ \text{e.u.}) + \Delta S_{pos.}\ (1.08\ \text{e.u.})$$

This contribution of a change of vibrational entropy $\Delta S_{vib.}$ to the total entropy of fusion S_f marks a difference from the Lennard-Jones theory in which $\Delta S_{vib.}$ is assumed zero.

2. Melting of Metals

Types of molecules are known which have quasispherical (globular) repulsion envelopes, when close packed in the crystals. For these too, $S_f \sim 3$ e.u., showing that a simple model for positional melting has quite wide generality. However, a large class of crystals is known, mostly metallic in properties, in which the units of structure are atoms, but for which $S_f < 3$ e.u. The reason why many metals have a lower S_f and thus a lower overall disorder in the melt than rare gases has not yet been fully elucidated.

The repulsion force fields may be lower, since $\Delta V_f/V_s$ for metals is markedly lower than for inert gases. Reasons for lower repulsion force fields are however not at all apparent: even alkali metals have S_f and $\Delta V_f/V_s$ much lower than the rare gases whose electronic core is nevertheless similar. Another possible explanation of the low values of melting parameters of metals is that factors contribute to S_f that do not greatly increase the enthalpy of fusion H_f, resulting in a lower T_f according to the expression $T_f = H_f/S_f$, where H_f is the molar enthalpy of fusion. Indications of this possibility may be found from the abnormally long liquid range of metals as seen from the high value of $T_{crit.}/T_f$ or $T_b/T_f \approx 3$, compared with T_b/T_f of about 1.03 for rare gases and $T_b/T_f \approx 1.6$ for the structurally related halides with rare-gas configurations [10] (T_b is the boiling point at 1 atm).

3. Melting of Ionic Crystals of Simple Structure

For halides of inert-gas structure with low polarizability, for example salts of lithium, S_f and $\Delta V_f/V_s$ are close to values for the inert gases, suggesting that positional disordering is similar in both types of crystals. However, for the more polarizable ions of higher atomic number in similar salts, both these parameters fall below the inert gas values. Again, a review of all the evidence suggests that the liquid state is abnormally favored relative to the crystalline state for the more polarizable ions. This polarizability might favor cluster formation in ways to be discussed later.

4. Premelting Effects in Crystals

The Lennard-Jones and Devonshire model for positional melting indicates considerable premelting in the crystals. It does not allow for any quasi-crystalline or microcrystalline domains in the melt, since the Bragg-Williams treatment of cooperative interactions between defects excludes such considerations. For solid argon, the fraction of atoms in defect sites at the melting point T_f, where there is a discontinuous jump to the melt, is about 0.05 in the model originally proposed by these authors.

In this theory, the extent to which positional thermal defects are present in the crystals at T_f is unfortunately too sensitive to the precise assumptions made about intermolecular force fields to permit significant correlation with experiment. It is claimed that precise experiments on Ar, CO, N_2O, HCl, and HBr do not indicate any appreciable excess specific heat [11], such as premelting defect formation might require in crystals to which the model is expected to apply.

5. Orientational Disorder of Molecular Axes in Crystals

For molecules whose repulsion envelope is not wholly spherical, a model can be readily contrived which may be combined with positional disordering in a Lennard-Jones type of statistical theory of melting. This analysis confirms the experimental finding that in some crystals, two mechanisms of fusion, for which $S_f = \Delta S_{pos.} + \Delta S_{orient.}$, occur simultaneously at T_f. For others, orientational randomization occurs at a transition temperature T_c in the solid well below T_f [12,13]. For some molecules, orientational randomization may not be complete even above T_f; this may be the case when molecular repulsion envelopes do not permit free

[6] *J. W. H. Oldham* and *A. R. Ubbelohde*, Proc. Roy. Soc. (London) A *176*, 50 (1940).

[7] *S. Mizushima*, J. physic. Soc. Japan *15*, 70 (1960).

[8] *A. Ookawa*, J. physic. Soc. Japan *15*, 2119 (1960).

[9] *S. Glasstone*, *K. J. Laidler*, and *H. Eyring*: Theory of Rate Processes. McGraw-Hill, New York 1941.

[10] *W. A. Weyl* and *E. C. Marboe*, J. Soc. GlassTechnol. *43*, 417 (1959).

[11] *K. Clusius* and *L. Staveley*, Z. physik. Chem. *49* B, 1 (1941).

[12] *A. R. Ubbelohde*, Quart. Rev. (Chem. Soc., London) *4*, 365 (1950).

[13] *J. A. Pople* and *K. E. Karasz*, J. physic. Chem. Solids *18*, 28 (1961); ibid. *20*, 294 (1961).

rotation about the three principal axes in the space available in the melt [14–16].

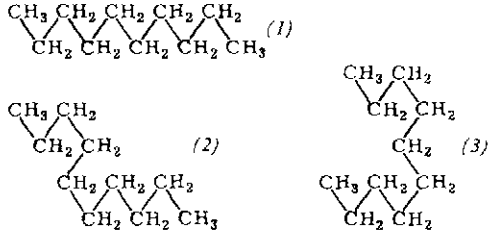
As a guide to mechanisms of melting, a great merit of any reasonably workable theory of positional disorder is that it permits more precise discussions of various departures from the norm. Many of those referred to above can still be discussed within the framework of a quasi-crystalline model for the melt. A quasi-crystalline model signifies an assembly which can be arrived at by positional (and orientational) disordering of units of structure definable with respect to the crystal lattice. The molecular arrangement of a quasi-crystalline melt defined in this way is arrived at by increasing the entropy of position (including vibrations) and orientation, *i.e.*:

$$S_f = \Delta S_{vib.} + \Delta S_{pos.} + \Delta S_{orient.}$$

II. Melts that are Not Quasi-Crystalline

Considerable attention is being paid at present to melts whose structure is not quasi-crystalline in the sense described, but is more complex.

One important group of crystals whose melts cannot be described on any quasi-crystalline model is formed by flexible molecules, such as n-alkane hydrocarbons and their derivatives, or *meta*-polyphenyls, or in general whenever the molecules can assume a variety of different configurations in free space. In the case of n-decane, for example, some of these may be represented by *(1)–(3)*.



(1)

(2)

(3)

When the different configurations in free space have free energies differing by not more than one or two units of kT, a mixture of configurations will be formed in the vapour, and somewhat less freely in the melt. On the other hand, the crystal normally selects only one configuration (usually the fully stretched one) for economical packing into a crystal lattice. For such crystals, the overall entropy of fusion includes an additional contribution due to configurational disorder *i.e.*:

$$S_f = \Delta S_{vib.} + \Delta S_{pos.} + \Delta S_{orient.} + \Delta S_{config.}$$

It has long been known that this additional mechanism leads to convergence melting points in homologous series of molecules whose skeleton is flexible. Currently, increasing attention is being paid to the fact that these melts cannot be represented by a quasi-crystalline model, for example in theories of transport processes, since they constitute a mixture of different molecular configurations. Similar remarks apply to molecular tautomerism in which the free energies of the tautomers are comparable and rates of change are sufficiently high. Anomalies have been reported in some of the transport properties, *e.g.* in *o*-terphenyl, as T_f is approached [17]. These may indicate the onset of prefreezing phenomena, which are best discussed in general terms of cluster formation on approaching the melting temperature.

III. Cluster Formation and Prefreezing Phenomena in Melts

Fluctuation theories of phase transformations, such as the theory of *Frenkel* [18], indicate a kind of symmetry in the concentration of micro-regions or domains of any phase, in the bulk of the other phase, near a transition temperature T_c or melting point T_f. In discussing possible structure anomalies of a melt as its freezing point T_f is approached or traversed, conventional forms of co-operative fluctuation theory as discussed by *Frenkel* [18], *Lukasik* [19], and *Turnbull* and *Fisher* [20] indicate the presence of minute concentrations of micro-domains of crystalline structure, swimming in the more disordered melt. Below a critical nucleation temperature T_N, crystalline micro-domains can act as crystal nuclei inducing spontaneous crystallization of the melt. For a variety of crystal types, it has been established that normally $T_N \approx 0.8\ T_f$ [21]. However, certain melts fail to nucleate spontaneously in this way [22,23]. Brief comment may be made about the origin of this difference in behaviour.

One view attempts to focus any anomaly in the prefreezing region in terms of the "free volume" in a melt. This parameter, which has analogies with the Bragg-Williams treatment of cooperative effects in solids, represents the difference between the occupation volume of a melt (the specific volume) and the volume of repulsion envelopes of all the molecules. If the "free volume" falls below critical limits before T_N is reached, spontaneous nucleation may be inhibited, and a melt may pass smoothly and progressively into a glass as its temperature falls. This approach does not predict any particular anomaly of properties as T_f is approached, and traversed, on cooling the melt. However, it appears to be grossly oversimplified. An alternative view draws attention to the fact that many molecules can be close-packed or clustered together with their repulsion envelopes in contact, in domains with various configurations. When the number of units in a cluster is small, space can usually be filled more economically by this

[14] *A. A. K. Al Mahdi* and *A. R. Ubbelohde*, Proc. Roy. Soc. (London) A *220*, 143 (1953).

[15] *J. N. Andrews* and *A. R. Ubbelohde*, Proc. Roy. Soc. (London) A *228*, 435 (1955).

[16] *J. H. Magill* and *A. R. Ubbelohde*, Trans. Faraday Soc. *54*, 1811 (1958).

[17] *J. K. Horrocks* and *E. McLaughlin*, Proc. Roy. Soc. (London) A *273*, 259 (1963).

[18] *J. Frenkel*, J. chem. Physics 7, 538 (1939).

[19] *S. J. Lukasik*, J. chem. Physics *27*, 523 (1957).

[20] *D. Turnbull* and *J. Fisher*, J. chem. Physics *17*, 71 (1949).

[21] *E. R. Buckle* and *A. R. Ubbelohde*, Proc. Roy. Soc. (London) A *259*, 325 (1960); A *261*, 197 (1961).

[22] *E. R. Buckle* and *C. N. Hooker*, Trans. Faraday Soc. *58*, 1939 (1962).

[23] *D. G. Thomas* and *L. A. K. Staveley*, J. chem. Soc. (London) (1952) 4569.

denser packing than is given by the mean density of the melt or vapour. A reduction in enthalpy of the order H_f/N per unit may be expected to accompany clustering, where N is Avogadro's number. A melt near T_f may contain such clusters, regarded as cooperative fluctuations from more open packing, in appreciable concentrations. However, as more and more units attempt to aggregate onto any particular cluster, an important discrimination must be made. If all the molecules in a cluster are arranged on a crystalline lattice so that they form regular repeat sequences in space, the cluster can act as a crystal nucleus. It can grow indefinitely by aggregation, without change of packing. This leads to spontaneous crystallisation below T_f. By contrast, if a cluster is close-packed in a non-crystallizable way, attempts to aggregate more and more units inevitably lead to the formation of fronds or inclusions of voids and clefts, with consequent lowering of its mean density. Quite soon, a non-crystallizable cluster ceases to grow by aggregation because the reduction in enthalpy resulting from closer packing ceases to operate if the number of units it comprises is too large. This second model emphasises local, more condensed regions. If it fails to crystallize on a regular crystal nucleus, such a melt eventually congeals, through contact between non-crystalline clusters.

Cooperative fluctuations of packing in melts, as they are progressively cooled, may be expected to involve more or less marked anomalies with respect to quasi-crystalline behaviour regarded as the norm. The extent to which departures from a quasi-crystalline model are found will depend on intermolecular forces. For example, different non-crystallizable types of aggregation have been proposed in hydrogen-bonded melts, such as water [24]. Clustering is also suspected in various molten metals, as well as in certain ionic melts [25].

Methods of studying the micro-structure of melts experimentally are still too scanty to investigate theories of cooperative fluctuations directly. Indirect methods include the studies of spontaneous crystallization or failure to crystallize spontaneously already mentioned. Another line of approach is to measure various transport processes in the melt as this is progressively cooled to and below T_f. When cooperative fluctuations lead to significant aggregation into clusters, the relaxation time for their dispersal may be compared with the normal relaxation time characteristic for the property under examination. For example, in viscous flow, the characteristic normal relaxation time in a quasi-crystalline melt seems to be of the order indicated by the Eyring theory [9] of hopping frequency of viscosity and of mass transport. If clusters are formed whose duration is long compared with this time, these can only be moved as a whole in the melt, *i.e.* they behave like colloidal particles suspended in it. On this basis, an increase of viscosity should be observed of the order

$$\frac{\eta_{actual}}{\eta_{ideal}} = 1 + 2.5\,\Phi + 7\,\Phi^2 + \ldots$$

where Φ is the volume fraction occupied at any instant by the clusters regarded as spherical. A decrease of mass diffusion constant should likewise be observed, due to the volume blocking of clusters [26].

In order to avoid complications from possible modifications in attractive forces due to changes of local configurations in hydrogen bonding or intermetallic bonding, a series of studies on prefreezing anomalies have been carried out on melts of polyphenyls [27]. In these, opportunities for molecular close-packing in the melt are determined predominantly by the shapes of the repulsion envelopes. Determinations of room to rotate in the melt show that for the majority of such molecules, nearest neighbors must in any case be roughly aligned, since as already stated, the free space is much too small to permit random orientation of molecular axes of neighbors. Transport properties do not necessarily show marked prefreezing anomalies; in many cases an Arrhenius type of equation is obeyed over considerable ranges of temperature, with fair accuracy, down to T_f. However, when the repulsion envelopes have marked re-entrant cavities, as for *o*-terphenyl or for 1,3,5-tri-α-naphtbylbenzene, marked excess viscosities are found as T_f is approached and traversed. It is quite difficult to cause such melts to crystallize. Normally, they pass smoothly into glasses on sufficient cooling [16, 27].

As a working hypothesis, excess viscosities defined by the Arrhenius equation as norm (with the melt at high temperatures regarded as a free fluid and treated as reference), and other excess properties above those of a normal fluid whose behaviour can be studied, may be interpreted on the hypothesis that transient cluster formation blocks easy configurational rearrangements that involve hopping in the melts.

What is urgently needed is a greater diversity of physical means for examining the structures and local density fluctuations of melts. When the latter are not quasi-crystalline, this can have a close bearing on their freezing and melting behaviour.

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[24] *G. Nemethy* and *H. A. Scheraga*, J. chem. Physics *36*, 3382 (1962).

[25] *A. R. Ubbelohde*: Melting and Crystal Structure. University Press, Oxford 1965.

[26] *A. R. Ubbelohde*, unpublished work.

[27] *E. McLaughlin* and *A. R. Ubbelohde*, Trans. Faraday Soc. *53*, 628 (1957).

Bis-(*p*-hydroxyphenyl)alkylphosphonic Acid Esters and Derived Polycarbonates

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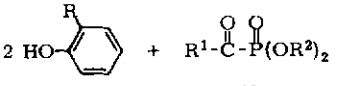
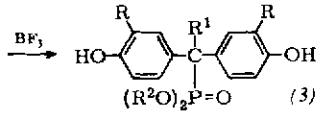
Dialkyl 1-bis-(*p*-hydroxyphenyl)alkylphosphonates *(3)* are made by condensation of the adduct obtained from the phenol *(1)* and BF_3 with dialkyl acylphosphonates *(2)* in a molar ratio of 3:1 to 6:1, cooling being applied to maintain the reaction temperature at 30–40 °C. The same products are also obtained under similar conditions by passing BF_3 into a mixture of *(1)* and *(2)*. When the condensation is complete, the reaction mixture is diluted with acetic acid and poured into water. The crude product crystallizes out and can be recrystallized from methanol/water.



(1) *(2)*

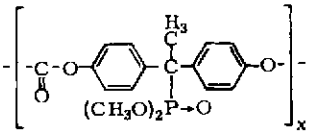


(3)

	R	R^1	R^2	Mp. [°C]	Yield [%]
(3a)	H	CH_3	CH_3	217	70
(3b)	Cl	CH_3	CH_3	213	49
(3c)	Cl	CH_3	C_2H_5	143.5	64
(3d)	H	C_6H_5	CH_3	270	89
(3e)	Cl	C_6H_5	CH_3	259–260	70

If sulfuric or hydrochloric acid is used instead of BF_3, the dialkylacylphosphonate *(2)* is split into the corresponding carboxylic acid and dialkyl phosphite. No condensation takes place with polyphosphoric acid.

Dimethyl 1-bis-(*p*-hydroxyphenyl)ethylphosphonate *(3a)* undergoes a two-phase condensation with phosgene to yield a polycarbonate *(4)*. The compound *(3a)* is dissolved in 0.75 N sodium hydroxide, and triphenylbenzylphosphonium chloride is added as catalyst and dichloromethane as solvent for the polycondensation product to be formed. The mixture is stirred vigorously and a slight excess [based on *(3a)*] of phosgene is passed in. The pH is maintained above 10 throughout the reaction. The resultant polycarbonate *(4)* has an intrinsic viscosity of 0.038 l/g and a molecular weight of 16000; its phosphorus content is 8.9 %.



(4)

Sheets of *(4)* 0.085–0.090 mm thick ignite when held in a Bunsen burner pilot flame 5–6 cm long but cease to burn immediately upon removal from the flame. Films made from the polycarbonate produced from phosgene and 2,2-bis-(*p*-hydroxyphenyl)propane burn out completely under the same conditions.

The phosphorus content of the polycarbonates can be reduced by copolycondensation of *(3)* and 2,2-bis-(*p*-hydroxyphenyl)-propane, but the fire-resistance of the products is reduced correspondingly.

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[1] University Exchange Fellow of the Alexander-von-Humboldt Stiftung 1965.

Synthesis of *N,N'*-Bis(chlorodimethylsilyl)-tetramethylcyclodisilazane [1]

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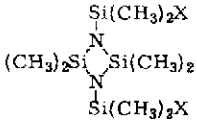
Department of Chemistry,
Harvard University, Cambridge, Mass. (U.S.A.)

1,3-Dichlorotetramethyldisilazane *(2)* [2,3] was hitherto obtainable only in unsatisfactory yields but can now be conveniently prepared in yields of 80 % by refluxing octamethylcyclotetrasilazane *(1)* with an excess of dimethyldichlorosilane (molar ratio 1:5) for 24 h. The product is isolated by subsequent distillation.

$$[-Si(CH_3)_2-NH-]_4 + 4\,(CH_3)_2SiCl \rightarrow 4\,[Cl(CH_3)_2Si]-NH-[Si(CH_3)_2Cl]$$

(1) *(2)*

Compound *(2)* reacts with sodium bistrimethylsilylamide [4] with substitution of one or both chlorine atoms. The products formed are not stable but decompose even at room temperature to hexamethyldisilazane and *N,N'*-bis(chlorodimethylsilyl)tetramethylcyclodisilazane *(3)* or *N,N'*-bis(trimethylsilyl)tetramethylcyclodisilazane *(4)* [5], respectively.



(3), X = Cl
(4), X = CH_3

When a solution of sodium bistrimethylsilylamide in ether is added dropwise to a vigorously stirred solution of *(1)* in petroleum ether at room temperature (molar ratio of the components = 1:1), *(3)* can be secured in yields of up to 70 %. Compound *(3)* forms beautiful colorless crystals, m.p. 70 °C, which can be purified by recrystallization from petroleum ether and sublimation at 55 °C/0.03 mm. The NMR spectrum of a 20 % solution of *(3)* in CCl_4 has only a single sharp proton signal (δ = 0.33 ppm). In benzene, on the other hand, two signals are observed. It appears that the two types of protons present in *(3)* happen to have the same chemical shifts in CCl_4. The structure of *(3)* was proved by elemental analysis, ebullioscopic molecular-weight determinations and by its infrared and mass spectra.

We consider *(3)* to be a potential starting material for the synthesis of polymers containing cyclodisilazane structures.

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[1] This work was supported by the National Science Foundation, Washington, D.C. (U.S.A.).

[2] *H. Kriegsmann* and *G. Engelhardt*, Z. anorg. allg. Chem. *310*, 100, 320 (1961).

[3] *U. Wannagat*, *P. Geymayer*, and *E. Bogusch*, Mh. Chem. *95*, 801 (1964).

[4] *U. Wannagat* and *H. Niederprüm*, Chem. Ber. *94*, 1540 (1961).

[5] *W. Fink*, Chem. Ber. *96*, 1071 (1963).

1,6-Anhydroidose Derivatives with Rings Containing Nitrogen [1]

By Priv.-Doz. Dr. H. Paulsen and Dipl.-Chem. K. Todt

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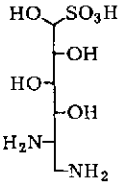
In acidic solution, the piperidinoses obtained from 5-amino sugars are always spontaneously dehydrated to form 3-hydroxypyridine derivatives [2]. We have found that free piperidinoses – in contrast to all other monosaccharides –

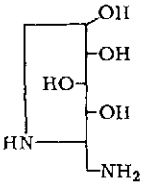
are stable only in alkaline solution and can be prepared only in such media. For instance, the piperidinose *(2)* is obtained from 5,6-diamino-5,6-dideoxy-L-idose-1-sulfonic acid *(1)* [3,4] by cleavage with barium hydroxide in aqueous solution, and is converted spontaneously and quantitatively into the idosan derivative *(3)* comprising two rings containing nitrogen. After deionization and concentration of the solution *(3)* is obtained either as the free base or as its monohydrochloride ($[\alpha]_D^{23} = +58°$, c = 2 in water) in crystalline form. The cyclization is made possible by the amino substituent on the secondary alcohol grouping at C-1 of the piperidinose *(2)*, which facilitates displacement of the hydroxyl group by the more strongly nucleophilic amino group on C-6 of *(2)*. Ring closure is also promoted by the transition to the 1-C conformation, in which all of the hydroxyl groups in *(3)* are in equatorial positions.

The tendency of piperidinoses to react as Mannich bases and to form the 1,6-anhydro ring is also illustrated by the alkaline cleavage of 5-amino-5-deoxy-L-idose-1-sulfonic acid [3]. Conditions analogous to those used for the preparation of *(3)* lead here to the anhydro compound *(4)*, $[\alpha]_D^{23} = +114°$, c = 2 in water. Even 6-amino-6-deoxy-L-idose, whose hydrochloride has long been known [5], can be cyclized with surprising ease to the indosan derivative *(5)* containing nitrogen in the five-membered ring ($[\alpha]_D^{23} = +39°$, c = 2 in water), by mere concentration of the aqueous solution of the free base.

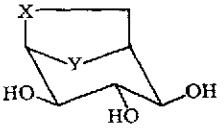
Compounds *(3)* and *(4)* are the first crystalline carbohydrate derivatives containing a free amino group in the glycosidic ring.



(1)



(2)



(3), X = Y = NH
(4), X = O; Y = NH
(5), X = NH; Y = O

Acetylation of *(3)–(5)* with acetic anhydride/pyridine affords the peracetylated derivatives, which can be partially saponified with catalytic amounts of sodium methoxide in methanol to the *N*-acetyl compounds. Free rotation in the latter compounds is hindered by amide mesomerism [6]. The NMR-spectra of the amides of *(4)* and *(5)* indicate that both isomeric forms are present. The coalescence temperature for the signal of the amide with the five-membered ring is 95 °C; that for the signal of the amide with the six-membered ring is 10 °C. The *N,N'*-diacetate of *(3)* contains two amide groups whose free rotations are hindered. Accordingly, four isomers can be detected from the NMR spectrum: the acetylamino signal consists of four peaks which converge to a single line at 95 °C.

The structures of all the compounds made were confirmed by infrared, NMR, and mass spectroscopy.

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[1] Monosaccharides with Rings Containing Nitrogen, Part 7.– Part 6: [3].

[2] *H. Paulsen*, Liebigs Ann. Chem. *665*, 166 (1963).

[3] *H. Paulsen, K. Todt*, and *F. Leupold*, Tetrahedron Letters *1965*, 567.

[4] *H. Paulsen, K. Todt*, and *K. Heyns*, Liebigs Ann. Chem. *679*, 168 (1964).

[5] *H. O. L. Fischer*, J. Amer. chem. Soc. *70*, 1476 (1948); *H. Ohle* and *R. Lichtenstein*, Ber. dtsch. chem. Ges. *63*, 2905 (1930).

[6] *W. A. Szarek, S. Wolfe*, and *J. K. N. Jones*, Tetrahedron Letters *1964*, 2743.

Preparation of Triphenylphosphine from Triphenylphosphine Oxide by Reduction with Boranes

By Dr. R. Köster and Yoshiharu Morita

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Triphenylphosphine oxide can be reduced by boranes, *e.g.* trialkylboranes, alkyldiboranes, or trialkylamineboranes, to give high yields of triphenylphosphine. The reaction with compounds containing BH groups begins a little above 100 °C, but trialkylboranes, *e.g.* triethylborane or tripropylborane, react only above 220 °C.

Equimolar amounts of triphenylphosphine oxide and tetrapropyldiborane rapidly release about 0.5 mole of hydrogen at ca. 120 °C; further 0.5 mole hydrogen is released afterwards, but only slowly. The total amount of gas liberated corresponds to the following transformation of the phosphorus compound.

$$(C_6H_5)_3PO + (R_2BH)_2 \rightarrow (C_6H_5)_3P + R_2BOBR_2 + H_2$$

Dialkylboric acids R_2BOH are formed as intermediates and react immediately with R_2BH to form hydrogen and tetraalkyldiboron oxides

$$(C_6H_5)_3PO + R_2BH \rightarrow (C_6H_5)_3P + R_2BOH$$
$$R_2BOH + R_2BH \rightarrow R_2BOBR_2 + H_2$$

and then undergo ligand exchange to yield in addition alkylboroxines and trialkylboranes.

$$3\ R_2BOBR_2 \xrightarrow{+\ BH} 3\ BR_3 + (RBO)_3$$

Since boron hydrides form various stable adducts with triphenylphosphine, *e.g.* $(C_6H_5)_3P{-}BH_2(C_2H_5)$, m.p. 115 °C, or $(C_6H_5)_3P{-}BH_3$, m.p. 182 °C, complete utilization of the BH entities available for the reduction of the triphenylphosphine oxide occurs only above 180 °C.

$$(C_6H_5)_3P{-}BH_2R + (C_6H_5)_3PO \rightarrow 2\ (C_6H_5)_3P + 1/3(RBO)_3 + H_2$$

If triphenylphosphine oxide and diethylborane are therefore allowed to react in a molar ratio of 1:5 at 120 °C, a quantitative yield of triphenylphosphinylborane is obtained.

$$(C_6H_5)_3PO + 5\ R_2BH \rightarrow (C_6H_5)_3P{-}BH_3 + R_2BOBR_2 + 2\ BR_3 + H_2$$

Trialkylamineboranes $H_3B{-}NR_3$ are also suitable as reducing agents.

$$3(C_6H_5)_3PO + 2\ H_3B{-}NR_3 \rightarrow 3(C_6H_5)_3P + 3\ H_2 + B_2O_3 + 2NR_3$$

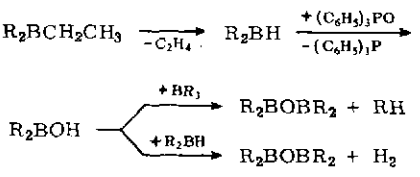
Here the reaction proceeds in steps as indicated by the following equations.

$$3\ (C_6H_5)_3PO + 5\ H_3B{-}NR_3 \xrightarrow{>120°C} 3\ (C_6H_5)_3P{-}BH_3 + 3\ H_2 + B_2O_3 + 5NR_3$$

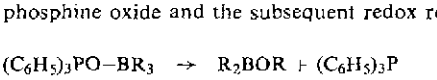
$$3\ (C_6H_5)_3PO + 2\ (C_6H_5)_3P{-}BH_3 \xrightarrow{>180°C} 5\ (C_6H_5)_3P + 3\ H_2 + B_2O_3$$

Triphenylphosphine oxide reacts with trialkylboranes BR_3 only above about 250 °C. However, since the phosphines do not form stable adducts with trialkylboranes the latter are particularly suitable for preparing pure triphenylphosphine from its oxide. This reaction proceeds mainly *via* compounds containing BH groups as intermediates. The rate-determining

step is a dehydroboration (formation of alkene) which is followed by a protonolysis which results in the formation of the alkane alongside a little hydrogen; for example:



The addition of the trialkylboranes onto the triphenylphosphine oxide and the subsequent redox reaction



are insignificant compared with the reactions proceeding *via* the BH compounds.

Preparation of Triphenylphosphine: A mixture of 24.8 g (89.3 mmoles) of triphenylphosphine oxide and 37.5 g (268 mmoles) of tripropylborane is heated for 5 h at about 250 °C in an autoclave of 200 ml capacity; the pressure rises to 38 atm at 250 °C. When the autoclave is cooled (ca. 10 atm at 20 °C) and vented [3.41 l (S.T.P.) exhaust gas (152 mmoles) consisting of 48.8 % propylene, 49.6 % propane, and 1.6 % hydrogen] and the organoboranes are distilled off (ca. 27.5 g, b.p. 30–85 °C/12 mm), 22.5 g or 96.2 % of pure triphenylphosphine, m.p. 81 °C, b.p. 123–125 °C/10^{-3} mm, is obtained.

The reaction of triphenylphosphine oxide with trialkylaluminum compounds R_3Al or dialkylaluminum compounds R_2AlH is not so straightforward since organoaluminum derivatives form adducts with organophosphorus compounds [1]. Despite the redox reactions that occur, the isolation of pure triphenylphosphine is only possible after complete hydrolysis of the organoaluminum components of the reaction mixture.

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[1] *F. Schindler, H. Schmidbaur*, and *G. Jonas*, Angew. Chem. 77, 170 (1965); Angew. Chem. internat. Edit. 4, 153 (1965).

Preparation of Peptides with 3-Pyridyl Esters

By Prof. Dr. E. Taschner and Dr. B. Rzeszotarska
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During peptide syntheses using the *p*-nitrophenyl ester method [1] the reaction mixture finally contains not only the *N*-protected peptide ester desired but also some unchanged *p*-nitrophenyl carbobenzoxyamino ester and the *p*-nitrophenol which has been released during the synthesis. Both are very difficult to separate from the main product.

Following an observation made by *Y. Ueno* et al. [2], we used esters of hydroxypyridines, which are soluble in dilute acids, instead of *p*-nitrophenyl esters. 3-Pyridyl esters are obtained in high yields from the carbobenzoxyamino acids or Cbo-peptides and 3-hydroxypyridine with dicyclohexylcarbodiimide [3] in the form of colorless or yellow oils or waxes.

In order to prepare peptides, 1.1 mmole of the crude 3-pyridyl ester in 2 ml of ethyl acetate is mixed with 1 mmole of another amino ester hydrochloride and 1 mmole of triethylamine and left standing for 16–18 h at 20 °C. The solution is then washed with 5 % $NaHCO_3$, 1 N HCl, or 5 % citric acid in order to remove the excess pyridyl ester and then three to four times with water in order to remove the 3-hydroxypyridine released; the ethyl acetate layer is then dried with $MgSO_4$. After evaporation of the solvent, the required carbobenzoxypeptide ester is obtained in high purity and in good yields.

3-Pyridyl ester	Peptide ester	M.p. [°C] Crude product	Lit. value
Cbo-Ala-3-OPy (94 %) [a]	Cbo-Ala-Gly-OEt (88 %)	94.5–96	97.5–98
Cbo-Gly-3-OPy (81 %)	Cbo-Gly-DL-Phe-OEt (92 %)	85–88	92
Cbo-Phe-3-OPy (95 %)	Cbo-Phe-Phe-OEt (92 %)	130	140
Cbo-Phe-3-OPy (95 %)	Cbo-Phe-Gly-OEt (90 %)	98–107	110–111
Cbo-Gly-Phe-3-OPy (94 %)	Cbo-Gly-DL-Phe-Gly-OEt (50 %)	127–129	132–134
Cbo-Leu-Gly-3-OPy (75 %)	Cbo-DL-Leu-Gly-Gly-O-Et (72 %)	90–92	102

[a] The figures in parentheses give the crude yields.

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[1] *M. Bodanszky*, Nature *175*, 685 (1955); Acta chim. Acad. Sci. hung. *10*, 335 (1957).

[2] *Y. Ueno, T. Takaya*, and *E. Imoto*, Bull. chem. Soc. Japan *37*, 864 (1959).

[3] *M. Bodanszky* and *V. du Vigneaud*, J. Amer. chem. Soc. *81*, 6074 (1959).

Tri(isopropylidene)cyclopropane [1]

By Doz. Dr. G. Köbrich and cand. chem. H. Heinemann

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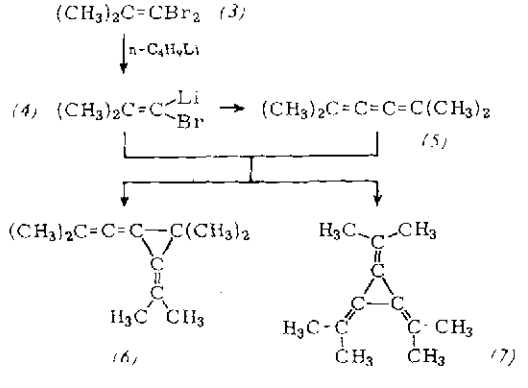
The ring system of trismethylenecyclopropane *(1)*, the lowest member of the class of radialenes *(2)*, is still unknown. A free-valence index of 0.90 was calculated for the parent compound *(1)* using a simple molecular-orbital method; this value indicates a high tendency for *(1)* to polymerize in the condensed state [2].

(1) *(2)*

We have prepared the hexamethyl derivative *(7)* as the first – remarkably stable – representative of the class of compounds *(1)* as follows. Thermal decomposition of α-halogeno-β,β-dialkylvinyl-lithium compounds in tetrahydrofuran gives rise to tetraalkylbutatrienes [3,4], *e.g.* tetramethylbutatriene *(5)* from *(4)* [4]. When, however, carbenoid compounds of type *(4)* are created under conditions where they are unable to dimerize on account of their short lifetime, *e.g.* at elevated temperatures or in diethyl ether [5–7], they can react with



(6) *(7)*

olefins. When both processes are combined by producing some *(4)* from 1 mole of the dibromide *(3)* and 0.63 mole of n-butyl-lithium in tetrahydrofuran at −110 °C [4,8], converting it into the butatriene *(5)* by allowing the solution to warm up to −60 °C, and transforming the residual dibromide *(3)* into the carbenoid *(4)* at the same temperature by adding a further 0.37 mole of n-butyl-lithium, processing of the reaction mixture with exclusion of oxygen affords a 2 % yield of a colorless solid, which crystallizes in needles from ethanol and which forms compact crystals on vacuum sublimation; the latter melt almost without decomposition in an evacuated capillary at 131–132 °C.

Evidence for the structure *(7)* for this compound was derived from its sum formula $C_{12}H_{18}$ (elemental analysis, mass spectrum) and the equivalence of all eighteen protons in its NMR spectrum, which contains only a single sharp peak at −2.01 p.p.m. (tetramethylsilane as internal standard). Hydrogenation of *(7)* over Raney nickel in ethanol at 25 °C led to an uptake of 2.94 moles of hydrogen. The absorption bands in the double-bond region of the infrared spectrum of *(7)* are at relatively low frequencies for a methylenecyclopropane structure [1610 (vs), 1690 (m), and 1710 cm^{-1} (m) in carbon tetrachloride] and its ultraviolet absorption maximum is at a rather long wavelength [λ_{max} = 309.5 mμ; log ε = 4.26 in hexane]; both phenomena are probably due to the conjugation of the three double bonds.

Another reaction product is compound *(6)*, which was identified by comparison of its spectra with those of another sample recently prepared by *Bleiholder* and *Shechter* [7] by a different route.

This first example of a reaction between a butatriene derivative and a carbenoid has prompted us to examine now whether the reaction has general applicability.

The diffraction pattern obtained from the hexagonal crystals of *(7)* in a preliminary X-ray structural analysis carried out by *J. D. Dunitz* and *A. Mugnoli*, Zürich (Switzerland), is compatible with an arrangement of planar or almost planar molecules in layers 3.6 Å apart.

A calculation by *E. Heilbronner*, Zürich, revealed that the long-wavelength maximum in the ultraviolet spectrum of *(7)* is due to a transition that is allowed in *(1)* but forbidden in all radialenes *(2)* with $n \gg 3$.

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[1] Carbon Atoms with Halogeno and Alkali-Metal Substituents, Part X. – Part IX: *G. Köbrich, K. Flory*, and *H. R. Merkle*, Tetrahedron Letters *1965*, 973. Work supported by the Deutsche Forschungsgemeinschaft, the Wirtschaftsministerium des Landes Baden-Württemberg, and the Fonds der Chemischen Industrie.

[2] *J. D. Roberts, A. Streitwieser*, and *C. M. Regan*, J. Amer. chem. Soc. *74*, 4579 (1952); see also *M. J. S. Dewar* and *G. J. Gleicher*, ibid. *87*, 692 (1965)

[3] *G. Köbrich* and *W. Drischel*, Angew. Chem. 77, 95 (1965); Angew. Chem. internat. Edit. *4*, 74 (1965).

[4] *G. Köbrich, W. E. Breckoff, H. Heinemann*, and *A. Akhtar*, J. organomet. Chem., in press (1965).

[5] *M. Tanabe* and *R. A. Walsh*, J. Amer. chem. Soc. *85*, 3522 (1963); *H. D. Hartzler*, ibid. *86*, 526 (1964).

[6] *G. Köbrich* and *W. Drischel*, unpublished results.

[7] *R. F. Bleiholder* and *H. Shechter*, J. Amer. chem. Soc. *86*, 5032 (1964).

[8] *G. Köbrich* and *H. Trapp*, Z. Naturforsch. *18b*, 1125 (1963).

Curtius Reaction with Boron Halides

By Priv.-Doz. Dr. E. Fahr and Dipl.-Chem. L. Neumann [1]

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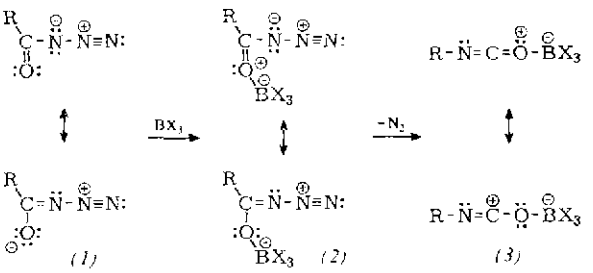
The acyl azides *(1a)–(1f)* react with boron trifluoride or trichloride in toluene at ca. −60 °C to give the adducts *(2a)–(2f)*. The infrared spectra of the adducts in dichloromethane indicate that the BX_3 molecules add onto the carbonyl group, for the azide bands remain unchanged whereas the carbonyl bands are shifted to longer wavelengths (1645–1667 cm^{-1}) [2].



(1) *(2)* *(3)*

(a), R = C_6H_5– *(d)*, R = p-O_2N–C_6H_4–
(b), R = p-H_3CO–C_6H_4– *(e)*, R = m-O_2N–C_6H_4–
(c), R = o-H_3C–C_6H_4– *(f)*, R = p-Cl-m-O_2N–C_6H_3–

When analytically pure, the adducts obtained from *(2a)*, *(2b)*, *(2d)*, and *(2f)* with BF_3 and from *(2a)* and *(2b)* with BCl_3 are colorless to pale yellow crystalline substances. They decompose between −20 and 0 °C by releasing nitrogen and undergoing the Curtius rearrangement to yield the corresponding isocyanate-BX_3 adducts *(3)* [3].

Dichloromethane is used as solvent for the Curtius reaction and the adducts are not isolated. The solution of acyl azide is cooled with solid carbon dioxide/acetone and saturated with BF_3 or BCl_3; it is then warmed up to room temperature, and a little alcohol and twice the volume of the reaction mixture of water are added. The urethane formed can be isolated from the organic phase.

Acyl azide	Yield [%] of urethane [a] from the reaction with BF_3		BCl_3	
	[b]	[c]	[b]	[c]
(1a)	70	66	–	46
(1b)	67	56	–	71
(1c)	94	67	92	68
(1d)	91	81	68	60
(1e)	92	69	77	66
(1f)	100	78	100	76

[a] Based on acyl azide.

[b] Determined by infrared spectroscopy.

[c] Determined by isolation.

If the adduct obtained from benzazide and BF_3 is decomposed in toluene, the C_6H_5–NH–CO– residue formed by the rearrangement substitutes in the benzene ring of the toluene; we therefore obtained *p*-toluylanilide in 29 % yield. On the other hand, decomposition of the adduct made from benzazide and BCl_3 in toluene afforded 89 % *N,N'*-diphenylallophanyl chloride.

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[1] Part of Doctorate Thesis, *L. Neumann*, Universität Würzburg.

[2] An analogous shift was observed by *R. Kreher* and *G. Jäger*, Z. Naturforsch. *20b*, 276 (1965), for the $AlCl_3$ adduct of methyl azidoformate.

[3] Analogously, the temperature of decomposition of diazoketones is also reduced by formation of their BX_3 adducts; cf. *E. Fahr* and *W. D. Hörmann*, Liebigs Ann. Chem. *682*, 48 (1965). – *M. S. Newman* and *H. L. Gildenhorn*, J. Amer. chem. Soc. *70*, 317 (1948), mentioned that acids catalyse the decomposition of acyl azides. They assumed that a proton attacks the nitrogen atom adjacent to the carbonyl group. – The kinetics of the decomposition of acyl azides in the presence of Lewis acids (Fe, Sb, Ti, Te, Sn, Ga, and Al halides) were measured by *R. A. Coleman, M. S. Newman*, and *A. B. Garrett*, J. Amer. chem. Soc. *76*, 4534 (1954) without isolating the adducts.

Preparation of 1,3-Oxazolidines from Isonitriles and Aldehydes by a Multicomponent Reaction

By Prof. Dr. G. Hesse, Dr. H. Witte, and cand. chem. W. Gulden [1]

Institut für Organische Chemie
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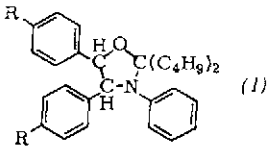
If a mixture of 1 mole of phenyl isonitrile and 2 moles of an aromatic aldehyde in diethyl ether or tetrahydrofuran is added dropwise to 1 mole of tri-n-butylborane, oxazolidine derivatives *(1)* are obtained.



(1)

	Aldehyde	M.p. [°C]	Yield [%]
(1a)	Benzaldehyde	101	72
(1b)	*p*-Chlorobenzaldehyde	136	72
(1c)	*p*-Nitrobenzaldehyde	164	66

The products crystallize after evaporation of the solvent and addition of methanol and are recrystallized from methanol.

Hydrolysis of *(1a)* with 6 N hydrochloric acid in dioxane yielded 58 % di-n-butyl ketone and 82 % *threo*-1,2-diphenyl-2-(*N*-phenylamino)ethanol, m.p. 112 °C; these products clarified the structures of the oxazolidines *(1)*. The NMR spectrum of *(1a)* with tetramethylsilane as internal standard contains an unresolved multiplet at 0.8–2.5 p.p.m. due to the 18 protons of the butyl groups and a signal for 15 aromatic protons at 6.5–7.3 p.p.m. The aliphatic protons on the ring appear as an AB system at 4.75 p.p.m. with $J \approx 8$ c.p.s. The structures of *(1b)* and *(1c)* follow from their elemental compositions, molecular weights, and infrared spectra.

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[1] *W. Gulden*, Diploma Thesis, Universität Erlangen-Nürnberg, 1965.

1,3,5-Tris(di-p-biphenylylmethyl)benzene, a New Triradical

By cand. chem. G. Schmauss, Dr. H. Baumgärtel, and Prof. Dr. H. Zimmermann

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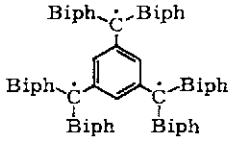
R. Kuhn et al. [1] recently prepared the triradical 1,3,5-tris-(1,5-diphenyl-3-verdazylyl)benzene. We have been working independently on the preparation of carbon triradicals and have synthesized the triple free radical 1,3,5-tris(di-*p*-biphenylylmethyl)benzene *(1)*.



(1), Biph = Biphenyl-4-yl

Treatment of triethyl trimesate with *p*-biphenylyl-lithium in diethyl ether yields 1,3,5-tris(di-*p*-biphenylhydroxymethyl)benzene *(2)* as colorless crystals, m.p. 280–281 °C. When *(2)* is refluxed with acetyl chloride, 1,3,5-tris-[(di-*p*-biphenylyl)chloromethyl]benzene *(3)* is obtained as colorless crystals, m.p. 210–211 °C. Removal of three atoms of chlorine from *(3)* with zinc powder in benzene yields the triradical *(1)* as red-violet crystals, m.p. 205–210 °C (decomp.). Molecular-weight determinations indicated that in benzene, associated molecules are present alongside monomeric triradical molecules.

The triradical *(1)* is extremely sensitive towards oxygen and reacts with chlorine to re-form *(3)*.

The free-radical nature of *(1)* was ascertained by ESR measurements. Spectra taken with the solid and its solutions did not exhibit hyperfine structure on account of interactions among the unpaired electrons. The same situation was encountered with 1,3,5-tris-(1,5-diphenyl-3-verdazylyl)benzene [1].

We also made renewed attempts to prepare the triradical 1,3,5-trisdiphenylmethylbenzene *(4)* [2]. Trisdiphenylchloromethylbenzene *(5)* [2] was treated with sodium in liquid ammonia to give 1,3,5-tris(diphenylsodiomethyl)benzene; the resultant Bordeaux red solution was treated with an equivalent amount of *(5)* in toluene. Sodium chloride was eliminated, giving rise to a yellow product which was isolated from the toluene phase. This product is amorphous to X-rays and has no definite melting point; the results of elemental analyses, molecular-weight determinations, and infrared and ESR-spectra indicate it to be polymeric with composition *(4)* containing varying amounts of toluene. In contrast to the ESR-spectrum of *(1)*, the polymeric product in benzene does exhibit hyperfine structure.

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[1] *R. Kuhn, F. A. Neugebauer*, and *H. Trischmann*, Angew. Chem. 77, 43 (1965); Angew. Chem. internat. Edit. 4, 72 (1965).

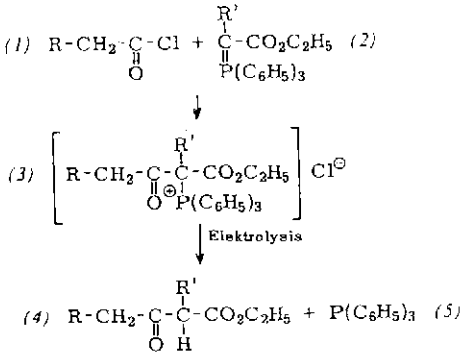
[2] Earlier experiments: *M. Leo*, Ber. dtsch. chem. Ges. 70, 1691 (1937).

A New Synthesis of α-Branched β-Keto Esters

By Prof. Dr. H. J. Bestmann, Dipl.-Chem. G. Graf, and Dr. H. Hartung

Institut für Organische Chemie der Technischen Hochschule München und der Universität Erlangen-Nürnberg (Germany)

The reaction of acyl chlorides *(1)* with alkylidenetriphenylphosphoranes *(2)* in a molar ratio of 1:2 at 65 °C in THF yields allenecarboxylic esters [1], but when equimolar amounts of *(1)* and *(2)* interact between 0 and 20 °C in benzene, the products are phosphonium salts *(3)*. Electrolysis of *(3)* [2] in aqueous solution at a mercury cathode below



R	R'	Yield of *(4)* [%]	Yield of *(5)* [%]	B. p. of *(4)* [°C/mm]
CH_3–	CH_3	77	87	70–71/13
C_3H_7–	CH_3	64	86	93/10
C_5H_{11}–	CH_3	78	93	115/10
$H_3CO_2C(CH_2)_2$–	CH_3	68	84	95–97/0.2
C_6H_5–	CH_3	84	94	99–100/0.4
C_6H_5–CH=CH–	CH_3	70	92	117–120/0.3
C_6H_5–$(CH_2)_2$–	CH_3	73	90	115/0.2
C_5H_{11}–	C_3H_7	50	78	75/0.3
C_6H_5–$(CH_2)_2$–	C_3H_7	40	70	114–116/0.4

35 °C with a voltage of 20–25 V and a current of 1 3 amp produces triphenylphosphine *(5)* and α-branched β-keto esters *(4)*.

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[1] *H. J. Bestmann* and *H. Hartung*, Angew. Chem. *75*, 297 (1963); Angew. Chem. internat. Edit. *2*, 214 (1963).
[2] *L. Horner* and *A. Mentrup*, Liebigs Ann. Chem. *646*, 65 (1961).

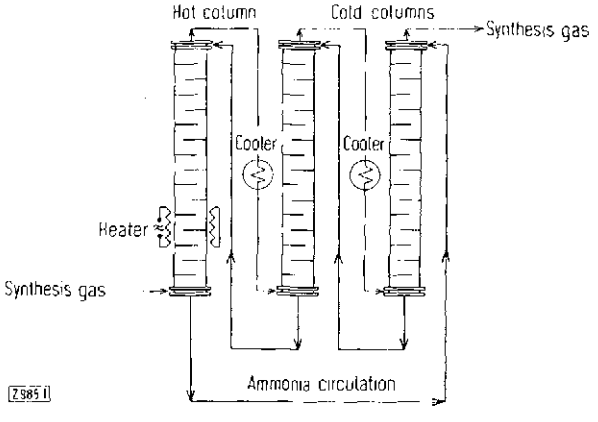
Enrichment of Deuterium by Countercurrent Isotope Exchange between Hydrogen and Ammonia in a Hot-and-Cold Plant

By Dr. S. Walter,
Friedrich Uhde GmbH., Dortmund (Germany)

and Doz. Dr. U. Schindewolf
Institut für Kernverfahrenstechnik der Technischen Hochschule und des Kernforschungszentrums Karlsruhe (Germany)

Heavy water is produced mainly by the hydrogen sulfide process [1] which is based upon the temperature dependence of the isotope exchange equilibrium between hydrogen sulfide and water. Replacement of the system hydrogen sulfide/water by ammonia/water with dissolved potassium amide as catalyst has been frequently proposed [2, 3], since here the isotope exchange is much larger and is more dependent upon the temperature [*] and since here there is the thermodynamically favorable possibility [2] of using hydrogen as starting material. However, no enrichment attempts have been published to date.

Our plant consists of two cold columns in series with a total length of 28 m and a hot column with a total length of 17.5 m (see Figure). The cold columns are cooled by two deep freezers, and the hot column is heated by an electrical heating



element. Each column has an internal diameter 120 mm and contains about 200 sieve plates. The upper and lower plates of the hot column act as direct heat exchangers. Ammonia containing dissolved potassium amide is circulated in the system. Synthesis gas (hydrogen-nitrogen mixture for ammonia synthesis) which is taken directly from the producer plant, is passed through the deuterium enricher, and then on to the consumer. At a pressure of 200 atm and a temperature of 60 °C in the hot column and −20 °C in the cold column, with a potassium amide concentration of 50 g per kg of ammonia, and with a throughput of 450 m³ (S.T.P.) of synthesis gas and 50–100 kg of ammonia per hour, a six- to sevenfold enrichment of the deuterium was achieved in the hydrogen at the top of the hot column and an over twentyfold enrichment in the ammonia, based on the original deuterium content of the hydrogen introduced at the foot of the hot column. The enrichment is expressed by the ratio of the relative deuterium contents in the enriched hydrogen or ammonia and in the original hydrogen, *i.e.* $(n_D/n_H)_{product}$: $(n_D/n_H)_{starting\ hydrogen}$, where n_D and n_H are the mole fractions of HD and H_2, or NH_2D and NH_3, respectively [4].

The degrees of enrichment achieved are in agreement – within the limits of error – with values calculated from laboratory experiments with single sieve plates.

Received: May 19th, 1965 [Z 985/811 IE]
German version: Angew. Chem. 77, 620 (1965)

[1] *W. P. Bebbington* and *V. R. Thayer*, Chem. Engng. Progr. *55*, No. 9, 70 (1959); *W. P. Bebbington, J. F. Proctor, W. C. Scotton*, and *V. R. Thayer*, Third United Nations Internat. Conf. on the Peaceful Uses of Atomic Energy, Geneva 1964, Paper 290.
[2] Cf. for example *E. W. Becker*: Heavy Water Production. Internat. Atomic Energy Agency Rev. Ser. No. 21, Vienna 1962.
[*] Temperature dependence of the ideal enrichment factors $\alpha = (n_D/n_H)_{liq.}/(n_D/n_H)_{gas}$ [4].

T [°C]	α hydrogen/ammonia	α hydrogen sulfide/water
−25	5.1	2.6
0	4.25	2.15
50	3.1	1.9
100	2.4	1.75
150		

[3] *B. Lefrancois, J. M. Lerrat*, and *E. Roth*, Third Internat. Conf. on the Peaceful Uses of Atomic Energy, Geneva 1964, Paper 28/P/91; *R. Haul, H. Ihle*, and *H. Schierholz*, Chem.-Ing.-Techn. *33*, 713 (1961).
[4] The mole fractions n relate to the reactions $HD + NH_3 \rightleftharpoons H_2 + NH_2D$ and $HDS + H_2O \rightleftharpoons H_2S + HDO$ respectively.

The Quaternary Structure of Catalase from Beef Liver

By Dr. K. Weber and Doz. Dr. H. Sund

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der Universität Freiburg/Breisgau (Germany)

Denaturing agents cause catalase (molecular weight *ca.* 250000 [1]) to dissociate into subunits. Depending on the experimental conditions, fractions are obtained with molecular weights which have been found to be one-sixth, one-third, one-half, or two-thirds of that of native catalase [2]. However, in accordance with the iron and heme content of catalase, dissociation into 4 or 4n subunits should be expected.

We succinylated catalase with succinic anhydride according to [3] and obtained a dissociation product which was found to be monodisperse in the analytical ultracentrifuge and still contains bonded heme. Extrapolation to infinite dilution gives a value of 4.4×10^{-7} cm²/sec for the diffusion coefficient $D^{\circ}_{20,w}$ and 3.2×10^{-13} sec^{-1} for the sedimentation coefficient $s^{\circ}_{20,w}$ (measured in 0.067 M potassium sodium phosphate buffer at pH 7.6 and 20 °C). Taking a partial specific volume of 0.73 ml/g [1], the molecular weight of this dissociation product was calculated by the Svedberg formula to be 65000. Succinylation therefore causes dissociation of the catalase molecule into four subunits which according to sedimentation and diffusion measurements are of equal size. This finding is in agreement with the results of electron-microscopic investigations [4]. The action of dodecyl sulfate leads to a dissociation product with the same sedimentation constant.

If it is assumed that each of the four heme groups in the enzyme is located at an active site, then there must be an active site in each of the catalase subunits. The question whether the subunit of molecular weight 65000 is already the polypeptide chain or whether it contains several –

probably different – polypeptide chains cannot yet be answered. Investigations of the amino acid sequence [5] also permit no definite conclusions so far.

Received: May 19th, 1965 [Z 988/814 IE]
German version: Angew. Chem. 77, 621 (1965)

[1] *J. B. Sumner* and *N. Gralén*, J. biol. Chemistry *125*, 33 (1938).

[2] *T. Samejima*, J. Biochem. (Tokyo) *46*, 155, 1101 (1959); *T. Samejima* and *K. Shibata*, Arch. Biochem. Biophysics *93*, 407 (1961); *M. Itoh*, *Y. Nakamura*, and *K. Shibata*, Canad. J. Biochem. Physiol. *40*, 1327 (1962); *C. Tanford* and *R. Lovrien*, J. Amer. chem. Soc. *84*, 1892 (1962); *T. Samejima* and *J. T. Yang*, J. biol. Chemistry *238*, 3256 (1963).

[3] *I. M. Klotz* and *S. Keresztes-Nagy*, Biochemistry *2*, 445 (1963).

[4] Unpublished experiments with *E. Mölbert*.

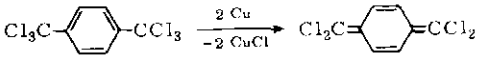
[5] *W. A. Schroeder*, *J. R. Shelton*, *J. B. Shelton*, and *B. M. Olson*, Biochim. biophysica Acta *89*, 47 (1964).

Synthesis and Reactions of α,α,α′,α′-Tetrachloro-p-xylylene

By Dr. H. Gilch [1]

Union Carbide Plastics Division, Research and Development, Bound Brook, N.J. (U.S.A.)

If *p*-bis(trichloromethyl)benzene *(1)* is passed at a pressure of 0.1–1.0 mm over a copper gauze (42 cm² surface area per gram of copper) at 300–600 °C, α,α,α′,α′-tetrachloro-*p*-xylylene *(2)* is formed.



(1) *(2)*

Pressure [mm]	Temp. [°C]	Yield [%] of *(2)*
0.1	300	1
0.1	400	19
0.1	500	92
0.1	600	87
0.3	300	12
0.3	400	22
0.3	500	91
0.3	600	83
1.0	400	35

The cuprous chloride formed can be separated off by cooling the mixture to 250 °C, and the product *(2)* is then passed into toluene which is stirred rapidly at −78 °C. The yellow suspension of *(2)* in toluene obtained is filtered at −78 °C, and the solid residue is crystallized from tetrahydrofuran between 0 and −60 °C. All manipulations must be carried out under nitrogen.

The yellow needles of *(2)* secured in this way can be stored under nitrogen at −78 °C for at least a month. At room temperature they become white and form poly-(α,α,α′,α′-tetrachloro-*p*-xylylene). A 0.0244 M solution of *(2)* in tetrahydrofuran is 50 % polymerized after abont 30 min at 20 °C.

The ultraviolet spectrum of *(2)* in cyclohexane has maxima at 349 mμ (ε = 45000), 331 (26000), 316 (9200), and 247 mμ (6300).

Solvents that are electron donors stabilize *(2)*. A solution of *p*-bis(dimethylamino)benzene in toluene reacts with a solution of *(2)* to form dark blue crystals with a specific resistivity of 4×10^{-8} ohm cm [2], a value of the same order of magnitude as that of the electron donor-acceptor complex obtained from chloranil and *p*-bis(dimethylamino)benzene [3]. Bromine adds onto *(2)* to yield *p*-bis(bromodichloromethyl)benzene, m.p. 130–131 °C.

Nitrogen dioxide and *(2)* react to form *p*-bis(dichloronitromethyl)benzene, m.p. 95 °C. This melting point rises from 95 °C to 105 °C when the compounds is kept for a few weeks at room temperature or heated for a short time at 105 °C, but no change in the infrared spectrum is observed.

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German version: Angew. Chem. 77, 592 (1965)

[1] Present address: Farbenfabriken Bayer AG., Werk Uerdingen, Wissenschaftliches Hauptlaboratorium.

[2] The resistivity measurements were carried out by Dr. *R. W. Kluiber*.

[3] *G. Briegleb*: Elektronen-Donator-Acceptor-Komplexe. Springer Verlag, Berlin 1961, p. 37.

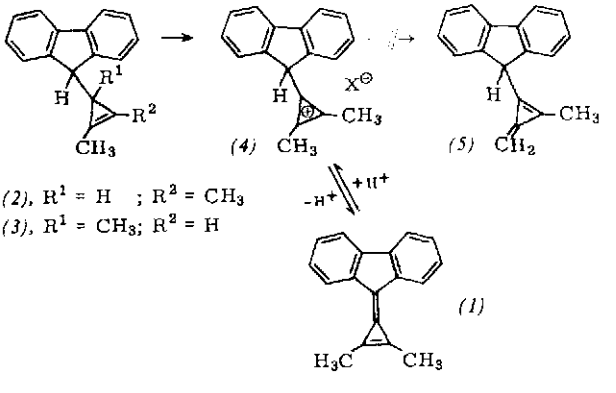
Synthesis and Properties of 5,6-Dimethyldibenzo[*a*,*c*]calicene

By Doz. Dr. H. Prinzbach and Dipl.-Chem. U. Fischer

Chemisches Laboratorium der Universität Freiburg/Breisgau (Germany)

We recently reported the synthesis of 5,6-dimethylbenzo[*a*]-calicene [1], a compound which exists only in dilute solutions. We have now made a crystalline, fairly stable derivative of calicene, namely 5,6-dimethyldibenzo[*a*,*c*]calicene *(1)*, which is suitable for dipole moment measurements and X-ray structural analysis.

The reaction of fluorenyl-lithium (20.0 mmoles) with dimethylcyclopropenium fluoroborate (20.0 mmoles) in ether at −30 °C leads to a 4:1 mixture of the isomers *(2)* and *(3)*. After evaporation of the ether, *(2)* can be obtained in 50–70 % yield in pure form by recrystallization from ethanol (m.p. 121–122.5 °C); its structure is established *inter alia* by its infrared spectrum in KI (low-intensity C=C absorption at 1852 cm⁻¹) and its NMR spectrum in chloroform [multiplet at 2.2–2.9 τ, doublet at 6.46 τ (J = 5.5 cps), singlet at 8.0 τ, doublet at 8.46 τ (J = 5.5 cps) in ratios 8:1:6:1]. Abstraction of a hydride ion from *(2)* to give *(4)* can be achieved quantitatively with trityl fluoroborate [1]. The salt *(4)*, X = BF_4^-, forms light green crystals, m.p. 180–187 °C, with λ_{max} = 261 mμ (ε = 14900) in 70 % $HClO_4$; its NMR spectrum in CF_3COOH has a multiplet at 2.0–2.6 τ, a broad singlet at 4.26 τ, and a singlet at 7.09 τ in ratios of 8:1:6. The proton on C–9′ is exchanged for D within a few minutes in CF_3COOD, but the intensity of the methyl proton resonance signal decreases noticeably only after several days.



In accordance with this observation, mainly (75–80 %) the calicene derivative *(1)* is produced from *(4)* by reaction with water or triethylamine; no *(5)* can be detected.

Compound *(1)* crystallizes from pyridine or dimethyl sulfoxide as pale yellow platelets, m.p. 205–207 °C. Its infrared spectrum contains the strong absorption for the endocyclic cyclopropene C=C bond at 1859 cm⁻¹ plus two other C=C absorptions, *viz.* at 1605 and 1553 cm⁻¹, the latter band being the most intense absorption in the whole spectrum [3]. The NMR spectrum consists of a broad multiplet at 1.90–2.80 τ due to the 8 fluorene protons and a singlet at 7.35 τ for the

two methyl groups. This position of the methyl proton signal is in good agreement with the value calculated for the chemical shift of the methyl protons in a polar 1,1-dicyanodimethyltriafulvene [4]. Differences in the polarity of the solvents used for taking the electronic spectrum of *(1)* influence mainly the long-wavelength region, the fine structure undergoing significant but the positions of the maxima only slight changes: λ_{max} in ethanol = 356 mμ (shoulder, ε = 14000), 325 (22000), 295 (16650), 271 (shoulder, 14000), 262.5 (20600), 247 (28100), 237 (shoulder, 44000), and 233 (46000); λ_{max} in cyclohexane = 353 mμ (ε = 17200), 336 (18600), 325 (18600), 295 (17400), 283.5 (shoulder, 12200), 265 (12100), 258.5 (13600), 254 (shoulder, 15000), 248 (shoulder, 25800), 241 (46500), and 235 (49000).

The solvatochromism observed with the phenyl-substituted analogues of *(1)* [2a] is obviously caused by the phenyl substituents. As expected, even in media of low proton activity, *(1)* is protonated to give *(4)*. It combines with tetracyanoethylene to give a π-complex which crystallizes in blue-black needles from CH_2Cl_2; the complex has λ_{max} at 780 mμ in tetrahydrofuran and at 795 mμ in dichloromethane.

Dimethyldihydrocalicene is obtained in 40% yield by condensation of cyclopentadienylsodium and dimethylcyclopropenium fluoroborate in tetrahydrofuran; attempts to dehydrogenate this compound with benzoquinone derivatives by analogy to the production of sesquifulvalene [5] have so far not led to satisfactory results.

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German version: Angew. Chem. 77, 621 (1965)

[1] *H. Prinzbach, D. Seip,* and *U. Fischer,* Angew. Chem. 77, 258 (1965); Angew. Chem. internat. Edit. 4, 242 (1965). Shortly afterwards, two U.S. research groups [2] reported the synthesis of additional calicene derivatives.

[2a] *W. M. Jones* and *R. S. Pyron,* J. Amer. chem. Soc. 87, 1608 (1965).

[2b] *A. S. Kende* and *P. S. Ito,* J. Amer. chem. Soc. 87, 1609 (1965).

[3] The corresponding band in the spectrum of the vinylogous dibenzosesquifulvalene is only slightly shifted (1577 cm^{-1}): *H. Prinzbach,* Habilitation Thesis, Universität Freiburg, 1962.

[4] *A. S. Kende* and *P. T. Izzo,* J. Amer. chem. Soc. 86, 3587 (1964).

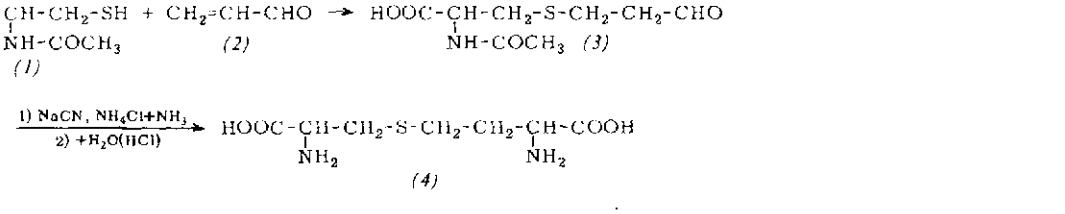
[5] *H. Prinzbach* and *W. Rosswog,* Tetrahedron Letters *1963,* 1217.

A New Synthesis of Cystathionine and Allocystathionine [*]

By Prof. Dr. A. Schöberl and Dipl.-Chem. J. Borchers

Chemisches Institut
der Tierärztlichen Hochschule Hannover (Germany)

Reaction of 1 mole of acrolein *(2)* and 1.25 mole of L-(+)-*N*-acetylcysteine *(1)* [1] in a mixture of pyridine and water at pH 5.5 for 3 h at 55 °C leads to a quantitative yield of the thioether *(3)*. This compound can be subjected without further purification to a Strecker synthesis to produce a mixture of L-cystathionine *(4)* and L-allocystathionine in 43% yield [based on *(1)*].



It is even better to condense *(1)* with acrolein cyanohydrin (1-cyano-1-hydroxyprop-2-ene) [2] at 75 °C. Here, instead of *(3)*, the corresponding cyanohydrin is obtained, which then undergoes the Strecker synthesis to give a 70% yield [based on *(1)*] of a disulfide-free mixture of the cystathionine isomers. This mixture contains equal amounts of L-(+)-cystathionine *(4)* and L-(−)-allocystathionine, which can be purified and separated [3] *via* their dibenzoyl derivatives [m.p. 233 (decomp.) and 186 °C, respectively].

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German version: Angew. Chem. 77, 591 (1965)

[*] This work was supported by the Deutsche Forschungsgemeinschaft.

[1] We wish to thank Dr. *P. Rambacher,* Messrs. Pharmazell, Redenfelden (Germany) for supplying us with this material.

[2] *R. Rambaud,* Bull. Soc. chim. France *1* [5], 1318 (1934); *J. W. E. Glattfeld* and *R. E. Hoen,* J. Amer. chem. Soc. *57,* 1406 (1955).

[3] *A. Schöberl* and *G. Täuber,* Liebigs Ann. Chem. *599,* 140 (1956).

Reinvestigation of the Assumed Homopolar Dissociation of the Sn—Sn Bond

By Prof. Dr. W. P. Neumann,
cand. rer. nat. E. Petersen, and Dr. R. Sommer

Institut für Organische Chemie
der Universität Gießen (Germany)

Free stannyl radicals exist as reactive intermediates [1], can be generated by photolysis of organotin hydrides, and are stable at low temperatures [2].

Cryoscopic determinations of the molecular weights of aliphatic and aromatic distannanes resulted in values lower than the formula weights [3]; it was therefore assumed that homopolar dissociation of the Sn–Sn bond occurred giving rise to free stannyl radicals.

$$R_3Sn\text{-}SnR_3 \rightleftharpoons 2\ R_3Sn\bullet \qquad (a)$$

However, when we measured the molecular weights of hexacyclohexyldistannane and hexaphenyldistannane in a thermistor vapor-pressure osmometer [4], we always obtained the calculated values, even at concentrations as low as 10^{-3} molar in benzene. Hence there cannot be any significant dissociation in the sense of Equation (a). Nevertheless, we confirmed the anomalous cryoscopic results using highly purified distannanes. On the other hand, no dissociation could be detected with the magnetic balance [5], and ESR measurements on our solutions did not indicate any free radicals [6]. These results do not exclude the possibility that dissociation occurs to a slight extent. If this were so, an unsymmetrical distannane should disproportionate slowly, at higher temperatures at least. We therefore prepared pure triethyltrimethyldistannane with careful exclusion of air [7].

$$(CH_3)_3Sn\text{–}N(C_2H_5)_2 + H\text{–}Sn(C_2H_5)_3 \rightarrow (CH_3)_3Sn\text{–}Sn(C_2H_5)_3 + HN(C_2H_5)_2$$

This compound distils without decomposing at 106.5–107 °C/11 mm and is completely homogeneous in gas chromatograms (2 m of PH 300 silicone oil at 190 °C). It is completely unaltered after heating for several hours at 170 °C. Since control experiments revealed that hexaethyldistannane and hexamethyldistannane appear as clearly separated peaks in the gas chromatogram, no disproportionation and hence no dissociation according to Equation (a) can take place.

Above 190 °C, traces of the two symmetrical distannanes begin to appear, but so do tetraethyltin and tetramethyltin. In addition, some elemental tin is deposited, hence the reaction at 190 °C is not a well defined disproportionation but a drastic decomposition.

Analogously, the two symmetrical distannanes can be mixed and heated without formation of unsymmetrical distannane in more than trace amounts.

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German version: Angew. Chem. 77, 622 (1965)

[1] Review: *W. P. Neumann*, Angew. Chem. *76*, 849 (1964).

[2] *U. Schmidt, K. H. Kabitzke, K. Markau*, and *W. P. Neumann*, Chem. Ber., in press.

[3] Reviewed in *E. Krause* and *A. von Grosse*: Die Chemie der metallorganischen Verbindungen. Verlag Gebrüder Borntraeger, Berlin 1937. *R. K. Ingham, S. D. Rosenberg*, and *H. Gilman*, Chem. Rev. *60*, 459 (1960).

[4] Mechrolab 301 A instrument, temperature = 37 °C.

[5] *H. Morris* and *P. W. Selwood*, J. Amer. chem. Soc. *63*, 2509 (1941); *64*, 1727 (1942); however, the purity and even the identity of the hexa-(*o*-tolyl)distannane used are uncertain. Instead of m.p. 298 to 300 °C [*H. Gilman* and *S. D. Rosenberg*, J. org. Chemistry *18*, 1554 (1953)], a value of 208–210 °C is given.

[6] We wish to thank Dr. *G. von Foerster*, Gießen (Germany) for making the ESR measurements.

[7] *R. Sommer, W. P. Neumann*, and *B. Schneider*, Tetrahedron Letters *1964*, 3875.

Reaction of Organolithium Compounds with Silicon Dioxide

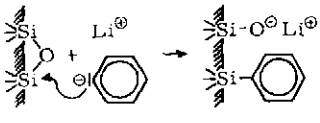
By Doz. Dr. H. P. Boehm, Dr. M. Schneider, and Dipl.-Chem. H. Wistuba

Anorganisch-Chemisches Institut
der Universität Heidelberg (Germany)

Treatment of finely divided silicon dioxide (Aerosil or silica gel) with solutions of lithium alkyls or aryls in ether produces organosilicon compounds. The reaction mixture is refluxed for about 8 h, filtered, and washed with 2 N HCl and water; the ether is then driven off on a steam bath, and the residual oil is dissolved in a little benzene and fractionated by precipitation with acetone.

The following compounds obtained in this way from phenyllithium were identified in the reaction products: tetraphenylsilane (melting point and mixed melting point 235 °C; infrared spectrum [1]), triphenylsilanol, diphenylsilandiol, and polymeric phenylsilicones (by infrared spectroscopy). The infrared spectra of the products obtained with butyllithium indicated the presence of hexa-n-butylcyclotrisiloxane, probably octa-n-butylcyclotetrasiloxane, and long-chain polymers.

The reaction can be interpreted as a nucleophilic attack of the siloxane bonds lying on the surface of the SiO_2 lattice analogous to the cleavage of Si–O–Si bonds by alkali hydroxides. The reaction proceeds mainly to SiR_4, even



though $Si(OH)_2R_2$ compounds should be favored statistically. This appears to be due to the influence of the first substituents introduced upon the electron density on the silicon atoms. An effect of this kind has already been observed by *Gilman* et al. [2] during the nucleophilic cleavage of hexaaryldisiloxanes.

In contrast to the findings of *Kautsky* and *Bartocha* [3], no reaction occurred with Grignard reagents.

The yield of organosilicon compounds is normally low (corresponding to about 30–40 mg of SiO_2 per g of Aerosil). The reaction stops as soon as the surface of the SiO_2 particles is covered with organic substituents and $\rangle Si-O^{\ominus}Li^{\oplus}$ groups. The amount of silicon solubilized corresponds approximately to the number of surface silicon atoms. Aerosil is attacked most strongly by butyl-lithium, but only very minute amounts of organosilicon compounds are formed by methyl-lithium. After thorough washing following the reaction, the residual Aerosil contains 40–100 meq. of phenyl or n-butyl groups on its surface per 100 g of SiO_2, depending on its specific surface area. Phenylated Aerosil is hydrophobic and exhibits an infrared absorption band at 1435 cm^{-1} [4].

Received: May 24th, 1965 [Z 989/815 IE]
German version: Angew. Chem. 77, 622 (1965)

[1] We wish to thank Prof. *W. Noll* and Dr. *Meise*, Leverkusen (Germany) for measuring and interpreting the infrared spectra.

[2] *H. Gilman, H. N. Benedict*, and *H. Hertzfeld*, J. org. Chemistry *19*, 419 (1954).

[3] *H. Kautsky* and *B. Bartocha*, Z. Naturforsch. *10b*, 422 (1955).

[4] *H. P. Boehm* and *M. Schneider*, Z. anorg. allg. Chem. *301*, 326 (1959).

Aluminum-Arene Complexes

By Dr. H. Lehmkuhl [1]

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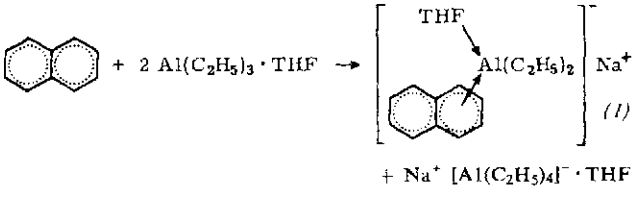
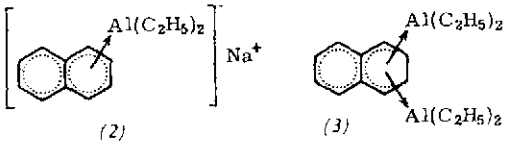
Mülheim/Ruhr (Germany)

Treatment of 2 moles of triethylaluminum with 2 moles of sodium in tetrahydrofuran (THF) at 20–30 °C in the presence of 1 mole of naphthalene results in deep yellow-brown solutions from which diethylaluminonaphthalenesodium *(1)* precipitates as its tetrahydrofuran adduct in the form of bright yellow crystals in about 75 % yield.



Sodium tetraethylaluminate is formed as by-product; no metallic aluminum is deposited. Corresponding complexes are also obtained with Li or K. When heated at 60–80 °C/ 10^{-3} mm, *(1)* releases THF and is converted into deep yellow *(2)*.



Compounds *(1)* and *(2)* give no ESR signal. Alcoholysis of *(1)* and *(2)* produces ethane in the theoretical amount together with 1,2-dihydronaphthalene and a little 1,4-dihydronaphthalene. Oxidation with dry oxygen yields only naphthalene from the aromatic part of the molecule.

The reaction of *(2)* with diethylaluminum chloride affords bisdiethylaluminumnaphthalene *(3)*, which decomposes already at 20 °C with separation of aluminum.

In THF, the stable bistetrahydrofuran adduct of *(3)* is formed; it is a deep yellow liquid which on alcoholysis yields 1,2-dihydronaphthalene plus a little 1,4-dihydronaphthalene. Oxidation of this liquid with oxygen gives naphthalene; this suggests that *(3)* and its bis-THF adduct are ion-pair com-

pounds of the naphthalene dianion and two $[AlEt_2]^{\oplus}$ or two $[THF{\rightarrow}AlEt_2]^{\oplus}$ cations and not derivatives of dihydronaphthalene. They can be only slightly dissociated, however, for the specific conductance of a 0.5 M solution of the THF adduct of *(3)* in THF is 1.3×10^{-5} ohm^{-1}/cm at 20 °C, whereas that of a 0.5 M solution of *(1)* is 1.1×10^{-3} ohm^{-1}/cm.

Compounds corresponding to the THF adduct of *(3)* can be obtained by dehalogenation of Et_2AlCl or $EtAlCl_2$ with solutions of alkali metal arenes (*e.g.* anthracenesodium or naphthalenelithium) in ethers (*e.g.* THF or dimethyl ether). The THF adduct of bisdiethylaluminobiphenyl obtained from sodium biphenyl and $Et_2AlCl{\leftarrow}THF$ decomposes at 20 °C/15 mm with release of biphenyl. A free $Et_2Al{\leftarrow}THF$ radical, which becomes stabilized by disproportionation to form aluminum, THF, and $Et_3Al{\leftarrow}THF$, is formed as an intermediate in this reaction.

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German version: Angew. Chem. 77, 623 (1965)

[1] Experimental work in collaboration with *H. Nehl.*

Synthesis of 2,4-Dinitrophenyl α- and β-*O*-Glycosides

By Dipl.-Chem. W. Hengstenberg and Prof. Dr. K. Wallenfels

Chemisches Laboratorium
der Universität Freiburg/Breisgau (Germany)

2,4-Dinitrophenyl glycosides were previously known only in the form of acetylated derivatives [1] since the very labile 2,4-dinitrophenyl-*O*-glycosidic bond cannot withstand acidic or basic deacetylation.

We have prepared free 2,4-dinitrophenyl glycosides in the following manner. Ethyl thioglycosides are protected according to *Bently* et al. [2] with a trimethylsilyl group, which is easy to remove by hydrolysis. The ethylthio residue is then replaced by a bromo substituent by treatment of the protected glycosides with bromine in carbon tetrachloride [3]. The sirupy trimethylsilylated bromohexose obtained is converted into the glycoside of 2,4-dinitrophenol with silver oxide according to *Koenigs* and *Knorr* [4]. The trimethylsily groups can then be removed with a mixture of methanol water, and glacial acetic acid (20:20:1 v/v) at room temperature. The excess 2,4-dinitrophenol is separated by chromatography on silica gel with benzene as eluant. The 2,4-dinitrophenyl glycoside is then eluted with ethyl acetate.

The anomers of the 2,4-dinitrophenyl glycosides can be separated by thin-layer chromatography with benzene/methanol (2:1 v/v) as solvent or by column chromatography on silica gel with ethyl acetate as eluant.

2,4-Dinitrophenyl glycoside	M.p. [°C] (decomp.)	Yield [%] [a]	$[\alpha]_D^{22}$
α-D-Galactoside	158	22	+322°, c = 0.66 [c]
β-D-Galactoside	150–151	22	−105°, c = 1.0 [c]
β-D-Glucoside [b]	100–101	10	−92.8°, c = 1.06 [c]
α-D-Mannoside	149	28	+161°, c = 1.0 [c]
α-L-Arabinoside	167	32	−103°, c = 1.05 [d]
β-L-Arabinoside	158	32	+367°, c = 0.96 [d]

[a] Based on the amount of ethyl thioglycoside taken.
[b] Crystals contain 1 mole of acetone.
[c] In methanol.
[d] In dimethylformamide.

2,4-Dintitrophenyl β-D-galactoside and 2,4-dinitrophenyl α-L-arabinoside are both split rapidly by the β-galactosidase from *Escherichia coli*. 2,4-Dinitrophenyl β-D-glucoside is also a substrate – albeit a very poor one – for this crystalline β-galactosidase. 2,4-Dinitrophenyl α-D-galactoside is a substrate only of the α-galactosidase from coffee beans. Dilute alkali hydrolyses all the glycosides listed in the table.

Received: May 31st, 1965 [Z 993/821 IE]
German version: Angew. Chem. 77, 623 (1965)

[1] *H. G. Latham, I. R. E. L. May*, and *E. Mosettig*, J. org. Chemistry *15*, 884 (1950).

[2] *C. C. Sweeley, R. Bentley, M. Makita*, and *W. W. Wells*, J. Amer. chem. Soc. *85*, 2497 (1963).

[3] *W. A. Bonner*, J. Amer. chem. Soc. *70*, 770, 3491 (1948); *F. Weygand* and *H. Ziemann*, Liebigs Ann. Chem. *657*, 179 (1962).

[4] *W. Koenigs* and *E. Knorr*, Ber. dtsch. chem. Ges. *34*, 957 (1901).

CONFERENCE REPORTS

International Symposium on Thermal Analysis

On April 13th and 14th, 1965, the Chemistry Department of the Northern Polytechnic in London (England) arranged a Symposium on Thermal Analysis.

From the lectures:

Differential Thermal Analysis of Polymer Dissolution

D. A. Blackadder and *H. M. Schleinitz*, Camhridge (England)

Polyethylene precipitated from a dilute solution crystallizes in thin diamond-shaped lamellae whose thickness increases regularly with temperature of crystallisation. Annealing crystals in a solvent at a temperature between the crystallization and melting temperatures causes partial dissolution starting at the crystal edges and subsequent reprecipitation on the same sites at a thickness characteristic of the annealing temperature. The melting or dissolution temperature is dependent upon the thickness and consequently upon the thermal history of the crystals.

Differential thermal analysis at low heating rates was applied to suspensions of polyethylene single crystals in various solvents. The melting point of the crystals increases monotonically with the temperature of crystallization. It was found that crystals prepared at lower temperatures anneal to a greater extent and at a greater rate than those prepared at higher temperatures. Samples annealed for short times showed a multiplicity of peaks characteristic of both the original crystallization temperature and the annealing temperature. The implication is that under annealing conditions the crystals do not thicken regularly. Either some crystals thicken as expected and others not at all, or else only parts of each crystal thicken. Electron microscopy revealed that the latter interpretation is correct.

Simultaneous Thermogravimetric and Differential Thermal Analysis of the Decomposition of Chromates and Dichromates

E. L. Charlsley and *J. P. Redfern*, London (England)

Thermal decompositions can be studied by thermogravimetric analysis (TGA), but the results often must be supplemented with other data, notably from differential thermal analysis

(DTA). Correlation of the two sets of data often is difficult, since the instruments used normally do not employ the same experimental conditions. A Stanton HT–D thermobalance was therefore modified to enable simultaneous DTA and TGA measurements to be made.

With this instrument, the thermal decompositions of numerous chromates and dichromates were investigated, where the following reactions occur (among others):

$$M_xCrO_4 \cdot n\ H_2O\ (s) \rightarrow M_xCrO_4\ (s) + n\ H_2O\ (g) \quad (1)$$

[x = 1 or 2]

This reaction may be multi-stage.

$$M_xCrO_4\ (s) \rightarrow M_xCrO_4\ (l) \quad (2a)$$

$$2\ M_xCrO_4\ (s) \rightarrow 2\ M_xO \cdot Cr_2O_3\ (s) + 3/2\ O_2\ (g) \quad (2b)$$

$$2\ M_xO \cdot Cr_2O_3\ (s) \rightarrow M_xO \cdot Cr_2O_3\ (s) + M_xO\ (s) \quad (3a)$$

$$2\ M_xO \cdot Cr_2O_3\ (s) \rightarrow 2\ M_xO\ (s) + Cr_2O_3\ (s) \quad (3b)$$

These reactions may be simultaneous to or even precede reaction 2(b)

$$M^{II}OCr_2O_3\ (s) + MO\ (s) \rightarrow M_2^{I}Cr_2O_4\ (s) + {}^1/_2\ O_2\ (g) \quad (4)$$

Thermal Analysis of Inorganic Azides

H. Rosenwasser and *O. F. Kezer*, Fort Belvoir, Virginia (U.S.A.)

The reaction of rare earth sesquioxides with hydrazoic acid yields basic azides. These compounds containing the elements from lanthanum through dysprosium in the lanthanide series have a metal to nitrogen ratio of 1:6 and may be formulated as $Ln(OH)(N_3)_2 \cdot 1{,}5\ H_2O$, whereas the heavier lanthanide elements (and yttrium) form compounds with lower azide contents, which fit the formula $Ln_2(OH)_5N_3 \cdot H_2O$. Infrared spectra, however, indicate that the compounds have an oxo-structure.

These compounds were studied by means of differential thermal analysis. In general, the thermograms show the endothermic peaks caused by loss of water, and exothermic peaks due to the conversion of azide groups to nitrogen molecules. Both processes sometimes occur simultaneously. From thermogravimetric analyses, an oxyazide and an oxyhydroxide are postulated as intermediates in the decompositions.

Although the thermal decomposition of the basic azides of lanthanum and praseodymium proceeds smoothly in air, the reactions taking place in vacuum often lead to explosions. Studies with a DuPont micro-DTA unit show the effect of heating rate as a factor in determining whether or not the samples will explode. Information recorded on the thermograms includes crystalline phase transitions, melting points, and decomposition of the azide ions. In the case of thallium azide, a crystal structure change has been indicated for the first time.

Thermal Analysis of Poly-(m-Aminostyrene) and Related Polymers

R. H. Still and *C. J. Keattch*, Hatfield and Boreham Wood (England)

m-Aminostyrene was homopolymerized using two different concentrations of α,α'-azobisisobutyronitrile to yield two homopolymers *(1)* and *(2)* of differing molecular weight. Copolymerization with styrene yielded a 2:1 copolymer *(3)* (2 moles styrene : 1 mole *m*-aminostyrene). Acetylation of these polymers yielded poly-(*m*-acetamidostyrene) *(4)* and *(5)*, and the corresponding 2:1 copolymer *(6)*. These substances were studied by TGA in static air. The homopolymers *(1)* and *(2)*, owing to the presence of amino groups, are thermally more stable than polystyrene, but the copolymer *(3)* showed no enhanced thermal stability.

An acetamido group in the *meta* position of styrene increases the thermal stability of the resultant homopolymers *(4)* and *(5)* to a lesser degree than an amino group does, whereas the acetylated copolymer *(6)* has a thermal stability similar to that of the acetylated homopolymers *(4)* and *(5)* but shows enhanced thermal stability over the amino copolymer *(3)*. The molecular weight apparently has no effect upon the thermal stability. On pyrolysis in nitrogen, practically no difference was found for the polymers *(1)*, *(5)*, and *(6)* from the pyrolysis in air.

Thermogravimetric Analysis of Oxides

H. Uwents, Drogenlos (Belgium)

The reduction of simple oxides in a hydrogen atmosphere or hydrogen stream using a thermobalance allows their stoichiometry to be determined.

This method was extended to mixtures of a non-volatile (A_mO_x) and a volatile (B_nO_y) oxide. After preparation under conditions (calcination at high temperature) where partial evaporation of the volatile compound could be expected, the composition of the final product was determined by the following procedure: The weight loss on reduction gave the total amount of oxygen bound in the mixture. From the weight of the residue the total quantity of metal (A+B) became known. In a separate run the volatile oxide B_nO_y was evaporated at high temperature under vacuum. The subsequent reduction of the residue gave the amount of the metal A. The quantity of the metal B was calculated by difference.

When the oxides form a solid compound ($A_pB_qO_z$), an excess of the volatile oxide can be removed at high temperature and atmospheric pressure. Subsequent reduction of the residue gives the amount of the combined metallic components (A_pB_q). The oxygen content of the combination $A_pB_qO_z$ is obtained by the weight loss during reduction. Finally the amount of component A is determined as decribed above.

[VB 922/229 IE]

German version: Angew. Chem. 77, 592 (1965)

Microanalytical Redox Titrations

J. Zýka, Prague (Czechoslovakia)

Suitable solutions for redox microtitrations include lead(IV) acetate in glacial acetic as an oxidizing agent and hydrazine sulfate or hydroquinone as reducing agents. The redox potentials of other solutions can be shifted by combining the oxidized or reduced form of the reagent in a complex or sparingly soluble product. Examples of this are titrations with iron(II) sulfate in triethanolamine [1]. Under alkaline conditions and in the presence of triethanolamine, iron(II) sulfate is a strong reducing agent. Compounds of trivalent manganese, copper(II) and bismuth(III) salts, as well as dichromates and tellurates can be titrated directly. The titration of dichromate by this method is more sensitive than in acid solution. It is suitable for the microdetermination of dichromate in the presence of vanadate(V) which is not reduced under these conditions. Tellurates can be determined in the presence of tellurites and compounds of four- and six-valent selenium. The method can also be used for the potentiometric microdetermination of aromatic nitro groups (reduction to NH_2 groups) and of nitroso and azo compounds.

[Österreichische Gesellschaft für Mikrochemie und Analytische Chemie, Leoben (Austria), January 29th and 30th, 1965] [VB 912/220 IE]

German version: Angew. Chem. 77, 626 (1965)

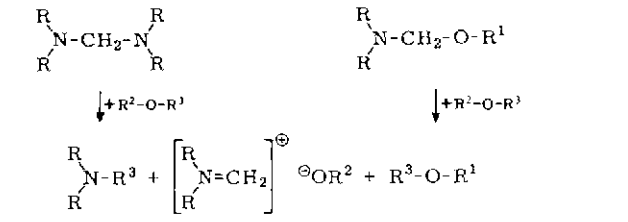
[1] *J. Doležal, E. Lukšyte, V. Rybáček*, and *J. Zýka*, Coll. czechoslov. chem. Commun. *29*, 2597 (1964).

New Cleavage Reactions of Methylenediamine Derivatives and α-Dialkylamino Ethers

H. Böhme, Marburg/Lahn (Germany)

α-Halogenated amines are formed by cleavage of aminals with acid halides. Analogously, *N,N,N',N'*-tetraalkylmethylenediamines react with sulfonic anhydrides to yield dialkylmethyleneimonium sulfonates and dialkylsulfonamides. Tetraethyl pyrophosphate reacts with aminals or α-dialkylamino ethers to produce carbimonium salts of diethylphosphoric acid and phosphoric ester amide or triester. The carbimonium salts of diethylphosphorous acid, formed from tetraethyl pyrophosphite, undergo a Michaelis-Arbusow rearrangement, whereby dialkylaminomethylphosphonic esters can be isolated.

If mixed anhydrides are used for the cleavage reaction, the imonium salt of the stronger acid present in the anhydride is formed, together with the amide or ester of the weaker acid.

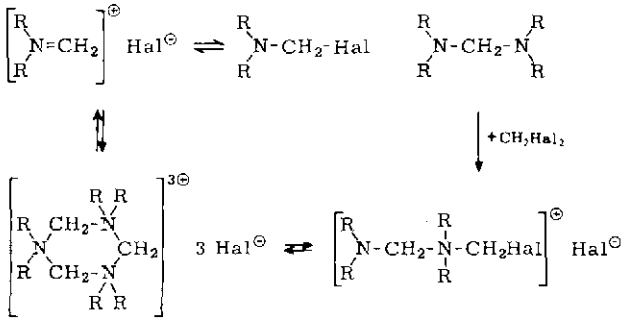


R, R^1 = Alkyl

R^2, R^3 = R-CO-, R-SO_2-, R-SO-, $(RO)_2PO$-, $(RO)_2P$-

On the other hand, the reactions of acetyl nitrate with aminals yield dialkylnitramines and acetoxymethyldialkylamines which are also obtainable by cleavage of aminals with carboxylic anhydrides. When the reaction is carried out using the mixed anhydride of acetic and formic acids, the primary product α-formyloxymethyldialkylamine is decarboxylated even at −20 °C and methyldialkylamine is formed.

Carbimonium halides which are usually considered to be α-halogenated amines, on heating or on recrystallization from aprotic polar solvents, yield dimers and trimers which are also formed in the reaction of methylenediamine derivatives with methylene halides. Contrary to the monomers, the dimers and trimers do not possess the band of the C=N double bond in the infrared spectrum at 5.95 μ.



[GDCh-Ortsverband Süd-Württemberg, Tübingen (Germany), February 19th, 1965] [VB 916/218 IE]

German version: Angew. Chem. 77, 594 (1965)

The Bond Character in Aromatic Phosphorus Compounds – a Contribution to the Problem of the Existence and Properties of $p_\pi-d_\pi$ Bonds

G. P. Schiemenz, Kiel (Germany)

The participation of vacant d-orbitals of the valence electron shell of hetero-atoms of the fifth main group in aromatic π-bonding systems ($p_\pi-d_\pi$ bond) can be expected, according to theory, to be most pronounced for phosphorus. This is the case particularly if the phosphorus carries a positive charge. Three models were discussed for phosphonium salts containing one to four *p*-dimethylaminophenyl groups, and for phosphine oxides, phosphine sulfides, and phosphines with one to three *p*-dimethylaminophenyl groups:

1. No participation of phosphorus d-orbitals.

2. Participation of a phosphorus d-orbital, with conjugation across the phosphorus atom.

3. Participation of a phosphorus d-orbital, the phosphorus atom inhibiting conjugation.

The ultraviolet absorption of all compounds investigated could not be explained on the basis of models 1 and 2 or of a model which had previously been suggested by other authors [1]. On the other hand, all predictions based on the third model were found to be verified in the ultraviolet and infrared spectra. An acceptor effect of phosphorus was found experimentally which is greater than that of a CN group in the salts, and which is nearly equal to CN in the phosphines, oxides and sulfides. Increase of the electron density at the phosphorus atom (replacement of C_6H_5 by CH_3; solvation of the phosphonium group; comparison of the phosphines, oxides, and sulfides with onium salts) lessens the acceptor effect. As borne out by the infrared spectra of the oxides and sulfides, the same holds for the $p_\pi-d_\pi$ character of the P=O and P=S bonds: the frequency and intensity of the PO- and PS-valence vibrations decrease (as would be expected according to model 3) with an increase of the donor effect acting on the phosphorus.

The acceptor effect is not unambiguously discernible in compounds with unsubstituted phenyl groups; however, the small participation of the phosphorus 3p-orbital in the aromatic π-bond systems of triphenylphosphine may be caused by a counteraction of 3p- and 3d-orbital participation. As strong electron donors demonstrated the participation of 3d-orbitals, it seemed possible that 3p-orbital participation would be detected after introduction of strong acceptor substituents. This was in fact the case, as indicated hy the properties of the phosphines $(C_6H_5)_2P-C_6H_4-A(p)$, where A = NO_2, CN, CHO, $COOCH_3$, COOH, $CON(CH_3)_2$, or $CONH_2$.

[GDCh-Ortsverband Kiel (Germany), February 25th, 1965] [VB 917/216 IE]

German version: Angew. Chem. 77, 593 (1965)

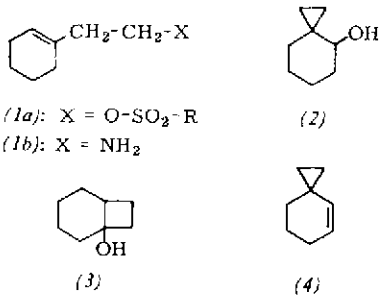
Cyclopropane and Cyclobutane Derivatives by Rearrangement of Unsaturated Compounds

M. Hanack, Tübingen (Germany)

Open-chain homoallyl compounds are isomerized smoothly to cyclopropylmethyl compounds, hut yields are lower in the case of cyclic homoallyl compounds. Here, the primarily formed homoallyl cations are partly stabilized by hydride shift. Thus, cyclohexen-4-yl tosylate is isomerized to an extent of only 10 % during acetolysis to yield the stereoisomeric bicyclo[3.1.0]hex-2-yl acetates. On hydrolysis, cyclopenten-4-yl sulfonates yield 40 % cyclopenten-4-ol and 60 % cyclopenten-3-ol. Similarly, the reaction of 4-bromocyclopentene with Ag_2O in water, proceeding by an S_N1-mechanism, does not result in a bicyclic compound. The reduction of cyclopenten-4-yl sulfonate with $LiAlH_4$, on the other hand, yields 4 % bicyclopentane, together with other hydrocarbons.

On hydrolysis, 2-(cyclohexen-1-yl)ethyl sulfonates *(1a)* isomerize, as does 2-(cyclohexen-1-yl)ethylamine *(1b)* during deamination with nitrous acid, to form spiro[2.5]octan-4-ol *(2)* and bicyclo[4.2.0]octan-1-ol *(3)*; both alcohols can thus he obtained in high yield.

[1] *H. Goetz*, Angew. Chem. *75*, 675 (1963); Angew. Chem. internat. Edit. *2*, 552, (1963).



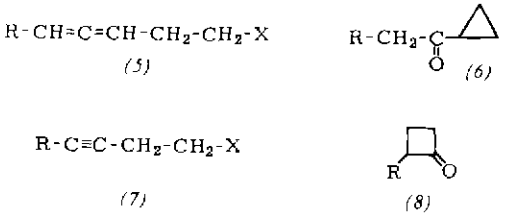
(1a): X = O-SO_2-R
(1b): X = NH_2

(2)

(3)

(4)

On the other hand, 2-(cyclopenten-1-yl)ethylamine and cyclopenten-1-yl tosylate, on deamination or hydrolysis respectively, afford predominantly bicyclo[3.2.0]heptan-1-ol. Derivatives of bicyclo[4,2,0]octan-1-ols *(3)* behave anomalously: the *p*-nitrobenzoate yields, both on pyrolysis and by elimination reactions with strong bases, mainly spiro[2,5]oct-4-ene *(4)*.



(5)

(6)

(7)

(8)

Allenes (such as *(5)*, X=OSO_2R or NH_2) also rearrange readily during solvolysis reactions to give cyclopropane derivatives in good yields. These reactions may be compared to homoallyl rearrangements and afford alkyl cyclopropyl ketones *(6)*. In strongly ionizing solvents, acetylenes such as *(7)* can be cyclized with formation of cyclobutanones *(8)*.

[GDCh-Ortsverband Freiburg-Südbaden (Germany), February 26th, 1965] [VB 919/225 IE]
German version: Angew. Chem. 77, 624 (1965)

Interactions of Plasticizers with Poly(vinyl chloride)

H. Luther, Clausthal (Germany)

The interactions of plasticizers with poly(vinyl chloride) (PVC) were studied by infrared spectroscopy [1], NMR and dielectric measurements [2] on the pure substances and their solutions, microscopic observation of the swelling of PVC in individual plasticizers and mixtures of plasticizers [3]; viscometric measurements of the solubility of PVC in plasticizers using a rotation viscometer and the plastograph [4], infrared spectroscopical observation of plasticizer separation [5] and diffusion [6].

Plasticizers do not form associates of definite stoichiometric composition with PVC but simply dissolve in the polymer. Chloroform/plasticizer mixtures can serve as model systems of low molecular weight; their heats of mixing are determined from the shifts in the infrared bands of the plasticizers on alteration of the concentration.

The solubility of PVC in esters of plasticizers with aliphatic alcohols is greatest when the alcohols contain 3–4 carbon atoms. NMR spectra reveal that the good solubility is due to dissociation of intramolecular associates of the esters as the chain length of the alcohol component increases, for the PVC can then undergo intermolecular association with the ester. However, as the chain length increases, the intermolecular association is again suppressed.

When mixtures of plasticizers are used, the interactions among them determine their solvent powers. The Flory-Huggins interaction parameters do not reflect this situation satisfactorily. The measured (apparent) diffusion coefficients of plasticizers in PVC exhibit a large discontinuity in the glass transition range but are only slightly dependent upon the concentration beyond this range, being proportional to the vapor pressure of the plasticizer at the temperature of the experiment. This proportionality can be explained by the fact that the limiting conditions assumed for measurements of the diffusion of plasticizers out of plasticized PVC plates are seldom fulfilled. The diffusion of the plasticizer is generally overlapped by processes that occur during the drying of a porous system and which depend on the vapor pressure of the volatile components.

A theory developed by *G. Kanig* [7] for the glass temperature of plasticized polymers can account satisfactorily for some of the values so far found by experiment and thus forms a good starting point for further research.

[GDCh-Ortsverband Mülheim/Ruhr, Mülheim/Ruhr (Germany), March 31st, 1965] [VB 932/235 IE]
German version: Angew. Chem. 77, 625 (1965)

[1] *H. Luther* and *W. Stein*, Z. Elektrochem. *60*, 1115 (1956); *H. Luther*, *H. Meyer*, and *H. Loew*, Z. analyt. Chem. *170*, 155 (1959).

[2] *H. Luther* and *G. Weisel*, Kolloid Z. *154*, 15 (1957).

[3] *H. Luther*, *F. Glander*, and *E. Schleese*, Kunststoffe *52*, 7 (1962).

[4] *E. Schleese*, Doctorate Thesis, Technische Hochschule Clausthal, 1962.

[5] *G. Pessier*, Doctorate Thesis, Technische Hochschule Clausthal, 1962.

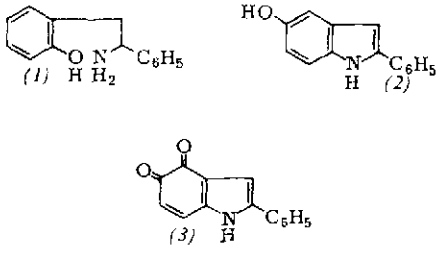
[6] *H. Luther* and *H. Meyer*, Z. Elektrochem. *64*, 681 (1960).

[7] *G. Kanig*, Kolloid-Z. *190*, 1 (1963).

New Reactions in the Quinone and Heterocycle Series

H.-J. Teuber, Frankfurt/Main (Germany)

o-Hydroxyphenethylamine derivatives are oxidized by potassium nitrosodisulfonate to 5-hydroxyindoles, which on further oxidation yield *o*-quinones. For instance, compound *(1)* affords red-violet 2-phenylindole-4,5-quinone *(3)* in an overall yield of 80 % *via* the isolable intermediate *(2)* [1].

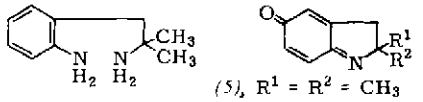


(1)

(2)

(3)

If a tertiary phenethylamine such as *(4)* is used, the product is a yellow cyclic quinone imine such as *(5)* or *(6)*.



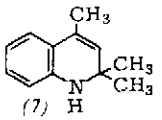
(4)

(5), $R^1 = R^2 = CH_3$
(6), $R^1 + R^2 = -(CH_2)_5-$ or $-(CH_2)_4-$

2,2,4-Trimethyl-1,2-dihydroquinoline *(7)* [2] also yields a yellow *p*-quinone imine, *viz.* *(8)*; however, when the *p*-position is substituted, the product is a red *o*-quinone imine, *e.g.* *(9)*.

[1] Experimental work in collaboration with *O. Glosauer*.

[2] *G. Reddelien* and *A. Thurm*, Ber. dtsch. chem. Ges. *65*, 1511 (1932); *D. Craig*, J. Amer. chem. Soc. *60*, 1458 (1938); *D. Craig* and *E. C. Gregg*, ibid. *75*, 2252 (1953).



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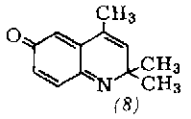
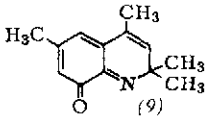


(8)

The only oxotetrahydrocarbazolenine that behaves like a ketone is the 3-oxo compound *(10)*. 2-Oxotetrahydrocarbazolenine occurs in the form of the vinylogous amide *(11)*, 1-oxotetrahydrocarbazolenine *(12)* is enolized in the manner of a diosphenol and gives a blue color with ferric chloride, and 4-oxotetrahydrocarbazolenine cannot be isolated since a β-dicarbonyl cleavage occurs under the conditions of its formation [3].



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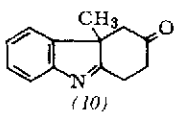

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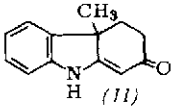
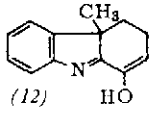


(11)



(12)

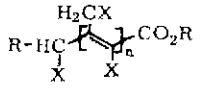
[GDCh-Ortsverband Leverkusen (Germany), April 8th, 1965] [VB 930/233 IE]

German version: Angew. Chem. 77, 624 (1965)

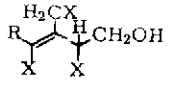
Synthesis and Reactions of Organic Fluoro Compounds

H. Machleidt, Biberach/Riss (Germany)

Carbonyl olefinations of ketones or fluoroketones with ethyl diethoxyphosphinoacetate or ethyl diethoxyphosphinofluoroacetate or their vinylogues lead to fluoro-substituted α,β-unsaturated esters of type *(1)*.

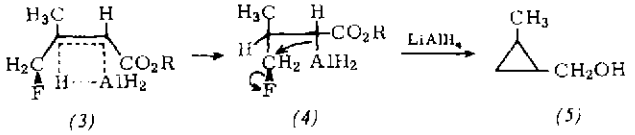


(1), X = H or F



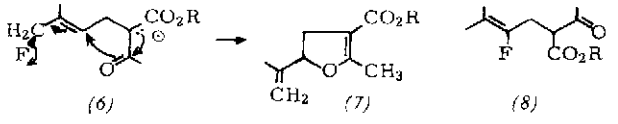
(2), X = H or F

$LiAlH_4$ reduces compounds of type *(1)*, X = F, n = 1, at −78 °C to fluoroisoprenols. At higher temperature, a reductive elimination of the γ-fluoro substituent occurs with partial isomerization of the double bond to isoprenols of type *(2)*. At the same time, an intramolecular nucleophilic substitution of the fluorine occurs which is largely independent of the temperature and proceeds *via (3)* → *(4)*. Further reduction leads to the cyclopropane derivative *(5)*.



(3) *(4)* *(5)*

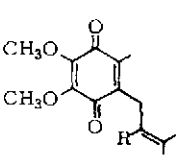
A similar substitution of fluorine is observed with β-keto esters *(6)*, leading to dihydrofuran derivatives *(7)*. Fluoro-β-keto esters of type *(8)* are stable.



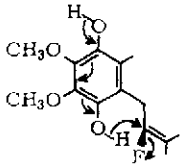
(6) *(7)* *(8)*

[3] *H.-J. Teuber, D. Cornelius*, and *E. Worbs*, Tetrahedron Letters *1964*, 331; *H.-G. Teuber* and *D. Cornelius*, Chem. Ber., in press.

Fluoroisoprenols are used to synthesize fluoro-coenzyme Q, *e.g.* FQ_1 *(9)*.



(9), R = F
(11), R = H



(10)

The dihydro derivative of enzyme FQ_1 *(10)* is unstable and undergoes an intramolecular redox reaction by an addition-elimination mechanism to yield coenzyme Q_1 *(11)* and HF.

Fluoroisoprenols were converted into their pyrophosphates, some of which are inhibitors of steroid biosynthesis.

[GDCh-Ortsverband Nordbayern, May 7th, 1965 in Erlangen (Germany)] [VB 927/232 IE]

German version: Angew. Chem. 77, 625 (1965)

Inorganic Ring Systems with Silicon and Nitrogen Atoms as Ring Members

U. Wannagat [1], Graz (Austria)

1,3-Dihalogenodisilazanes $X-SiR_2-NR'-SiR_2-X$ *(1)* are excellent starting materials for the synthesis of inorganic rings with Si–N units. They can be prepared by the following methods:

a) By cleavage of cyclotrisilazanes, cyclotetrasilazanes, or polysilazanes with hydrogen halides in yields of 40–70 % (X = F, Cl, or Br):

$$-SiR_2-NH-SiR_2-NH- + 3\,HX \rightarrow X-SiR_2-NH-SiR_2-X + NH_4X$$

b) By intermolecular condensation of dialkylchloroaminosilanes in yields of 40 % (based on the amount of chloroaminosilane charged):

$$4\,R_2Si(NHR')Cl \rightarrow Cl-SiR_2-NR'-SiR_2-Cl + Cl-SiR_2-NR'-SiR_2-NHR' + [R'NH_3]Cl$$

c) By equilibration of cyclotrisilazanes or cyclotetrasilazanes with dimethyldichlorosilane by boiling in yields of 70 %[2]:

$$(-R_2Si-NH-)_3 + 3\,R_2SiCl_2 \rightarrow 3\,Cl-SiR_2-NH-SiR_2-Cl$$

d) By the action of the adducts of silicon halides on cyclosilazanes:

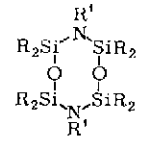
$$-SiR_2-NH-SiR_2-NH- + SiF_4(NH_3)_2 \rightarrow F-SiR_2-NH-SiR_2-F + 2\,NH_3 + 1/x\,[SiF_2(NH)]_x$$

The 1,3-dihalogenodisilazanes are readily converted by alcohols, amines, and hydrazines in the presence of triethylamine into the corresponding derivatives *(1)*, X = RO, R_2N, and R_2NNH. Analogous reactions, some of which require prior metallation of NH groups, lead to numerous new ring systems. Compounds made include *(2)* from *(1)* plus water, *(3)* from *(1)* plus ammonia, *(4)* from *(1)* plus hydrazine, *(5)* from *(1)* plus ethylene diamine, and *(6)* from *(1)* plus bistrimethylsilylurea. The Si–N four-membered ring of *(7)* is formed in surprisingly high yields during attempts to produce dichlorotrisilazanes according to method (c) but with different ratios of reagents [3].

[1] In collaboration with *E. Bogusch* and *G. Schreiner*.

[2] *P. Geymayer* and *E. G. Rochow* independently carried out this reaction in a sealed tube (personal communication).

[3] *P. Geymayer* and *E. G. Rochow* also obtained this compound from *(1)*, X = Cl, and sodium bistrimethylsilylamide (personal communication).



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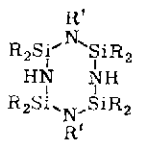

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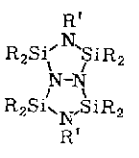

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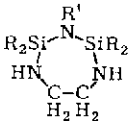

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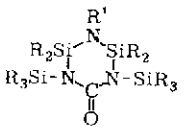

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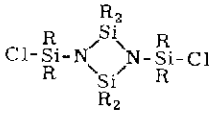


(7)

Melting and boiling points of some of the new compounds.

X-Si(CH$_3$)$_2$-NR'-Si(CH$_3$)$_2$-X				R	R'	M.p. [°C]	B.p. [°C/mm]
X	R'	B.p. [°C/mm]					
F	H	120/745	(2)	CH$_3$	CH$_3$	27–28	102/10
Cl	H	64/11	(3)	CH$_3$	CH$_3$	95–96	
Br	H	49/0.1	(4)	CH$_3$	CH$_3$		97/10
Cl	CH$_3$	69–70/12	(5)	CH$_3$	CH$_3$		88/10
Cl	n-C$_4$H$_9$	79–81/2	(7)	CH$_3$		68–69	

Compound *(5)* with R = CH$_3$ and R' = H or CH$_3$ decomposes without melting when heated; it can be characterized by its infrared and NMR spectra.

[GDCh-Ortsverband München (Germany), May 11th, 1965] [VB 924/231 IE]

German version: Angew. Chem. *77*, 626 (1965)

SELECTED ABSTRACTS

The structures of Gastrins I and II, two closely related polypeptide hormones from pig stomach mucosa, which on subcutaneous injection strongly activate the excretion of acid into the stomach, were elucidated by *H. Gregory* and collaborators by amino-acid analysis, end-group analysis, and determination of the amino-acid sequence (by degradation with papain, subtilisin, chymotrypsin, and cyanogen bromide). Gastrin II is pyro-Glu-Gly-Pro-Try-Met-(Glu)$_5$-Ala-Tyr (SO$_3$H)-Gly-Try-Met-Asp-Phe-NH$_2$ *(1)*, and is converted by removal of the sulfato group from the tyrosine residue into gastrin I. Resynthesis of *(1)* can be effected by treating gastrin I with the pyridine-SO$_3$ complex in alkaline solution. Investigation of 12 synthetic peptides closely related to the gastrins revealed that only the *C*-terminal tetrapeptide sequence is required for complete physiological activity. / Nature (London) *204*, 931,933,935 (1964) / –Ma.

[Rd 211/420 IE]

The mutagenic activity of thalidomide (Contergan®) in bacteria was examined by *A. Tumulka* and *R. W. Kaplan* on three auxotrophic strains of *Serratia* CV, since it is known that 29 out of 36 substances which are mutagenic for humans are significantly mutagenic for these strains, too. With the strains gly 1 and arg 1, the mutagenic action of Contergan could be demonstrated; this proves its direct or indirect attack on the bacterial DNA. There is therefore a considerable probability that Contergan is also mutagenic for the genes (DNA) of human cells. Fetal malformations do not however result from changes in the DNA in the embryonic cells, but by modifications of the embryonic development. It is not yet known whether there is any connection between the teratogenic activity of Contergan – RNA is partly responsible for phenogenetic development – and the mutagenic action. / Naturwissenschaften *52*, 20 (1965) / –De. [Rd 230/438 IE]

The behavior of alkali metal chlorates on heating was studied by *M. M. Markowitz, D. A. Boryta,* and *H. Stewart* by differential thermoanalysis and thermogravimetry. Mainly two reactions occur: direct decomposition of chlorate to chloride and oxygen, and disproportionation to chloride and perchlorate, which is also converted into chloride and oxygen at higher temperatures. The direct decomposition is the preferred reaction with the chlorates of the lighter alkali metals, the disproportionation with the chlorates of the heavier ones. MnO_2 accelerates the direct decomposition. All the alkali metal chlorates melt without decomposing; the temperatures at which decomposition starts lie 100–200 °C above the melting points. Of the perchlorates, only $LiClO_4$ melts unchanged. / J. physic. Chem. *68*, 2282 (1964) / Hz.

[Rd 233/441 IE]

Fluorosulfuric acid was used as an acid-base system in studies by *J. Barr, R. J. Gillespie,* and *R. C. Thompson,* who found that anhydrous HSO_3F, m.p. –89.0 °C, b.p. 162.7 °C, undergoes autoprotolysis. In this system, bases are substances

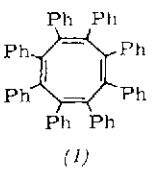
$$2\ HSO_3F \rightleftharpoons H_2SO_3F^{\oplus} + SO_3F^{\ominus}$$

which increase the $SO_3F^{\ominus}$ concentration, *e.g.* fluorosulfates of alkali and alkaline earth metals. Conversely, acids are substances which increase the concentration of $H_2SO_3F^{\oplus}$ ions. / Inorg. Chemistry *3*, 1149 (1964) / –La. [Rd 243/450 IE]

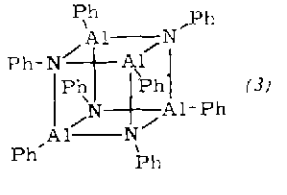
A one-step synthesis of 1,1-difluoroolefins from ketones is reported by *A. S. Fuqua, W. G. Duncan,* and *R. M. Silverstein.* A solution of sodium difluoroacetate in an anhydrous polar solvent such as *N*-methylpyrrolidone, tetramethylurea, dimethylformamide, dimethylacetamide, or dimethyl sulfoxide is added to a solution of the ketone and tributylphosphine in the same solvent under nitrogen at 160–180 °C. Fractional distillation after the reaction leads to 46 % difluoromethylenecyclohexane, b.p. 105–106 °C, from cyclohexane or 34.6 % 3,3-difluoro-α-methylstyrene, b.p. 58–59/21 mm, from acetophenone. / Tetrahedron Letters *1965*, 521 / –Ma.

[Rd 258/467 IE]

"Octaphenylcubane" is actually octaphenylcyclooctatetraene *(1)* according to the results of the three-dimensional Patterson analysis carried out by *H. P. Throndsen, P. J. Wheatley,* and *H. Zeiss.* This finding is surprising, since unsubstituted cubane *(2)* is known and since the Al–N compound *(3)*, which is isoelectronic with *(1)* – except for the extra L-shell of the



(1)



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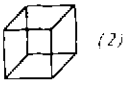


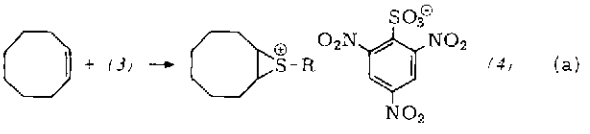
(2)

aluminum –, has the same space group ($I4_1/a$) as *(1)* and has very similar unit-cell dimensions. Hydrocarbon *(1)* forms tetragonal crystals (from diphenyl ether) with a = 19.388 Å, c = 10.606 Å, and Z = 4. / Proc. chem. Soc. (London) *1964*, 357 / –Kr. [Rd 232/440 IE]

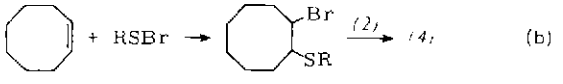
Stable episulfonium salts in the cyclooctane series have been isolated by *D. J. Pettitt* and *G. K. Helmkamp*. Alkanesulfenyl bromides *(1)* react in nitromethane with silver 2,4,6-trinitrobenzenesulfonate *(2)* in CH_2Cl_2 at −25 to 0 °C to form alkanesulfenyl 2,4,6-trinitrobenzenesulfonates *(3)*, which are unstable and are difficult to isolate. However, after removal of the AgBr formed by filtration, the salts *(3)* can be condensed in solution with cyclooctene to give 60–70 % cyclooctene-*S*-alkylepisulfonium salts *(4)*, which can be crystallized from hot nitromethane/ether or acetone/ether. The salts *(4)* are also obtained in pure form and in high yield by Route (b) and by direct alkylation of episulfides. Thus, for example, *(4a)* was produced from cyclooctene episulfide and trimethyloxonium 2,4,6-trinitrobenzenesulfonate *(5)* according to Equation (c) [1]. The salt *(5)*, m.p. 115–120 °C (decomp.),

(1) $RSBr + (NO_2)_3C_6H_2\text{-}SO_3^{\ominus}Ag^{\oplus}$ *(2)*

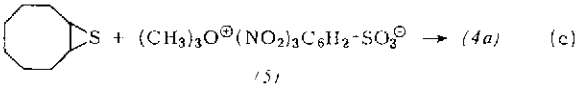
$\rightarrow AgBr + [(NO_2)_3C_6H_2\text{-}SO_3^{\ominus}RS^{\oplus}]$ *(3)*



(4) (a)



(4) (b)



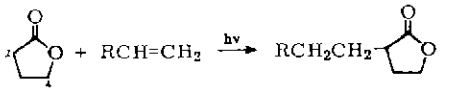
(4a) (c)

(5)

(4a): R = CH_3, m.p. 122–123 °C
(4b): R = C_2H_5, m.p. 123–124 °C
(4c): R = n-C_3H_7, m.p. 116–117 °C
(4d): R = n-C_4H_9, m.p. 104–105 °C

is readily obtainable by the reaction of 2,4,6-trinitrobenzenesulfonic acid and diazomethane in dimethyl ether at 35 °C [1]. The ring strain in the salts *(4)* is indicated *inter alia* by their reaction with NaI in acetonitrile: in contrast to the unstrained sulfonium salts, which can form stable iodides, here quantitative separation of iodine occurs, *(4)* being split into cyclooctene and the corresponding alkyl disulfide in a molar ratio of 2:1. / J. org. Chemistry *29*, 2702 (1964) / −Bi.
[Rd 224/448 IE]

Photoinduced addition of γ-butyrolactone *(1)* **onto terminal olefins** has been observed by *D. Elad* and *R. D. Youssefyeh*. The reaction proceeds at room temperature and affords mainly the corresponding 2-alkylbutyrolactone, together with some 4-alkyl derivative. A solution of the olefin in the lactone is irradiated. Photochemical induction with acetone leads to higher yields. For example, 1-heptene gives a 52 % yield (based on the olefin charged) of 2-heptylbutyrolactone,



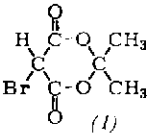
(1)

m.p. 9–10 °C, on irradiation with a Hanau Q81 mercury vapor lamp or a 63 % yield on irradiation with sunlight. Similarly, 1-octene gives 42 or 66 % 2-octylbutyrolactone, m.p. 19–20 °C, and 1-decene gives 48 or 58 % 2-decylbutyrolactone, m.p. 32–33 °C, respectively. / Chem. Commun. *1965*, 7 / −Ma.
[Rd 282/491 IE]

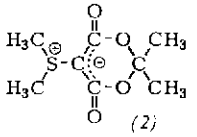
[1] *D. J. Pettitt* and *G. K. Helmkamp*, J. org. Chemistry *28*, 2932 (1963).

The biological activity of bradykinine was found to disappear on alteration of the configuration of the terminal arginine group by *E. D. Nicolaides*, *D. A. McCarthy*, and *D. E. Potter*. This vasodilator hormone is a peptide consisting of 9 L-amino acids in the sequence Arg-Pro-Pro-Gly-Phe-Ser-Pro-Phe-Arg. [1-D-Arginine]bradykinine was prepared by condensation of the heptapeptide with carbobenzoxynitro-D-arginylproline, and [9-D-arginine]bradykinine and [1,9-bis-D-arginine]bradykinine by conventional total synthesis. All three synthetic peptides had practically no biological activity (activity only $2 \cdot 30 \times 10^{-5}$ that of bradykinine). Their *in vivo* half-lives did not differ from that of bradykinine (about 30 sec). Since the [D-arginine]bradykinines are not attacked by carboxy- or aminopeptidases, and since the biological half-lives are the same as that of bradykinine itself, it can be concluded that exopeptidases are not involved in its degradation. / Biochemistry *4*, 190 (1965) / −Hö.
[Rd 303/512 IE]

New stable sulfonium ylides have been described by *A. Hochrainer* and *F. Wessely*. When the bromo derivative of Meldrum's acid *(1)* is allowed to stand in dimethyl sulfoxide for several hours, the hydrobromide of *(2)* is formed spontaneously; when the latter is dissolved in methanol and reprecipitated with ether, the free dimethylsulfonium ylide *(2)* of Meldrum's acid is obtained in 30–40 % yield. It melts



(1)



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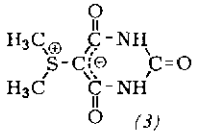
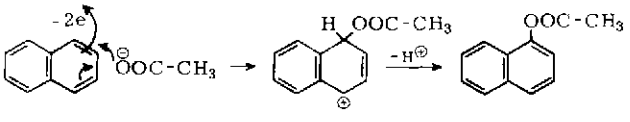


(3)

at 197 °C after purification by sublimation. The structure of *(2)* was proved by infrared, ultraviolet, NMR, and mass spectroscopy. Bromobarbituric acid gives a good yield of the analogous ylide *(3)*. / Tetrahedron Letters *1965*, 721 / −Ma.
[Rd 284/493 IE]

The anodic acetoxylation of aromatic compounds was found by *L. Eberson* and *K. Nyberg* not to proceed by the Kolbe mechanism. The acetate ions are not oxidized to acetoxyl radicals, which would then attack the aromatic compound; instead, two electrons are abstracted from the aromatic compound at the anode, and combination with acetate anions then occurs. In 0.5 M sodium acetate in acetic acid, the oxidation

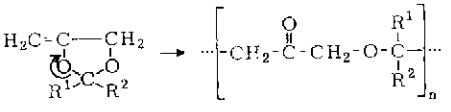


half-wave potential on a platinum electrode is 1.72 v for naphthalene and 1.67 v for anisole relative to the saturated calomel electrode. Here the acetoxylation cannot proceed *via* acetoxyl radicals, for the acetate ion is not discharged until 2.0 v. Moreover, the formation of specifically 1-acetoxynaphthalene and *o*- plus *p*-anisole is in contradiction to a free radical mechanism. Since the potentials measured at the anode for several electrolytic syntheses correlate well with the molecular-orbital coefficients for the highest occupied orbital, it is likely that numerous oxidations begin with oxidation of the substrates and not with that of the anionic species present. This assumption does not only apply to electrochemical oxidations. / Acta chem. scand. *18*, 1568 (1964) / −Eb.
[Rd 238/446 IE]

One peptide chain is formed at every protein-synthesizing ribosome. *J. R. Warner* and *A. Rich* estimated this using the protein-synthesizing system from rabbit reticulocytes, which produces only hemoglobin. The active ribosomes form poly-

somes with the messenger RNA and can therefore be separated from the inactive ribosomes in a sucrose concentration gradient. Tetrameric to hexameric polysomes were used for the experiments. On the average, six leucine and 2.7 phenylalanine residues become attached to each ribosome. Rabbit hemoglobin contains 16 leucine and 8 phenylalanine residues. It is assumed that in the steady state, the growing peptide chain has on the average half the length of the complete protein molecule. Various correction factors, particularly the known distribution of leucine and phenylalanine in the hemoglobin molecule, bring the values (twice 6 and 16 Leu and twice 2.7 and 8 Phe) into good agreement. Thus, the number of peptide chains synthesized simultaneously at a single molecule of messenger RNA, *i.e.* a polysome is equivalent to the number of ribosomes it contains, probably 4–6. / J. molecular Biol. *10*, 202 (1964) / –Hö. [Rd 217/426 IE]

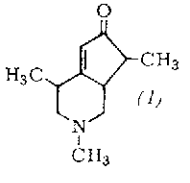
A vinyl polymerization coupled with polymerization by acetal ring opening has been observed by *M. Goodman* and *A. Abe* with the 4-methylene-1,3-dioxolane derivatives *(2)* and *(3)* in the presence of cationic catalysts at 178 °C (BF_3 etherate) or at room temperature ($AlCl_3$). For example, 4.7 g of monomeric *(3)* is polymerized with 0.2 ml of 48% BF_3 etherate in ether within 36 h at –78 °C to give a 64% yield of a polymer with a softening point of 85–90 °C and $[\eta]$ = 0.16 dl/g in CCl_4 at 26.8 °C. A strong carbonyl absorption is observed in the infrared spectrum of the product at 1725 cm^{-1}. This can be explained only by the assumption that the opening of the C=C double bond during molecular growth is coupled with a simultaneous opening of the acetal ring to form the



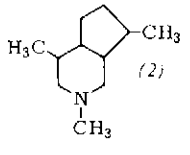
(1): $R^1 = R^2 = H$
(2): $R^1 = CH_3$, $R^2 = H$
(3): $R^1 = R^2 = CH_3$

keto-ether sequence shown. The parent compound 4-methylene-1,3-dioxolane *(1)*, on the other hand, polymerizes preferentially by opening of the vinylic double bond. / J. Polymer Sci. *A 2*, 3471 (1964) / –Hl. [Rd 227/435 IE]

Tecomine and tecostanine are two antidiabetic alkaloids which have been isolated from the leaves of *Tecoma stans* (Juss.) and tested clinically on animals by *Y. Hammouda, Abdel-Kader Rashid*, and *M. S. Amer*. Tecomine *(1)* and tecostanine *(2)* were injected intravenously into rabbits in doses of 20 mg/kg body weight and induced respectively 47 and 49% reduction of the blood sugar concentration; they are therefore much better than the antidiabetic tolbutamine (250 mg/kg *per os*).



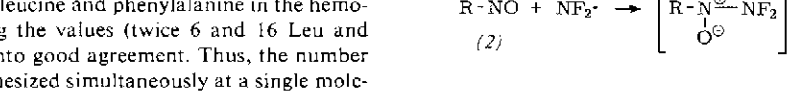
(1)



(2)

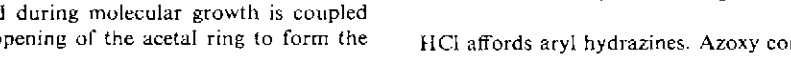
The hypoglycemic action was respectively 179 and 186% of that of tolbutamine. Hypoglycemics having this skeleton were hitherto unknown. / J. Pharmacy Pharmacol. *16*, 833 (1964) / –De. [Rd 228/436 IE]

Syntheses and properties of N'-fluorodiimide N-oxides R–N(O)=NF *(1)* are described by *T. E. Stevens* and *J. P. Freeman*. Monomeric *C*-nitroso compounds *(2)* in inert solvents, *e.g.* chlorobenzene, CCl_4, or CH_2Cl_2, absorb tetrafluorohydrazine N_2F_4 at reduced pressure and 0–20 °C, sometimes at 60–80 °C, to form *(1)*. The reaction of *(2)* in pyridine/CH_2Cl_2 with gaseous difluoroamine (HNF_2) diluted with nitrogen also leads to *(1)* in 23–90% yield. Trifluoronitrosomethane (CF_3NO) and N_2F_4 also undergo a thermal or light-induced reaction to yield *(1)* with R = CF_3 [1].



(2) *(1)*

The reaction probably proceeds *via* a radical mechanism; SiF_4 and fluorosilicates are formed as by-products. However, an ionic ($NF_2^{\ominus}$) or nitrene mechanism (:NF_2) cannot be excluded with certainty. Derivatives prepared include *(1)*, R = C_6H_5, b.p. 78 °C/4 mm, 53% yield; *(1)*, R = t-butyl, b.p. 56 °C/64 mm, 33%; *(1)*, R = benzyl, b.p. 70 °C/0.1 mm, 60%; and *(1)*, R = cyclohexyl, b.p. 70/0.1 mm, 90%. Aromatic derivatives are stable toward boiling acetic acid, diethylamine, concentrated HCl, sodium methoxide in methanol, cold concentrated H_2SO_4, and BF_3 etherate; decomposition into NO, N_2O, N_2, and SiF_4 occurs in concentrated H_2SO_4 at 70 °C. Aliphatic derivatives are less stable. Catalytic hydrogenation over Pt converts the aromatic derivatives, *e.g.* *(1)*, R = C_6H_5, into anilines; reduction with Sn/



(3)

HCl affords aryl hydrazines. Azoxy compounds *(3)* are produced from *(1)* and Grignard reagents at 0 °C in ether or tetrahydrofuran, but more readily from organonitrosohydroxylamine tosylates R–N(O) = N–OTos and RMgX [2]. / J. org. Chemistry *29*, 2279 (1964) / –Bi. [Rd 218/427 IE]

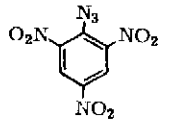
The existence of two isomeric cyclohexyl thiols was detected by *Y. Takeoka* by infrared spectroscopy. The isomerism is caused by the possibility of either an axial or an equatorial position for the substituent on the chair form of the cyclohexane ring. In the liquid form and between the melting point (–18 °C) and transition temperature (–87 °C), the two forms coexist; below –87 °C, only the more stable equatorial form is present. The difference in energy between the two forms is 0.78 kcal/mole in dilute solution in carbon disulfide, 0.80 kcal/mole in the pure liquid, and 0.58 kcal/mole in the solid between –87 and –18 °C. / J. molecular Spectroscopy *15*, 29 (1965) / –Hz. [Rd 280/489 IE]

The standard potentials of the gold/chloroaurate system in the forms $Au/AuCl_2^{\ominus}$, $Au/AuCl_4^{\ominus}$, and $AuCl_2^{\ominus}/AuCl_4^{\ominus}$ were determined by *J. Pouradier, M. C. Gadet*, and *H. Chateau*. In disagreement with earlier observations, it was found that the potential of a gold electrode immersed in a chloroaurate(III) solution is not determined by the concentration of chloroaurate (III) but by that of the chloroaurate (I) which is always present in lower concentration. On the basis of this discovery, the following standard potentials were then found with gold and platinum indicator electrodes: $Au/AuCl_2^{\ominus}$ = 1.148 V; $Au/AuCl_4^{\ominus}$ = 0.995 V; $AuCl_2^{\ominus}/AuCl_4^{\ominus}$ = 0.921 V. Diffusion potentials and activity coefficients were taken into account as far as possible. In the presence of metallic gold, the activities of chloroaurate(I) and chloroaurate(III) are related by $\log_{10}[a(AuCl_4^{\ominus}) \cdot a\text{-}(Cl^{\ominus})/a^3(AuCl_2^{\ominus})] = 7.68$. / J. Chim. physique *62*, 203 (1965) / –Hz. [Rd 281/490 IE]

Aziridines and Schiff bases were obtained from picryl azide *(1)* and olefins by *A. S. Bailey, J. J. Merer*, and *J. E. White*. Mild hydrolysis of the Schiff bases with acids gives picramide

[1] *J. W. Frazer* et al., J. inorg. nucl. Chem. *24*, 45 (1962).
[2] *T. E. Stevens*, J. org. Chemistry *29*, 311 (1964).

and a ketone. Chloroform is suitable as a solvent for preparative work. The duration of the addition reaction varies from a few minutes for norbornylene and dihydropyran to 4 days



(1)

for cyclohexene. Norbornylene, dicyclopentadiene, and α-pinene afford photolabile aziridines; simple olefins such as cyclopentene yield Schiff bases. The azide can be prepared by nitration of either *o*- or *p*-nitrophenyl azide. / Chem. Commun. *1965*, 4 / –Ma. [Rd 283/492 IE]

Surface area estimations according to *Brunauer*, *Emmett*, and *Teller* with krypton or xenon as adsorbate on nickel films deposited by evaporation sometimes lead to erroneous results. After chemisorption of oxygen or ethylene, for example, different values are obtained. *K. C. Cambell* and *D. T. Duthie* consider it probable that this effect is not caused by sintering of the metal due to the energy released on chemisorption; instead, they conclude from the variation in the apparent relative change of surface area after chemisorption of various gases that the polarization of the rare gas atoms is augmented by the metal surface if it is already partially occupied by other adsorbates. This polarization leads to a change in the effective cross-section of the Kr or Xe atoms. It follows that the BET assay of the surface areas of solids using heavy rare gases is not reliable in such cases. / Trans. Faraday Soc. *61*, 558 (1965) / –Hz. [Rd 278/487 IE]

The C-N bond between the benzene ring and the nitroso group of *p*-nitroso-*N*,*N*-dimethylaniline has some double bond character and is therefore restricted in its rotation. *D. D. MacNicol*, *R. Wallace*, and *J. C. D. Brand* found the heat and entropy of activation for the rotation to be $\Delta H^* = 11.2 \pm 1.1$ kcal/mole and $\Delta S^* = -3.0 \pm 5$ cal·deg^{-1}·mole^{-1}. The temperature dependence of the NMR spectrum of the aromatic protons in the compound was used to determine these figures. The rotation around the C–N bond between the benzene ring and the dimethylamino group has no influence on the spectrum. The activation enthalpies determined in this fashion are in good agreement with the position of the corresponding torsional vibration in the far infrared (166 cm^{-1}). / Trans. Faraday Soc. *61*, 1 (1965) / –Hz. [Rd 279/488 IE]

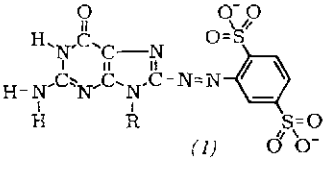
Enzymatic ω-oxidation of long-chain fatty acids containing 6, 8, 10, 12, 14, 16, or 18 carbon atoms was investigated by *M. Kusunose*, *E. Kusunose*, and *M. J. Coon*. They found that the enzyme concerned belongs to the group of the mixed-function oxidases, which generally catalyse oxidations by introducing an oxygen atom into the substrate molecule (one oxygen atom per substrate molecule). The second atom of the O_2 molecule is reduced to water by oxidation of a molecule of reduced diphosphopyridine nucleotide (DPNH). The

$$\text{Fatty acid} + O_2 + \text{DPNH} + H^{\oplus} \rightarrow \omega\text{-Hydroxy fatty acid} + \text{DPN}^{\oplus} + H_2O$$

oxidase isolated from a strain of *Pseudomonas* grown on hexane as sole source of carbon consists of two components, whose functions are not yet quite clear. The enzyme requires $Fe^{2\oplus}$ as cofactor besides DPNH and oxygen. – Lauric acid (C_{12}) is oxidized fastest, myristic (C_{14}), caprylic (C_8), and capric acids (C_{10}) almost as fast, and palmitic (C_{16}) and stearic acids (C_{18}) somewhat slower. Caproic acid (C_6) is not attacked. The Michaelis constants for the first four substrates are 3.3×10^{-5}, 3.9×10^{-5}, 1.2×10^{-3}, and 1.8×10^{-3} mole/l respectively. The pH optimum is near 7. The ω-hydroxy fatty acids are oxidized further by the same system with $\text{DPN}^{\oplus}$ as electron acceptor. / J. biol. Chemistry *239*, 1374, 2135 (1964) / –Hö. [Rd 262/471 IE]

Symmetrically substituted azobenzenes were produced from substituted aromatic amines by *C. H. Wheeler* and *D. Gonzales*. The amine (0.01 mole) is refluxed with 0.06 mole of dry activated MnO_2 in 50 ml of benzene for 6 h with a water trap. The hot solution of the product is then filtered. The yields of azobenzenes obtained from aniline and its *o*- or *p*-fluoro, *m*- or *p*-chloro, *p*-bromo, *o*- or *p*-iodo, *o*-ethyl, 3,5-dichloro, and 2,6-dimethoxy derivatives, and from *p*-anisidine, *p*-biphenylamine, and 2-aminopyridine were all over 90%. The oxidation is a bimolecular reaction at active sites on the MnO_2 surface; a mixture of two differently substituted anilines yields only the simple azo compounds and no mixed product. Nitranilines and aminobenzoic acids are not attacked by MnO_2, because here the nitro or carboxyl group is more strongly adsorbed on the MnO_2 surface. When these groups are sterically hindered, small yields of azo compounds are in fact obtained, *e.g.* 10% 4,4′dinitro-3,3′,5,5′-tetrachloroazobenzene from 3,5-dichloro-4-nitraniline. Polycyclic aromatic amines, *e.g.* 1-aminoanthracene, also fail to react, but polymerize instead, probably after oxidation to quinones. / Tetrahedron *20*, 189 (1964) / –Bi. [Rd 223/432 IE]

Selective labelling of guanine in polynucleotides has been achieved by *E. M. Moudrianakis* and *M. Beer*; this improves the chances of base sequence analysis by electron microscopy. Diazotized 2-aminobenzene-1,4-disulfonic acid reacts with guanine at pH 9 sixty times faster than with cytosine, adenine, thymine, or uracil, yielding the diazo compound *(1)*.


(1)

The reaction can be followed by spectrophotometry since *(1)* has λ_{max} at 382 mμ with $\varepsilon_{max} \approx 11000$. The 2-aminobenzene-1,4-disulfonic acid tag fulfils three demands placed upon chromophoric group for use in electron-microscopic investigations: it has sufficiently high specificity, the molecule is small enough not to disturb the native arrangement of the bases, and it introduces a substituent on the nucleic acid chain which causes a large local increase in electron density owing to its two sulfur atoms together with the nearby chain phosphorus atom. / Biochim. biophysica Acta *95*, 23 (1965) / –Hö. [Rd 263/472 IE]

The isoenzyme pattern of maize catalase has been determined genetically. *L. Beckman*, *J. G. Scandalios*, and *J. L. Brewbaker* investigated the endosperm catalase of two pure strains of maize and found that they differed in their rates of migration on electrophoresis (F = fast, S = slow). When they crossed the two species and the male parent plant had the S-property, they obtained a catalase isoenzyme pattern with an F-hand and three bands lying between F and S (FH bands). If the female parent was of the S type, the S-band and three bands lying between S and F (SH type) were observed. Crossing of the FH and SH species led to the S and F types again, together with FH and SH species in a ratio of 1:1. It is assumed that the enzyme is a tetramer, for this explains the occurrence of five isoenzymes: these have the compositions SSSS, SSSF, SSFF, SFFF, and FFFF. In a diploid organism, they ought to appear in the F_1 generation after crossing of F × S (male) types in numerical ratios of 16/81 FFFF, 32/81 FFFS, 24/81 FFSS, 8/81 FSSS, and 1/81 SSSS. The intensities of the bands correspond to these figures, and the appearance of only four bands can be explained by the fact that the concentration of SSSS was too low for detection. This work provides not only a feasible explanation of the phenomenon of isoenzymes, but also opens up a completely novel approach to the study of the structures of enzymes. / Science (Washington) *146*, 1174 (1964) / –Hö. [Rd 264/473 IE]

Base-catalysed addition of dimethylsulfoxide onto olefins and the pyrolysis of the resultant sulfoxides to give olefins with homologous carbon chains have been studied by *C. Walling* and *L. Bollyky*. The anion *(1)* formed from dimethylsulfoxide with, for example, potassium t-butoxide or NaH according to Equation (a) adds on rapidly and quantitatively to arylated olefins, *e.g.* 1,1-diphenylethylene *(2)*, to form new sulfoxides according to Equation (b), *e.g.* here *(3)*, m.p. 70 to 71 °C. The latter decompose at 150–200 °C under reduced pressure to a new olefin, here 3,3-diphenylpropene *(4)* in 96% overall yield, and probably methanesulfenic acid, which apparently decomposes further [Equation (c)]. – Thus, 1 mole of NaH is dissolved in 400 ml of dimethylsulfoxide and 1 mole of olefin is added. After dilution with water, the product is extracted with ether, the extract is concentrated, and the crude residue is subjected to pyrolytic distillation.

$$t\text{-}C_4H_9O^{\ominus} + CH_3SOCH_3 \rightleftharpoons t\text{-}C_4H_9OH + CH_3SOCH_2^{\ominus} \quad (1) \quad (a)$$

$$\underset{(1)}{CH_3SOCH_2^{\ominus}} + \underset{(2)}{(C_6H_5)_2C{=}CH_2} \rightleftharpoons \underset{(5)}{CH_3SOCH_2CH_2\overset{\ominus}{C}(C_6H_5)_2} \quad (b)$$

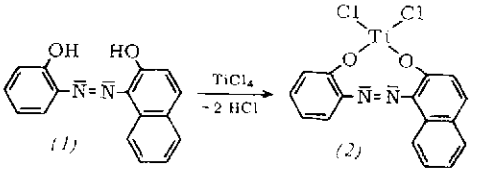
$$\underset{(5)}{CH_3SOCH_2CH_2\overset{\ominus}{C}(C_6H_5)_2} + CH_3SOCH_3 \rightleftharpoons \underset{(5)}{CH_3SOCH_2CH_2CH(C_6H_5)_2} + \underset{(3)}{CH_3SOCH_2^{\ominus}}$$

$$\underset{(3)}{CH_3SOCH_2CH_2CH(C_6H_5)_2} \xrightarrow{\Delta} \underset{(4)}{CH_2{=}CH{-}CH(C_6H_5)_2} + CH_3SOH\ (?) \quad (c)$$

Analogously, styrene yields 88% allylbenzene at 25 °C, while allylbenzene gives 92% 2-methyl-3-phenylpropene because of its isomerization to 1-phenylpropene in alkaline medium. The addition reaction [Equation (b)] does not take place with simple aliphatic olefins, *e.g.* cyclohexene, but any olefins that are capable of yielding resonance-stabilized carbanions such as *(5)* do react to give 3-arylpropylsulfoxides and hence 3-arylpropenes. / J. org. Chemistry *29*, 2699 (1964) / –Bi.

[Rd 222/431 IE]

Novel chelated catalyst systems for polymerizing ethylene at 60 °C and low pressures have been discovered by *K. J. Taylor*. When, for example, *o*-hydroxyphenylazo-β-naphthol *(1)* is treated with $TiCl_4$ in dry toluene at 20 °C, a dark opaque solution of the chelate *(2)* is obtained. If diethylaluminum chloride is then added, it combines with the free HCl to form



(1) *(2)*

ethylaluminum dichloride, which acts as cocatalyst during the

$$(C_2H_5)_2AlCl + HCl \rightarrow C_2H_5AlCl_2 + C_2H_6$$

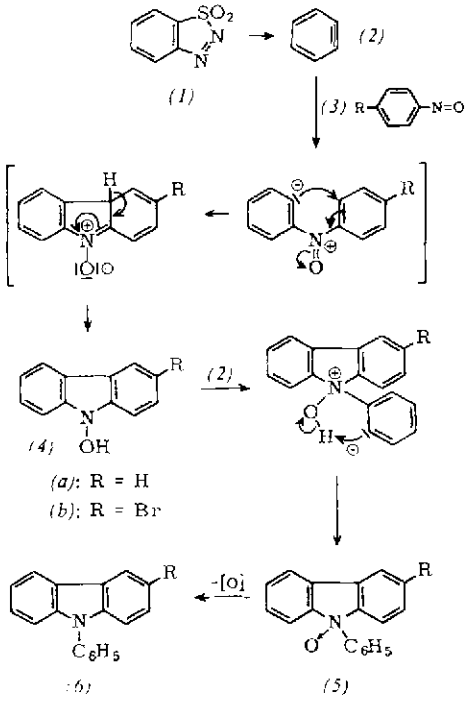
polymerization. The fact that it is the chelate *(2)* which participates in catalysing the reaction and not a Ziegler catalyst, which could be formed from dimethylaluminum chloride and $TiCl_4$ produced according to the equation

$$2\ TiCl_2R \rightleftharpoons TiCl_4 + TiR_2;\ R = -O-C_6H_4-N_2-C_{10}H_6-O-$$

is proved by the complete solubility of the catalyst system and the alterations in catalytic activity with changes in R. Further examples of R are *o,o'*-bis-*o*-hydroxyphenylazomethine and 3-chloro-6-hydroxy-2-methylphenylazo-β-naphthol. / Polymer *5*, 207 (1964) / –Hl. [Rd 225/433 IE]

The degradation of linear macromolecules during freeze-drying was studied by *F. Patat* and *W. Högner*. The concept developed by *W. Kuhn* [1] that the network fibers of high molecular-weight gels are ruptured by the growth of solvent crystals on freezing at –195 °C also applies to linear macromolecules, *e.g.* polystyrene PS 98 with $\bar{M} = 6.0 \times 10^5$ [2]. As the molecular weight rises, the probability of rupture increases for chain sections of equal length. In poor solvents, the macromolecules are coiled and have therefore less tendency to break than the straight macromolecules which occur in good solvents. Oxygen accelerates the degradation of polystyrene, for example: macroradicals produced by the homolytic cleavage of a bond have a great tendency to recombine owing to their close proximity; oxygen reduces this tendency by the formation of more stable peroxyl radicals. The degradation is also strongly influenced by the rate of freezing. At fast rates of freezing, the macromolecule behaves like a rigid body and is incapable of withdrawing before the advancing front of the growing solvent crystals and is therefore degraded more severely than at slower rates of freezing. / Macromolekulare Chem. *75*, 85 (1964) / –Hl. [Rd 226/434 IE]

Dehydrobenzene condenses with nitrobenzenes to form the carbazole ring system according to studies by *G. W. Steinhoff* and *M. C. Henry*. If dehydrobenzene (benzyne) *(2)* is prepared in the presence of nitrobenzene *(3a)* by thermolysis of 1,2,3-benzothiadiazole 1,1-dioxide *(1)* [3] in tetrahydrofuran by allowing the reaction mixture to warm up from –5 °C to room temperature, a 45.5% yield of *N*-phenylcarbazole *(6a)* is formed. Similarly, *(6b)* is obtained in 40% yield from *(3b)*. The reaction probably proceeds *via* the hydroxylamine derivative *(4)* and the unstable *N*-oxide *(5)*. If a one-step reaction occured instead, *(1b)* would be converted into *N*-(*p*-bromophenyl)carbazole, but the latter is not encountered. Support for the occurrence of the intermediates *(4)* and *(5)* is derived



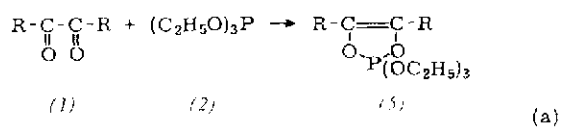
from the observation that diphenylhydroxylamine can be converted into triphenylamine in 40% yield by dehydrobenzene under the same reaction conditions. / J. org. Chemistry *29*, 2808 (1964) / –Bi. [Rd 221/430 IE]

[1] *W. Kuhn*, Helv. chim. Acta *39*, 1071 (1956).

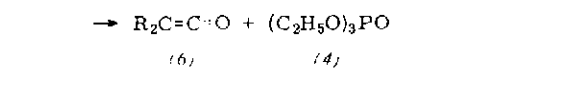
[2] From the Badische Anilin- und Soda-Fabrik, Ludwigshafen/Rhein (Germany).

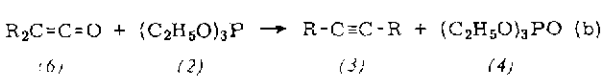
[3] *G. Wittig* and *R. W. Hoffmann*, Angew. Chem. *73*, 435 (1961); Chem. Ber. *95*, 2718 (1962).

Diarylacetylenes and 1-alkyl-2-arylacetylenes can be prepared by deoxidation of 1,2-diketones with triethyl phosphite, as was discovered by *T. Mukaiyama, H. Nambu*, and *T. Kumamoto*. When 1 mole of benzil *(1)*, R = C_6H_5, was heated with 2 moles of triethyl phosphite *(2)* for 2.5 h at 215 °C without solvent under nitrogen, 60% diphenylacetylene and 88% triethyl phosphate *(4)* were formed, together with 24% dimeric diphenylketene as by-product. The yield of acetylenic products could be markedly increased both here and in the following examples by heating the adducts *(5)* formed exothermally from equimolar amounts of *(1)* and *(2)* in the presence of excess triethyl phosphite [5 moles per 1 mole of *(5)*] for



(a)





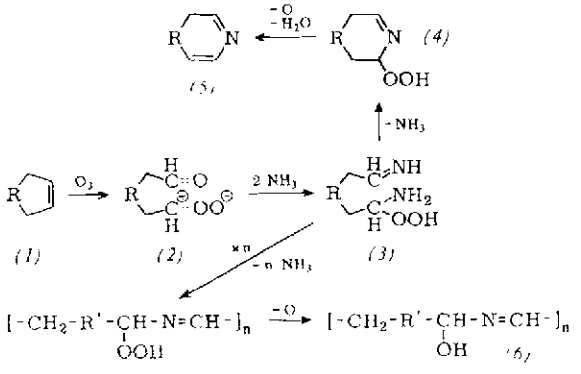
(b)

4–7 h in a sealed tube at 215 °C under nitrogen. Acetylenes prepared include diphenylacetylene *(3)*, b.p. 113–115 °C/2 mm, 81% yield; *(3)*, R = *p*-ClC_6H_4, m.p. 176 °C, 59%; *(3)*, R = *p*-$H_3COC_6H_4$, m.p. 146 °C, 58%; and propynylbenzene, b.p. 74 °C/15 mm, from 1,2-dioxopropylbenzene, 54%. Diphenylketene *(6)*, R = C_6H_5, also reacts directly with *(2)* to yield 65% diphenylacetylene according to Equation (b) [1]. / J. org. Chemistry *29*, 2243 (1964) / –Bi. [Rd 219/428 IE]

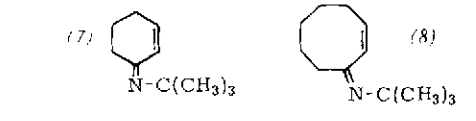
The ozonolysis of cyclo-olefins in ammonia was studied by *M. I. Fremery* and *E. K. Fields*. They treated olefins, *e.g. (1)*, as 5% emulsions in liquid ammonia or 50% aqueous ammonia containing a wetting agent (*e.g.* 0.5% Pronon 523) with one molar equivalent of ozone at −35 to −60 °C and obtained compounds such as *(2)*, which were either extracted from the reaction medium following evaporation of the ammonia or removed by steam distillation. The ammonia is relatively stable towards ozone in the presence of a more reactive olefin,

[1] *T. Mukaiyama* et al., J. org. Chemistry *27*, 3651 (1962).

but it reacts with *(2)* to form *(3)*. The further course of the reaction is largely determined by steric factors or by the ring size if the cyclo-olefins are unbranched. Cyclo-olefins with a five-membered ring, such as *(1)*, undergo a further intramolecular condensation leading to cyclic imines *(4)*, whose hydroperoxide group is reduced by NH_3 or by the K_2SO_3 added after the ozonization, the resultant alcohol then being dehydrated to form the six-membered N-heterocycle *(5)*, provided the latter is stable. If the cyclo-olefin ring is larger, the reaction proceeds by intermolecular polycondensation of *(3)* to yield hydroperoxy- and hence hydroxy-polyimines *(6)*, which produce dialdehydes on hydrolysis.



Thus, for example, cyclopentadiene yields 18% pyridine plus polymers, indene gives 62% isoquinoline, 3-methylindene gives 48% 4-methylisoquinoline, and indole gives 9% quinazoline. The poly(hydroxy imines) of type *(6)* produced from cyclohexene and cyclooctene can be hydrolysed to adipaldehyde, which condenses intramolecularly to cyclopentene-1-carboxaldehyde (18%), and suberic dialdehyde (26%), respectively. In contrast, when cyclohexene and cyclooctene are ozonolysed in t-butylamine, the imines *(7)*, b.p. 150 °C



(41%), and *(8)*, b.p. 75 °C/18 mm (49%), can be isolated; these probably arise from the 3-hydroperoxy derivatives formed in the O_2/O_3 current *via* the 3-ketones. / J. org. Chemistry *29*, 2240 (1964) / –Bi. [Rd 220/429 IE]

BOOK REVIEWS

Lexicon Alchemiae sive Dictionarium Alchemisticum (Lexicon of Alchemy and Alchemical Dictionary). By *Martin Ruland*. Photomechanical reprint of the 1612 Frankfurt/Main Edition. Georg Olms Verlagsbuchhandlung, Hildesheim 1964. VII + 487 pp., linen DM 68.– (about $ 17.00).

Soon after their appearance, the writings of *Paracelsus* initiated widespread controversy, for they contained many new names and concepts invented by their author or gave new shades of meaning to then known expressions. Consequently some disciples and admirers of *Paracelsus* compiled dictionaries designed to explain the meanings of his terms. These volumes included, for example, "Onomastica" by *Michael Toxites* (Strassbourg, 1574), the "Dictionarium Theophrasti Paracelsi" by *Gerhard Dorn* (Frankfurt/Main, 1583/84), and the "Onomasticum" by *Leonhard Thurneysser* (Berlin 1583). The "Lexicon Alchemiae" by *Martin Ruland*, was published in Frankfurt/Main in 1612 with a special imprimatur from the Kaiser for the period of ten years. It also contained, as the subtitle states, "Theophrast-Paracelsicarum Phrasium Planam Explicationem" (Distinct Explanations of Theophrastus Paracelsus' Phrases).

There is some uncertainty as to the person of the author, for *Jöcher* and *Ferguson* consider him to be *Martin Ruland the Elder* (1532–1602), who was physician-inordinary to *Philipp Ludwig*, the Duke of the Palatinate, and who introduced many chemicals, including antimony compounds, as medicines. *Thorndike*, on the other hand, considers the writer to be the son, *Martin Ruland the Younger* (1569–1611), who died in Prague as physician-inordinary to Kaiser Rudolph II. Since the dedication of the book bears the date 1611 and since the Kaiser's imprimatur – which was intended to suppress illicit copying of the book by another publisher under pain of retribution – is dated September 1607, it seems that *Thorndike's* opinion is more likely.

As usual, the "explicationes" (explanations) given here of *Paracelsus'* expressions are not unequivocal. For instance, it is written (p. 43) that "Annus philosophicus est mensis vulgaris" (the philosophical year is simply a month) but again (p. 330) that "mensis philosophicus est tempus putrefactionis... qui in aliquibus est triginta, in aliquibus quadraginta dierum" (the philosophical month is the time of putrefaction... which is sometimes thirty, sometimes forty days). The concept of

Alchemy is interpreted by *Paracelsus* to mean the preparation of pure substances for medicinal purposes: "Alchemia est impuri separatio a substantia puriori" (alchemy is the separation of impure from pure substance) on p. 26 or "est itaque ars chymica, ars physica separandi purum ab impuro ad conficiendum medicamenta tam corporibus humanis persanandis, quam metallicis ad summam perfectionem perducendis, accomodata" (the chemical art is a physical art adapted to separating the pure from the impure for making medicines, for curing human bodies, and for converting metals to the height of perfection) on p. 149.

A thorough knowledge of Latin is essential in order to understand the "Lexicon" even though explanations in German are frequently interspersed. However, anyone wanting to peruse original texts dating from the Middle Ages will have the necessary command of Latin and will be able to use this reprint with profit, for it often contains references to other classical authors of its day and age. *W. Ruske* [NB 322/180 IE]

Einführung in das anorganisch-chemische Praktikum (einschließlich der quantitativen Analyse) [Introduction to Practical Inorganic Chemistry, Including Quantitative Analysis]. By *J. H. Jander* and *E. Blasius*. S. Hirzel Verlag, Stuttgart 1964. 6th completely revised edit., XX + 483 pp., 97 figs., 4 tables, plastic covers DM 19.80 (about $ 5.–).

With this new edition of their book, the authors have succeeded in compiling a modern textbook which, like the previous editions, will certainly find resonance among students.

The theoretical chapters have been brought up to date, but it would have been pleasing if the concept of orbitals had been introduced and if the covalent bond had been dealt with more thoroughly in the section on "Ionic Theory and Bonding Types".

The preparative and analytical sections of the book are based on reliable practical procedures and characterization tests. The separation schemes for qualitative analysis are flawless and accurate, as the reviewer can confirm from his own experience. However, it is questionable whether the numerous organic reagents mentioned, *e.g.* magneson, sodium rhodizonate, morin, *etc.*, will be of much help to the student with chemistry as a minor subject, for the proper use of these substances generally demands some experience.

The quantitative section gives an excellent survey of the usual methods, including very modern methods, which are well illustrated by detailed descriptions of individual determinations. On the whole, the book can be highly recommended to both students and tutors alike.

O. Glemser [NB 353/211 IE]

Die Mutterkorn-Alkaloide (Ergot Alkaloids). By *A. Hofmann*. Sammlung chemischer und chemisch-technischer Beiträge. Edited by *R. Pummerer*, *L. Birkofer*, and *J. Goubeau*. New Series, No. 60. Ferdinand Enke Verlag, Stuttgart 1964. 1st Edit., VII + 218 pp., 27 illustrations, 50 tables, linen, DM 64.– (about $ 16.00).

The ergot alkaloids have undergone a dramatic history, first as the cause of devastating mass intoxications, then as valuable medicines, and finally as the subject of intense chemical investigations. Important advances within recent years, such as the total synthesis of the main ergot alkaloids by the author and his school and the succesful study of the biogenesis of lysergic acid, make the present volume particularly interesting.

The book has four sections, that dealing with the chemistry of the ergot alkaloids being the longest (159pp.). Descriptions are given of the properties and isolation of all the alkaloids of the lysergic acid and clavine types, including the identifications of their structures, their syntheses, analyses, biogeneses, and conversion into derivatives with different biological activities. The treatment given to the stereochemistry of lysergic acid and its derivatives is comprehensive and supplemented with explicatory formulae and therefore deserves special praise. In this connection, it is almost regrettable to think that these outstanding configurational studies were brought to a successful conclusion before there was a chance to apply the methods of NMR and mass spectrometry. Another notable feature of the book is the presentation given to the syntheses in the ergotamine group.

The other three chapters are much shorter and deal respectively with the botany (7 pp.) and history (6 pp.) of ergot and with the pharmacology and therapeutic applications of ergot alkaloids (22 pp.). The description of the psychotropic activity of lysergic acid derivatives and its discovery by the author in self-experiments will be read with excitement even by the non-pharmacologist.

The literature has been sifted up to the beginning of 1963. In addition, the book contains many more recent research results from the author's own laboratory. Regrettably, the book has no subject index, and a price of 7 cents per page. However, the condensed and lucid style and the complete coverage make it an extremely stimulating summary of this interesting field of natural products for chemists, botanists, and pharmacologists alike. *B. Franck* [NB 331/189 IE]

Taschenbuch für Chemiker und Physiker (D'Ans-Lax), Vol. II: Organische Verbindungen (Handbook for Chemists and Physicists, Vol. II: Organic Compounds). Edited by *Ellen Lax* in collaboration with *Claudia Synowietz*, Springer-Verlag, Berlin-Göttingen-Heidelberg 1964. 3rd completely revised edition, VIII + 1177 pp., linen DM 48.– (about $ 12.00).

"D'Ans-Lax" is due to appear in a new, completely revised edition. The reorganization of the book is noticeable already from its external appearance, for it has been divided up into three volumes. Volume II, "Organic Compounds", has just been published.

A feature that will be extremely valuable to many users of the book is the poignant introduction to the nomenclature of organic compounds written by *K. Dimroth*. Here the most important IUPAC rules for naming organic compounds are recorded in a version that is easy to read and to grasp; however, these are often mixed with older nomenclature habits, so that the list of methods for naming materials sometimes lacks in perspicuity. A table of the most important ring systems and their numbering is also included.

This introductory section is followed by a list almost 900 pages long – designated as Table 12 – of about 7000 organic compounds; for each substance; the name and a literature reference, the formula, molecular weight, melting or boiling point, and characteristic properties such as the state of aggregation, solubilities, odor, color, *etc.* are given. This table has always formed the core of the "D'Ans-Lax" for many chemists.

It is therefore regrettable that the nomenclature in this table is not uniform throughout. For example, the compound $CH_3–CO–CH_2OH$ is recorded under "Acetol" but $C_6H_5–CO–CH_2OH$ under "Benzolcarbinol". 4-Methyl-2-phenylpyrimidon-(6) is described as such, but its isomer 4-methyl-6-phenylpyrimidon-(2) is to be found – without any indication of the systematic name – under "Benzoylacetonharnstoff"! In the reviewer's opinion, the depiction of the formulae with dots instead of hyphens for bonds is unfortunate, because this notation is not as easy and rapid to scan.

The long list of compounds is followed by supplementary tables in which the compounds are arranged according to increasing melting and boiling points and according to their composition. A section with thermochemical data is also included.

It is hardly necessary to give "D'Ans-Lax" a good recommendation. This handbook is a standard work and the second volume of the new edition corresponds to this classification. The contents of the other volumes can be looked forward to. *H. Grünewald* [NB 315/173 IE]

Physical Methods in Heterocyclic Chemistry. Edited by *A. R. Katritzky*. Vol. I: Nonspectroscopic Methods. Vol. II: Spectroscopic Methods. Academic Press Inc., New York 1963. 1st edit., Vol. I: XI + 346 pp., numerous tables, linen $ 12.–. Vol. II: XI + 398 pp., numerous figs. and tables, linen $ 14.–.

It is the aim of this two-volume work to single out the application of the most important physical methods to the chemistry of heterocyclics and to summarize the literature on this subject. The following topics are discussed: in Vol. I: ionization constants (*A. Albert*), heteroaromatic reactivity, with a section on molecular-orbital calculations (*J. Ridd*), X-ray diffraction by heterocyeles (*W. Cochran*), solubilities of heterocyclic compounds (*W. Pfeiderer*), dipole moments in heterocyclic systems (*S. Walker*), and electrochemical properties in solutions (*J. Volke*); in Vol. II: electronic absorption spectra (*S. F. Mason*), nuclear quadrupole resonance (*E. A. C. Lucken*), nuclear magnetic resonance spectra (*R. F. M. White*), and infrared spectra (*A. R. Katritzky* and *A. P. Ambler*). As the titles of the chapters indicate, the selection of topics is somewhat random and by no means comprehensive. Some cnapters are somewhat beyond the general topic of the book.

Each chapter begins with a short, usually clear review of the principle of the specific method in question. This is followed by more or less detailed indications of its use in heterocyclic chemistry. The style of the individual chapters varies from author to author. Sometimes the treatment is superficial, but other chapters are very extensive and attack the subject matter with great thoroughness. On the whole, the hooks represent more a series of essays than a well rounded-off work, but the variety of their suhject matter and their numerous references (literature up to the start of 1962) provide many an incentive not only to the specialist in the field of heterocyclics.

K. Dimroth [NB 352/210 IE]

Fluorine Chemistry. Vol. III: Biological Effects of Organic Fluorides. By *H. C. Hodge, F. A. Smith*, and *P. S. Chen*. Edited by *J. H. Simons*. Academic Press, New York-London 1963. 1st edit., XI + 240 pp., 7 figs., 34 tables, linen $ 10.–.

The chemistry of organic fluorine compounds has developed rapidly since 1945. Fluorinated organic compounds are being used more and more as solvents, plastics, dyestuffs, and pharmaceuticals. Since the discovery of the high toxicity of fluoroacetate, the biological properties of organofluorine compounds have become part of the realm of toxicologists and biochemists. It is therefore a laudable enterprise that the authors have undertaken here in critically reviewing about 1600 publications which have appeared until 1961. The biological properties of fluoroacetate, fluorophosphoric acid derivatives, aliphatic fluoro compounds which may be used as solvents or working gases, and fluorinated pharmaceutical preparations are described on 54 pages. The metabolism of fluoroacetate is discussed critically and with reserve. The influence of organofluorine compounds on enzyme systems, microorganisms, viruses, and insects also receives mention. Next follow 130 pages of tables. The large number of articles to be evaluated makes any attempt at comprehensive treatment too difficult. It is therefore not surprising that the reviewer remarked the omission of some articles on enzyme inhibition with fluorine-substituted organic enzyme substrates. The authors have placed the main accent on toxicological aspects.

H. Machleidt [NB 349/207 IE]

Fluorine Chemistry. Vol. V. Edited by *J. H. Simons*. Academic Press, New York-London 1964. 1st Edit., XV + 505 pp., 89 figures, 80 tables, linen, § 16.50.

So far, Volumes I, II, III, and V of the series on "Fluorine Chemistry" started in 1950 are now available; Volume IV is still in preparation.

The first chapter of Volume V, which appeared in 1964, deals with the compounds of fluorine with other elements, including the actinides, but does not describe the inert gas fluorides, which have apparently become known only too recently. With this review, the corresponding twelve sections of Volumes I and II have been repeated in a highly condensed form and supplemented, particularly by preparative results obtained within the past two decades. In the second chapter, the physicochemical properties – mainly thermodynamic data – of carbon/fluorine compounds are collected and compared among themselves and with those of analogous hydrocarbons and chlorocarbons. This chapter supplements the discussion of preparative results in earlier volumes. The third section is devoted to the nuelear chemistry of fluorine, the production of radioactive fluorine isotopes, and their use as tracers in chemistry and biology. Also the radiation chemistry of fluorine compounds, particularly the influence of short-wave radiation on polymeric fluorocarbons, is dealt with.

In the final chapter, for the first time in the series, the applications of fluorine and its compounds in industry and technology are discussed. It is apparently assumed that the technology and use of inorganic fluorine compounds are familiar to the reader; the technical applications of hydrogen fluoride, boron trifluoride, and sulfur hexafluoride are only touched upon briefly, and it is only the application of fluorine and of some fluorine compounds as rocket fuels that receives extensive treatment. The main accent of this chapter lies on the multifarious uses of organic fluorine compounds, *e. g.* as refrigerants, fire-extinguishers, lubricant and aerosol solvents, dielectrics, plastics, and elastomers, and as surfactants in galvanizing and in the leather and paper industries for making products hydrophobic and oleophobic. Their increasing use as foaming agents for making foam rubber and plastics is not mentioned.

Thus, Volume V gives a comprehensive review of the present status of fluorine chemistry and at the same time recapitulates briefly the contents of the previous volumes.

H. Jonas [NB 342/199 IE]

Progress in Organic Chemistry. Vol. 6. Edited by *J. W. Cook* and *W. Carruthers*. Butterworths Scientific Publications, London 1964. 1st edit., VII + 256 pp., several figs. and tables, linen £2.17.6 (about $ 8.–).

As usual, the latest volume of this series brings progress reports from the pens of competent authorities. In the first chapter, *E. Haslam* and *R. D. Haworth* review the current status of research in the field of "Vegetable Tannins". In the second chapter, *M. F. Grundon* describes the interesting class of compounds of the "Bisbenzylisoquinoline Alkaloids". Structural elucidations, syntheses, stereochemistry, and biosynthesis are given particular attention. "Polyacetylenes and Related Compounds in Nature" and the biogenetic relationships between these compounds are discussed by *J. D. Bu'Lock*. *W. Schäfer* reviews the present situation of the "Chemistry of Phenoxazones" in the fourth chapter. Interest in this ring system has been augmented by the isolation and elucidation of the structures of the ommochromes, actinomycin, and the orceine dyestuffs. The next chapter on "Carbenes" by *W. Kirmse* gives an excellent review of the turbulent developments in this field of organic chemistry. In the final chapter, *S. F. Mason* demonstrates with examples the application of the molecular orbital theory to reaction equilibria and rate constants.

Progress reports by acknowledged experts, such as appear in so attractive a mixture in the present volume, are becoming more and more important in view of the ever increasing gush of articles flooding the chemical literature. Like its predecessors, the new volume of this series therefore represents a veritable embellishment of the chemical literature. However, it would have been useful for the reader if some indication were given of the date up to which the literature was reviewed for the individual topics.

H. Stetter [NB 355/213 IE]

Colloidal Surfactants. Some Physicochemical Properties. By *K. Shinoda, T. Nakagawa, B. Tamamushi*, and *T. Isemura*. Physical Chemistry. A Series of Monographs, Vol. 12. Edited by *E. Hutchinson* and *P. van Rysselberghe*. Academic Press, New York-London 1963. 1st Edit., 310 pp., numerous figures and tables, linen, $11.50.

This book is divided into four sections dealing with 1. the formation of micelles, 2. physicochemical studies in aqueous solutions of nonionic surfactants, 3. adsorption phenomena, and 4. monomolecular layers.

In parts 1 and 2, an extensive discussion is given of micelle formation, the critical micelle concentration (CMC), and the various factors effecting this concentration (*e.g.* the structure of the surfactant, additives, or mixtures of surfactants). This text is based on a particularly broad review of the literature. In part 3, the fundamentals for calculating adsorption and the influences on adsorption at air/solution, solution/oil, and solution/solid interfaces are dealt with. Also some special aspects of adsorption are described, *viz.* the adsorption at a solution/mercury interface and the interaction between surfactants and hydrophobic or hydrophilic colloids. In part 4, the behavior of films of surface-active compounds and polymers, particularly synthetic polymers, is discussed.

K. Shinoda and his colleagues have successfully evaluated recent literature in order to give a review mainly of micelle formation and adsorption phenomena from the standpoint of the physicochemical properties of surfactants, paying particular attention to Japanese publications. Many important research communications in this field were written in Japanese and were thus difficultly accessible to scientists in other countries.

P. Kurzendörfer [NB 340/198 IE]

Basic Principles of Organic Chemistry. By *J. D. Roberts* and *M. C. Caserio*. W. A. Benjamin, Inc., New York-Amsterdam 1964. 1st, edit., XXV + 1315 pp., numerous figs. and tables, clothbound $ 15.30.

This book is a successor to the 1935 edition of "Organic Chemistry" by *H. J. Lucas*, and is no less original than its predecessor. Despite the conventional subdivision according to substance classes, the authors manage to place the fundamental principles of synthesis, structure and stereochemistry, bonding phenomena, and reaction mechanisms in the forefront of their discussion. They also succeed in cleverly applying the latest developments in the subject in a didactic fashion without either becoming unintelligible for the beginner or giving only superficial treatments. In all discourses on reaction mechanisms, they carefully stress the pertinent experimental background.

The introduction to spectroscopic methods in Chapter 2 is particularly striking. Structure and bonding relationships are given a solid theoretical foundation on the basis of spectroscopic, thermochemical, and thermodynamic results. Atomic and molecular orbitals are introduced critically alongside the theory of resonance. The modern character of the book is emphasized by its chapters on the biogenesis of terpenes and steroids, color photography, organic photochemistry, polymers, and organosilicon, organophosphorus, and organoboron chemistry, *etc.* No important facet of organic chemistry has been overlooked.

The authors have successfully introduced a subdivision according to reaction types subordinate to their main division according to compound classes. For the compound classes, the modes of preparation are given only in tables, and a detailed discussion of their scope, the reaction conditions, and synthetic importance is then to be found under the reaction type. Thus, for example, "Aliphatic Substitution and Elimination" are to be found in the chapter on alkyl halides, and "Addition Reactions" under alkenes. Reaction mechanisms are always given if they are required to contribute to an understanding of the reaction. A separate index of methods of preparation of all classes of compounds shows how much importance the authors justifiably attach to adequate training in methods of synthesis.

The length of the book is not caused by an excess of material, but by the thorough discussion of essential principles that is given. There are several hundred – occasionally very difficult – questions and exercises interspersed in the text, which can only be answered by proper application and combination of these principles, not by unconnected knowledge of facts. These "Problems" often go beyond the material dealt with in the book. This raises a problem only when the answers to such questions are essential for an understanding of the subsequent text or when important reactions appear only in the exercises (*e.g.* sugar extension or sugar degradation reactions or peptide syntheses with carbodiimides).

There is very little fault to be found with the excellently illustrated text: the bridged bromonium radicals rejected on p. 189 have been positively detected in the meantime by *Skell*; the preference of a two-step mechanism for the Diels-Alder reaction is not necessarily correct (p. 268); the intermediates of the Bucherer reaction (p. 909) are tetralonesulfonic acids and not hisulfite adducts of the keto form of naphtholes (*A. Rieche* 1960); *Goldschmidt*'s 9-chlorophenanthroxyl (p. 916) does not give an electron spin resonance signal and is probably a dimeric quinol ether (*E. Müller* 1959).

This didactically outstanding textbook can be heartily recommended to every student of chemistry and to chemists who wish to refresh or renew their knowledge. It should be especially worthwhile for beginners to work through the not altogether easy text alongside their organic chemistry courses.

O. Rüchardt [NB 379/237 IE]

Advances in Organic Chemistry: Methods and Results. Edited by *R. A. Raphael, E. C. Taylor*, and *H. Wynberg*. Vol. 3. Interscience Publishers, a Division of John Wiley & Sons, New York-London 1963. 1st edit., 333 pp., several illustrs. and tables, linen £5.5.0 (about $ 14.50).

The valuable series on "Advances in Organic Chemistry" continues with this third volume, which contains four review articles. The first contribution by *R. I. Reed* on "Mass Spectrometry as a Structural Tool" discusses the most important applications of mass spectrometry to structure elucidations (74 pages). The literature is reviewed effectively only until 1959; since then, good monographs on this subject have appeared, which also take the latest rapid developments into account. However, the reviewer does not claim to be an expert judge in this field.

The next essay by *D. M. Brown* on "Phosphorylation" gives a surprisingly comprehensive survey in 83 pages. Such a complete review of this subject was hitherto not available. The report is critical and comprehensive, easy to read and well organized. The fact that it will nonetheless not always be easy for the newcomer to this field to find the most suitable phosphorylation methods for his purposes by mere perusal of this article, is probably due to the complicated nature of the phenomenon of phosphorylation.

The following articles by *R. A. Boissonnas* on amine protecting groups for peptide syntheses (31 pp.) and by *J. F. W. McOmie* on "Protective Groups" (103 pp.) fully discuss these topics without any significant overlapping. The review by *McOmie* is especially interesting and contains a wealth of information: it was an excellent idea of the editing committee to include articles containing a review of all protective groups. The series, particularly Vol. 3, belongs in every chemical library.

F. Cramer [NB 356/214 IE]

Physical Organic Chemistry. By *K. B. Wiberg*. John Wiley & Sons, Inc., New York-London-Sydney 1964. 1st Edit., VIII + 591 pp., numerous illustrations and tables, linen, £ 4.0.0 (about $ 11.00).

In the foreword to this book, *K. B. Wiberg* says that he has made an attempt to write a useful textbook which concentrates on the physical- chemical aspects of "Physical Organic Chemistry". By this he means the theoretical background of physical measurements on organic compounds, the mathematical treatment of experimental data, and the physical interpretation of empirical relations. This also includes the quantum-mechanical theory of the chemical bond, which is dis-

cussed together with electronic spectra and the theory of vibrational and nuclear magnetic resonance spectra in the first section on "Bonding and Spectra". The second section, "Equilibria", deals with chemical equilibria and includes chapters on the partition function, heats of formation, solvent and isotope effects, linear free energy relationships, and acidity functions, *etc.* The third section, entitled "Kinetics", first describes methods of determining the rate constants and rate laws from kinetic data and then discusses the absolute rate theory, kinetic isotope effects, the influences of solvents, linear free energy relationships, and acid catalysis. The book closes with a long appendix containing tables, a discussion of the mathematical treatment of NMR spectra and kinetic data, and an introduction to programming for electronic computers, together with a collection of Fortran programs for the problems dealt with in the book. "Physical Organic Chemistry" is expressly written as a textbook and therefore does not attempt an exhaustive compilation of the publications that have appeared on individual fields; instead, the methodology is explained by means of carefully selected examples, which are given a detailed treatment. Each chapter is rounded off with problems and reading lists.

This brief description of the contents suffices to show that precisely those borderline fields are dealt with which are essential for understanding many publications but which still receive only little attention in textbooks and lecture courses. From this point of view the attempt to write a useful textbook has been highly successful. The value of the book is not impaired by the relatively large number of misprints and by an occasionally subjective selection of material (*e. g.* the somewhat one-sided presentation of the arguments of *Dewar* and *Schmeising* on the delocalization of π-electrons). Unfortunately, however, the book is rather unbalanced and at times didactically inadequate, as the following examples indicate, which could easily be multiplied.

In the chapter on vibrational spectra, the terms normal modes, degenerate vibrations, and parallel and perpendicular type bands are applied without being explained. Methods are given for calculating the spectrum of an A_2X_2 spin system, but the definition of an A_2X_2 system is sought for in vain. Frequently (*e. g.* on pp. 5, 215, and 453), at the vital point in a detailed mathematical derivation, the next step is introduced merely by "it can be shown that...". On p. 16, the same symbol is used within a single formula with two different meanings. On p. 28, the text and the figure and on p. 420 the text and the table do not agree. The equations are not numbered, and thus the text is sometimes hard to understand and cross-references become difficult. Factual errors occur, for example, on p. 116, where it is stated that the integral (11/12) disappears when using orthonormal orbitals, but this is only true when applying the Mulliken approximation, which is not mentioned. On p. 453, it is stated: "The properties of determinants deduced previously (*e. g.* by multiplication of a row or a column with a factor, the determinant is multiplied by this factor) also apply to matrices".

Most of the inaccuracies and broken trains of thought could be remedied, and the missing definitions could be included without increasing the size of the book if the figures on pp. 29–35, *etc.* were reduced to reasonable dimensions and if the appendix were shortened: Especially since it is assumed that the reader makes use of electronic computers, 24 pages with tables of the thermodynamic functions of a harmonic oscillator and 13 pages of overlapping integrals are superfluous, when other sections are kept so brief (*e. g.* the treatment of symmetry by the group theory is restricted to 3 pages!) that they must necessarily remain incomprehensible without reverting to further literature.

One would like to see as many students as possible acquainted with the material presented here. The book should therefore be strongly recommended. Unfortunately, however, the reader must be willing to take the trouble that the author should have invested in order to develop this book into a really useful text. It can only be hoped that a completely revised edition will soon appear. *M. Klessinger* [NB 341/204 IE]

Radiolysis of Hydrocarbons. Edited by *A. V. Topchiev*. English edition edited by *R. A. Holroyd*. Elsevier Publishing Co., Amsterdam-London-New York 1964. 1st Edit., XII + 232 pp., 69 figures, 35 tables, linen, DM 36.– (about $9.00).

In the radiation chemistry of hydrocarbons, there are some reactions, *e. g.* cracking, that are of preparative and technological interest. Kinetic studies are of particular importance since they furnish information on the reactions of radicals, on energy-transfer mechanisms, and on the influence of catalysts on radiolytic reactions. *Topchiev*'s book goes into all of these matters insofar as they have been investigated in the Institute for Petroleum Research in the U.S.S.R. between 1957 and 1961. The book contains a lot of experimental results and theories on the radiation chemistry of hydrocarbons, and thus gives an excellent survey of advances in the radiolysis of hydrocarbons in the U.S.S.R. up till 1961.

Radiation chemistry flourishes and fades with the rapid changes in theoretical concepts, which in turn depend upon the advances in molecular and radiation physics and in experimental methods. *Topchiev*'s book conveys the impression of being dedicated especially to energy transfer. The phenomenon of energy transfer is demonstrated convincingly by electron spin resonance measurements on irradiated solid hydrocarbons containing minute amounts of an inhibitor which, although immobile, reduces the radical yield. The author presents a theory according to which inhibition occurs by radiationless transfer before the energy of electronic excitation is converted into vibrational energy. The assumption that this theory – which is developed in clear and precise mathematical terms – is generally applicable to inhibition effects, even in liquid systems, appears to be hardly justified, because of the complexity of radiochemical reactions.

Energy transfer from oxide catalysts to adsorbed hydrocarbon molecules is also described in detail and formulated mathematically. Attention is drawn to the difference between energy dissipation by fast charged particles in gases and in condensed materials. For example, the principle of "collective" excitation which is occupying the theoreticians in radiation chemistry so much at present, is anticipated by the discussion on p. 113.

In concluding it can be said that although some of the material presented is probably already superseded by newer results because of the rapid development in this field of research, *Topchiev*'s book contains many ideas on the theory of radiation chemistry with which the expert in this discipline ought to be familiar. *A. Henglein* [NB 343/200 IE]

Experimental Spectroscopy. By *R. A. Sawyer*. Dover Publications Inc., New York 1963. 3rd Edit., X + 358 pp., 110 figures, paperback, $2.00.

Sawyer restricts his discussion to spectroscopy in the range from the ultraviolet to the infrared available with prism or diffraction grating spectrographs: other ranges and interference methods are intentionally excluded. A simple, easily understandable discourse on the experimental aspects of spectroscopy is developed in 13 chapters, starting from fundamentals and going on to instrumentation, then to photographic processes, the determination of wavelengths and intensities, and finally discussing ultraviolet and infrared spectroscopy and spectrochemical analysis. However, some essential points are overlooked; for example, the light intensity of a spectrograph is characterized by its relative aperture, without making it clear to the inexperienced reader that the length of the basis of the refracting element is the most important factor for the energy density per wavelength region in the plane of the image.

The chapter on photographic processes contains so many elementary mistakes that it is hard to imagine how the author's attention has not been called to this by users of the previous editions. The photographic process is described in details that are unnecessary for practical spectroscopy and

which swell up the book with redundant and erroneous information. This section has apparently not been revised since the appearance of the first edition in 1944. – The subject index is unsatisfactory: it should be more extensive and built up on a better system of classification.

Despite these shortcomings, the book may be recommended as a cheap but authoritative introduction to spectroscopy.

W. F. Berg [NB 332/190 IE]

Infrared Spectroscopy and Molecular Structure. An Outline of the Principles. Edited by *M. Davies*. Elsevier Publishing Co., Amsterdam-London-New York 1963. 1st Edit., XIII + 468 pp., 171 figs., 70 tables, linen ca. DM 42.– (about $ 10.50).

This book is intended for all who use infrared spectroscopy not merely as an empirical fingerprint method but as a theoretically founded process for the investigation of the structures and properties of molecules. Here the theoretical and methodical principles as well as the scope and limitations of the various applications of infrared spectroscopy are presented by 13 authorities in clear and understandable terms. The most important concepts and facts, from both the chemical and physical points of view, are unraveled so lucidly even when the material dealt with is complicated that also those who are less experinced find a good introduction to this discipline. The fact that the authors have concentrated on important examples contributes significantly to this effect.

The introductory section written by the editor is followed by chapters on instrumentation and experimental techniques *(A. E. Martin)*, on long-wave infrared spectroscopy in the region from 1 to 200 cm^{-1} which has only recently become utilizable *(G. R. Wilkinson)*, on the infrared spectra of simple molecules *(W. J. Jones)*, on the calculation of force constants *(J. M. Mills)*, and on Raman spectra *(J. C. Evans)*. The chapter by *D. Hadzi* on the origin of characteristic group frequencies deserves special mention. Further sections deal with the infrared spectra of crystals and high polymers *(S. Krimm)* and of inorganic compounds *(E. A. V. Ebsworth)*. The technique of infrared intensity measurements, which becomes more and more important, and its application for the determination of polarity are discussed by *J. Overend*. The methods of dispersion measurements, including the practically important technique of attenuated total reflection, are described by *J. Fahrenfort*. The book then closes with chapters on hydrogen bonding and solvent effects *(H. E. Hallam)* and on infrared emission spectra *(W. C. Price)*. The text is supplemented by some 800 references.

The editor has succeeded well in coordinating the contributions from the individual authors into a largely homogeneous book with an up-to-date selection of themes. On account of its admirable didactic qualities, it is recommended in general as a textbook of spectroscopy for the advanced specialist and for those striving to attain this status, for it teaches the reader to think in spectroscopic terms. The outlay and print of the book are exemplary in their clarity.

W. Lüttke [NB 326/184 IE]

Infrared Spectra of Inorganic and Coordination Compounds. By *K. Nakamoto*. John Wiley & Sons, Inc., New York-London 1963. 1st Edit., XII + 324 pp., numerous illustrs. and tables, linen £ 2.12.0 (about $ 7.25).

There has long been a lack for a book reviewing the greatly increased literature on vibrational spectra of inorganic compounds and giving a critical appraisal of publications in this field with regard to both the practice of spectroscopy (*e. g.* for structural analysis) and the theory of molecular physics as related to force constants. The author attempts to satisfy this need, to assign the published data to normal vibrations, and to interprete their significance for the structures of molecules and ions. The first of the three sections of the book (63 pp.) gives a brief but lucid discourse on the theory of spectra. In the second part (69 pp.), the spectra of simple organic compounds are discussed, again very briefly. In the large third section, which forms the mainpart of the book, data for inorganic complex compounds are described. Five appendices (45 pp.) include *inter alia* tables of point groups, F and G matrix elements of model compounds, and, by way of an example, the complete normal coordinate analysis of an acetylacetonate. The text is supplemented by numerous tables, illustrations, and literature references.

On account of the expansiveness and ready surveyability of the material and its intelligible presentation, the book could be warmly recommended to inorganic chemists interested in spectroscopy and especially to complex chemists, if the author had only discussed the material (particularly in Part II) with greater criticism. For example, in contrast to the data given on p. 71, hydrogen halides (except for HF) do not associate in the condensed phase; this follows from the fact that the $\nu X-H$ frequencies of liquid hydrogen halides are lower by 2–3% than those of the gaseous compounds. It does not follow from the appropriate spectra that there are "essentially covalent bonds" in AgCN and AuCN (p. 73); the high CN frequencies indicate only the presence of Ag···CN···Ag···CN··· bridges (or Au). A free $UO_2^{\oplus}$ ion (p. 77) cannot be observed, according to more recent publications; ligands are always coordinated in the plane vertical to the UO_2 axis. Results dating from 1938 are given for H_2Se and D_2Se (p. 83), although more recent measurements *(Palik, 1959)* with some remarkably great differences in frequencies are available. NT_3, PT_3, and AsT_3 (p. 84) have never been measured, but were only calculated. The C_{2v} structure given for N_2F_2 on p. 102 has been shown to be incorrect; the compound is subject to geometric isomerism. The numerical values given for CH_4 and CD_4 (p. 104) are not up-to-date. The data for NH_4Cl (p. 104) are not characteristic of the $NH_4^{\oplus}$ ion, because ν_4 (1400 cm^{-1}) here is strongly split by Fermi resonance. Insufficiencies of this kind are easy to eradicate in a new edition, and it would also be desirable for the author to go deeper into the relations between spectra and molecular structures (*e. g.* how to derive information about the bond order from the force constants). Sufficient space can be made quite easily by omission or reduction of some figures (*e. g.* on pp. 74, 94, 147, 170, 174, and 200). All in all, the book is usefull for the critical, well-informed reader; the outward appearance and the print are good.

W. Lüttke [NB 327/185 IE]

Inorganic Thermogravimetric Analysis. By *C. Duval*. Translated from the French by *R. E. Oesper*. Elsevier Publishing Co., Amsterdam-London-New York 1963. 2nd Edit., XV + 722 pp., 77 figs., linen ca. DM 67.– (about $ 17.00).

The principle of thermogravimetry is the continuous registration of alterations in weight of a solid sample during a heating program. Thanks to the development of modern automatically recording thermobalances, this process is easy and rapid to execute and is a versatile aid in the investigation of inorganic compounds: determination of moisture contents and water of crystallization, controlled drying to constant weight, testing of analytical precipitates for their suitability for gravimetric estimations, detection of the limits of stable phases, quantitative analysis based on the loss of weight during decomposition reactions (even of two components of a mixture), investigations of reactions between solids and gases, *etc.*

Duval has compiled the first extensive monograph on this field, in the development of which he has himself taken a significant part. In the first section of the second edition (164 pp.), following a historical introduction, the apparatus and experimental methods of thermogravimetry are dealt with. This part has been extended by about 100 pp. in comparison with the 1953 edition, owing mainly to the description of the automatically recording thermobalances which have been developed in the meantime and which are now commercially available. The main section of the book (519 pp.) contains the results of thermogravimetric investigations of analytical precipitates from 78 elements, arranged according to increasing atomic weight. In all, the behavior of about 1200

precipitates during thermolysis is described; here the author has relied mainly upon the results of his own school. In contrast to the first edition, the reproduction of thermolysis curves for individual compounds has been omitted, because the detailed appearance of the curves depends too much upon the experimental conditions. The author restricts his description to the principal parts of the curves, the horizontal sections and the stability regions, and to the suitability of individual compounds for purposes of gravimetric analysis. *Duval*'s book is thus a comprehensive reference work on thermogravimetry.

Despite the widespread application of thermogravimetry, it appears to the reviewer that the relationships of this method to the thermodynamics of heterogeneous equilibria have not yet been sufficiently pointed out, even though a profitable field is offered here. The processes that occur during thermogravimetry are in fact often highly complex and depend upon the experimental conditions, since the ideal conditions of isobaric decomposition under equilibrium conditions are normally far from being attained. For this reason, the form of the thermolysis curves depends upon the particle size and pretreatment of the sample, upon the rate of flow and composition of the gaseous phase, and upon the rate of heating. Therefore, the decomposition points found in this way need not be identical with the temperatures at which the equilibrium pressure of a gaseous decomposition product, such as water vapor, reaches the value of 1 atmosphere.

These comments are not intended to depreciate the value of *Duval*'s book, but rather to serve as an incentive for its readers to occupy themselves with the still unused potentialities of thermogravimetry.

The lay-out and appearance of the book are excellent, in keeping with the high standards of the Elsevier publishing house. This volume should not be missing in any chemical library or inorganic chemistry laboratory.

Friedrich Becker [NB 325/183 IE]

Analytical Chemistry of Uranium $_{92}U^{238.03}$. Published by the Academy of Sciences of the U.S.S.R. and edited by *D. I. Ryabchikov* and *M. M. Senyarin*. Translated from the Russian by *N. Kaner*. Series: Analytical Chemistry of Elements. Israel Program for Scientific Translations, Jerusalem 1963. 1st Edit., VII + 374 pp., 70 figs., 51 tables, linen $14.00.

Because of the widespread use of uranium in nuclear technology, there are numerous methods for determining and detecting uranium in ores, uranium compounds, and alloys scattered in the literature, but so far no comprehensive monograph on the analytical chemistry of uranium has appeared (with the exception, perhaps, of a few difficultly accessible compilations [1–4]). The present volume is a critical review of material from over a thousand publications. Following a general introduction to the chemistry of uranium (Chapter 1), in which the most important properties of the element, its isotopes, and some of the most common uranium minerals are described, a short review is given in Chapter 2 on the special inorganic chemistry of uranium, with particular stress upon analytical aspects. Valuable tables of solubilities and complexing constants in various solvents are given.

In Chapter 3, on the qualitative detection of uranium, it is mainly color and fluorescence tests that are dealt with. Besides the well known fluorescence reaction in the NaF bead, reactions with inorganic and organic color reagents are described in detail and compiled in a long table. Although the interferences caused by other elements are described, no reference is made to the behavior of neptunium and plutonium. There is also no mention here of the classical precipitation reaction as sodium uranylacetate crystals, which also works with $NpO_2^{2\oplus}$, $PuO_2^{2\oplus}$, and $AmO_2^{2\oplus}$. This is found somewhat out of place on p. 236.

Chapter 4 contains 174 pages devoted to methods for estimating uranium and thus makes up over a third of the book. It is subdivided into three sections: A) chemical methods of analysis, B) physico-chemical methods of analysis, and C) physical methods of analysis. The subsection on colorimetric and spectrophotometric methods of analysis without and with the use of organic color reagents is worth mentioning. Here, too, the reader finds welcome extensive tabulations with data on extinction coefficients (pp. 89 and 114).

Methods for separating uranium from other elements are given in Chapter 5, and methods for determining uranium in minerals and industrial wastes in Chapter 6. Although, for example, the analysis of uranium/zirconium alloys is described briefly (p. 301), no attention is called to the danger of explosions on dissolution of such alloys in nitric acid. The book closes with Chapter 7 on the testing of the purity and estimation of impurities in uranium, and with a comprehensive bibliography (1093 references). Here the translator has made some errors in his retranscription of names from Kyrillic into Latin script, for it should be *Götte* and not *Gotte* in reference 554, and *Ladenbauer* and not *Ladenbayer* in reference 981. The numerous practical procedures given would have profited from tests of their experimental usefulness. The print is clean and tidy, but the lay-out could have been better arranged.

Despite these minor shortcomings, the book is recommended to all higher institutions of chemical learning, to uranium processing industries, and to analytical laboratories, for it covers practically the whole of the more important literature on the analytical chemistry of uranium in a single volume and helps one to find rapid recourse to original publications via its bibliography.

F. Weigl [NB 324/182 IE]

Nobel Lectures. Physiology or Medicine 1942 – 1962. Published by the Nobel Foundation. Presentation Speeches and Laureates' Biographies. Elsevier Publishing Co., Amsterdam-London-New York 1964. 1st edit., XIV + 839 pp., numerous illustrs., a few tables, price for complete 3-volume work in half-linen Hfl. 240.–.

The Nobel Prize in Physiology or Medicine was awarded twenty times between 1942 and 1962, including thirteen awards for work in biochemical research. For this reason, the present volumes can be recommended to the chemist. Many, especially biochemists, will find material in the contents which touches directly their own work. However, this does not represent the prime purpose of the book; its aims go much further. All the Nobel lectures held between 1942 and 1962 in the fields of physiology or medicine are reproduced here in English in chronological order, together with the laudations and biographies of the prize-winners. The result is an extremely vivid and fascinating picture of the development of medicine, physiology, and physiological chemistry over these two decades. When one reads at the end of the Nobel lecture by *Sir Alexander Fleming* (1945) "the time may come when penicillin can be bought by anyone in the shops..." and then considers how soon afterwards not only penicillin but also a great number of its derivatives became available in sufficient amounts, then one appreciates even as an outside observer just how much has been achiev-

[1] *M. A. DeSesa*: Raw Materials Development Laboratory Handbook of Analytical Methods. National Lead Co., Raw Materials Div., Winchester, Mass. (U.S.A.), TID-7002 (March 30th, 1956); TID-7002 (Rev. 1) (July 30th, 1957).

[2] *C. E. Rodden*: Current Procedures for the Analysis of UO_3, UF_4, and UF_6. New Brunswick Lab., U.S. Atomic Energy Comm., TID 7003 (Del.) (Feb. 1956).

[3] *H. P. Raaen*: Manual of Analytical Procedures for the U^{235} Recovery Process. Oak Ridge National Lab. Report ORNL-983 (August 20th, 1951).

[4] *L. C. Bassett, D. J. Pflaum, R. J. Rutman, C. J. Rodden*, and *N. H. Furman*, Manual of Analytical Methods. Vol. 1: Analysis of Ores; Vol. 2: Analysis of Refined Materials and By-products; Vol. 3: Analysis of Purified Materials. Manhattan Project Report A-2912, Vols. 1–3.

ed. The book will be indispensable to the historian, for it offers first-hand insight into scientific history, when, for example, *Hans Adolf Krebs* reports on the "evolution" of the tricarboxylic acid cycle or when *E. C. Kendall* relates the exciting developments which, though beset with disappointments, finally led to the synthesis and therapeutic application of cortisone.

The publishing house can be congratulated to this undertaking of making all the Nobel lectures available in collective volumes, and it is to be hoped that these reproductions of testimonies of great human achievements will arouse the interest they deserve.

H. Grünewald [NB 362/220 IE]

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Organic Dyes as Photoelectric Semiconductors

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Photoconduction in organic dyes is caused by the formation and migration of electronic charge carriers, and is not due to impurities or photochemical decomposition. The phenomena of dark and light-induced conduction in dyes can therefore be interpreted in the same way as in inorganic semiconductors.

A. Introduction

In spite of *Zcodro's* discovery in 1919 [1] that organic dyes undergo slight changes in conductivity on illumination, and the observation of similar phenomena in anthracene several years earlier [2, 3], systematic investigation of this effect did not commence until thirty years later. This delay might well have been due to the predominant application of inorganic semiconductors, brought about by the rapidly developing science of semiconductor physics after 1920 and initiated by the work of *Gudden* and *Pohl* [4–8]. The slow response, irreversibility, dependence on the surrounding gas, and small magnitude of the then known photoelectric effects of organic substances [1–3, 9, 10] suggested that changes in the resistivity on illumination were due to bleaching rather than to internal photoelectric effects analogous to those occurring in inorganic photoconductors.

Growing interest in the elucidation of the spectral sensitization of photographic materials and in photochemical aspects of biology led to a systematic investigation of the photoelectric behavior of dyes. *Vartanyan* [11] in Russia, *Nelson* [12] in the United States, and *Noddack et al.* [13–16] in Germany began independent studies in the early 1950's. *Vartanyan* and *Nelson* obtained evidence of photoconduction in basic dyes only, but *Noddack's* group demonstrated that acidic and nonionic dyes also exhibit this effect. From the very beginning, the laws established from a study of more than 50 dyes of various types indicated an electronic mechanism in accord with the phenomena observed in inorganic photoconduction effects [14–16]. Thermoelectric power measurements and the Hall effect have since established clearly that electronic charge carriers formed in the solid dyes, rather than impurities or decomposition products, are responsible for photoconduction.

B. Fundamentals

The agreement between photoconduction phenomena of organic and inorganic photoconductors leads to an approach to the fundamental semiconductor properties of organic dyes according to the theory of photoconductors in general [7, 17–20].

[1] *N. Zcodro*, Bull. Acad. St. Petersburg *6*, 727 (1919).
[2] *A. Byk* and *H. Borck*, Ber. dtsch. physik. Ges. *8*, 621 (1910).
[3] *M. Volmer*, Ann. Physik *40*, 775 (1913).
[4] *B. Gudden* and *R. W. Pohl*, Z. Physik *7*, 65 (1920); *16*, 170 (1923).
[5] *B. Gudden*: Lichtelektrische Erscheinungen, Springer, Berlin 1928.
[6] *B. Lange*: Die Photoelemente und ihre Anwendung, 1. Teil. Johann Ambrosius Barth, Leipzig 1940.
[7] *H. Simon* and *R. Suhrmann*: Der lichtelektrische Effekt und seine Anwendungen. Springer, Berlin 1958.
[8] *P. Görlich*: Photoeffekte II. Akademische Verlagsges. Geest & Portig, Leipzig 1963.
[9] *N. Zcodro*, J. Chim. physique *26*, 117, 178 (1929).
[10] *A. Petrikaln*, Z. physik. Chem. B *10*, 9 (1930).
[11] *A. T. Vartanyan*, Zh. fiz. Khim. *20*, 1065 (1946); *24*, 1361 (1950); *27*, 272 (1953).
[12] *R. C. Nelson*, J. chem. Physics *19*, 798 (1951); *20*, 1327 (1952).
[13] *W. Noddack*, *G. Eckert*, and *H. Meier*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *56*, 735 (1952).
[14] *W. Noddack* and *H. Meier*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *57*, 691 (1953).
[15] *H. Meier*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *58*, 859 (1954).
[16] *H. Meier*, Z. wiss. Photogr., Photophysik Photochem. *50*, 301 (1955).
[17] *P. Görlich*: Advances in Electronics and Electron Physics, Vol. XIV (C). Academic Press, New York *1961*, pp. 37–84.
[18] *G. Heiland* and *E. Mollwo* in Landolt-Börnstein, Vol. II.6. Springer, Berlin 1959.
[19] *W. Shockley*: Electrons and Holes in Semiconductors. Van Nostrand, New York *1950*, pp. 463.
[20] *L. Heijne*, Philips' techn. Rdsch. *25*, 233 (1963/64).

I. Thermal and Optical Excitation Energy

Photoconduction is based on the formation of negative and positive electronic charge carriers by optical means, whereas dark conduction depends on the thermal excitation of electrons and positive holes (dissociation or auto-excitation).

$$\sigma_D = \sigma_{D0} \exp(-\Delta E_{therm}/2kT) \quad (1)$$

The thermal activation energy, ΔE_{therm}, is obtained from the temperature coefficient of the dark conductivity σ_D and is in substantial agreement with the energy of the light quanta, ΔE_{opt}, which must be absorbed to produce photoconduction. ΔE_{opt} can be determined from the limiting wavelength λ_g corresponding to the absorption edge or from the long wavelength limit λ_g^* of the photoconduction. The required relationship is

$$\Delta E_{opt} = hc/\lambda_g;\ \Delta E_{opt} = hc/\lambda_g^* \quad (2)$$

The agreement of the excitation energies ΔE_{therm} and ΔE_{opt} of intrinsic semiconductors indicates that dark and light-induced conduction are distinguished merely by the nature of the excitation of the charge carriers. Propagation of the carrier through the solid is subject to the same laws in both the dark and illuminated state.

This rule is not vitiated by occasional deviations such as the displacement of the threshold wavelength of the internal photoelectric effect to longer wavelengths than the absorption edge, or the difference between excitation energies measured by thermal and optical means respectively. These deviations are simply due to the presence of impurity levels formed by added foreign atoms (*e.g.* in defined form in extrinsic semiconductors), lattice imperfections, and dislocations, which can also excite charge carriers.

II. n- and p-Type Conductivity

Thermal and optical excitation produces an equal number of electrons and positive holes (defect electrons) in the semiconductor. Both migrate through the solid under the influence of an electric field to produce the observed conductivity [21]. If dislocations are present in the solid, charge carriers can be excited also from these sites. In the case of donor centers, the conductivity is due predominantly to electrons (n-type conductivity); acceptor centers accept electrons to form displaceable positive holes which are the major charge carriers (p-type conductivity).

III. Characterization of Conductivity

To characterize the conductivity of a solid, data concerning the lifetime τ, the mobility μ, the mean free path w and, in the special case of photoconduction, the quantum yield G, are significant in addition to the nature of the charge-carrier. The relationships between these quantities can best be illustrated by a discussion of the photoconductivity of solids (semiconductor cross-section $B \times D$ [cm^2], electrode spacing L [cm], semiconductor volume v [cm^3].

1. *Lifetime, Mobility, Mean Free Path, Transit Time*

Free mobility of the optically (or thermally) formed charge carriers is limited to their mean lifetime τ which is terminated by recombination with ionized dislocations, capture centers, oppositely charged carriers, and so on. During this period, a charge carrier moving with a velocity u traverses a distance w, the mean free path:

$$w = \tau u \quad (3)$$

or

$$w = \tau \mu \mathfrak{E} \quad (4)$$

since

$$u = \mu \mathfrak{E} \quad (5)$$

In Equations (4) and (5), μ [cm^2 volt^{-1} sec^{-1}] is the mobility of the charge carriers and $\mathfrak{E}$ is the field strength. Assuming that g charge carriers are formed per cubic centimeter per second, *i.e.* gLBD or gv in the system considered, each of which travel an average distance w, the photocurrent flowing in the outer circuit is given by

$$I_{phot} = gve\tau\mu\mathfrak{E}/L \quad (6)$$

When the transit time T which a carrier requires to travel from one electrode to the other [given by Equation (7)] is substituted in Equation (6):

$$T = L/\mu\mathfrak{E} \quad (7)$$

it follows, since $u = L/T$ and $u = \mu\mathfrak{E}$ that:

$$I_{phot} = gLBDe\tau/T \quad (8)$$

At equilibrium the number of charge carriers formed per unit time is equal to the number of charge carriers which disappear by recombination, so that the carrier concentration Δn is given by

$$\Delta n = g\tau \quad (9)$$

and

$$I_{phot} = \Delta n ve\mu\mathfrak{E}/L \quad (10)$$

For a semiconductor in which L, B, and D are each 1 cm, the photocurrent density j is given by

$$j_{phot} = \Delta ne\mu\mathfrak{E} \quad (11)$$

Hence if Ohm's law ($j = \sigma\mathfrak{E}$) is valid, the photoconductivity is given by

$$\sigma_{phot} = \Delta ne\mu \quad (12)$$

For photoconduction by electrons and positive holes with equilibrium concentrations Δn_n and Δn_p and mobilities and μ_n and μ_p respectively, we have

$$\sigma_{phot} = e(\Delta n_n\mu_n + \Delta n_p\mu_p) \quad (13)$$

$$j_{phot} = e(\Delta n_n\mu_n + \Delta n_p\mu_p)\mathfrak{E} \quad (14)$$

Equation (14) presupposes that both the mobilities and the field strength $\mathfrak{E}$ inside the semiconductor do not change on illumination. This condition is practically fulfilled for the mobilities, but formation of space charges inside the semiconductor changes $\mathfrak{E}$, so that Ohm's law is no longer obeyed.

[21] *E. Spenke*: Elektronische Halbleiter. Springer, Berlin 1956.

2. *Quantum Yield*

The quantum yield G may be expressed as the ratio of the number of charge carriers flowing through the outer circuit (I_{Phot}/e) to the number of light quanta (gv) absorbed in the same time. From Equation (6) we therefore obtain:

$$\frac{I_{phot}/e}{gLBD} \equiv G = (\mu\tau)\mathfrak{E}/L \qquad (15)$$

Substitution of the transit time T from Equation (7) leads to:

$$G = \tau/T \qquad (16)$$

G is also known as the "gain factor" [22] (Section F).

IV. Effect of the Contacts on the Photocurrent

The photoconductivity of inorganic semiconductors often shows complex behavior due to the effect of the electrodes and possible space charges. The question thus arises whether charge carriers can enter the photoconductor from the electrodes.

1. *Blocking Contacts*

a) Electrons and Positive Holes are Mobile

If the charge carriers formed by illumination have the same mobilities, an increase in the field strength increases the rate at which carriers reach the electrodes, but no charge carriers are supplied from them if contact barriers are present. As soon as all optically formed charge carriers are being removed at a given field strength, saturation of the photocurrent occurs and the quantum yield reaches its maximum value of unity. Movement of the two types of charge carrier in opposite directions can give rise to a space charge which is superposed on the applied field in the semiconductor and leads to a deviation from the linear relationship between current and illumination intensity, especially at low fields.

Occurrence of saturation currents does not indicate the presence of contact barriers in every case. Saturation can take place at high fields also with electrodes which release charge carriers, because of the formation of space charges. This is the case, for example, when the transit time T ($=L/\mu\mathfrak{E}$) is less than the period $\tau_R = \varepsilon\varepsilon_0/\sigma$ required to compensate the space charge (ε = dielectric constant; $\varepsilon_0 = 8.86 \times 10^{-14}$ sec ohm^{-1} cm^{-1}; σ = conductivity), so that the elimination of the space charge by the injected charge carriers is no longer operative.

b) One Charge Carrier Only is Mobile

When only one type of charge carrier migrates towards the oppositely charged electrode, while the other remains effectively stationary, a high space charge is formed in the vicinity of one of the electrodes. Since the space charge neutralizes the field in the photoconductor, only the charge carriers formed in the vicinity of this electrode can contribute to form a very small photocurrent.

2. *Replenishment Electrodes*

When the thermal work function of one electrode is small compared to that of the semiconductor, the eliminated charge carriers can be replaced by the electrode. Strictly speaking, this is equivalent to an extension of the lifetime, so that quantum yields $G > 1$ are possible when $\tau > T$ as is clear from Equation (16). Since these replenished charge carriers can lead to the disappearance of space charges, the electric field inside the semiconductor remains substantially homogeneous.

Ohm's law is therefore obeyed at high fields, becoming invalid only when space-charge-limited currents are involved. Saturation currents are observed for the case $T < \tau_R$ (see Section B. II. 1. a)), since the injected charge carriers can no longer effectively compensate the space charges [17]. It is also possible for the current to be limited by space charges generated by the moving carriers as soon as the concentration of the injected carriers exceeds the concentration n_i of the excited carriers. From this limiting potential $V_R = n_i eL^2/2\varepsilon$ upwards, the current grows at a faster rate than indicated by Ohm's law (cf. Section D. II.).

It is noteworthy that space charges can be used to force a replenishment of charge carriers from electrodes having a higher thermal work function than the semiconductor (cf. Section F. II.).

A distinction was formerly made between a primary photocurrent ($G < 1$) and a secondary current ($G > 1$) [4, 5]. Since the replenishing process at the electrode – which is ultimately responsible for $G > 1$ – does not strictly represent a secondary process, this distinction is not necessary.

V. The Effect of Capture Centers

Lattice defects, impurities *etc.* produce so-called trapping centers in semiconductors. These can accept charge carriers, and consequently have a particularly strong effect on the response times, *i.e.* on the rate of change of current when the illumination is altered [22, 23].

As explained in Section D. VII., centers of this nature are probably responsible for a number of temperature effects in photoconduction.

VI. Energy Relationships in a Solid

1. *The Band Model*

The band model is a schematic representation of the energy states of the charge carriers in a solid. In this representation, the electron energies are plotted along the vertical coordinate, and the horizontal coordinate indicates the spatial distribution. This model shows a large number of energy levels, most of which can be unified to form groups or bands (Fig. 1).

[22] *A. Rose*, RCA Review *12*, 362 (1951).

[23] *H. Meier*, Z. physik. Chem. *208*, 340 (1958).

In principle, each band originates from a discrete energy level of an atom (or molecule) capable of being occupied by electrons. The electron interaction (exchange degeneracy) causes an originally discrete atomic or molecular level to be split into many components on transfer into the solid. Since these exchange degeneracy effects increase with decreasing spacing of the atoms and molecules in the lattice as a result of greater overlap of the wave functions, a reduction in the spacing will lead to a greater band width, *i.e.* to a greater energy difference among the partial levels. Energy bands can be formed from particles up to 10 Å apart [24].

Electrons which pass into the level of an empty or partially filled band by thermal excitation can be regarded as freely mobile when they take up energy from an applied field. When the predominant migration is in the conduction band E_L, n-type conductivity occurs. In a filled ground-state band E_V, any holes behave as positive charge-carriers (defect electrons), as is confirmed by Hall-effect measurements and other evidence. Hence, p-type conductivity is obtained when these carriers predominate.

2. *Definition of Important Energy Levels in Solids*

A knowledge of the following energy magnitudes (see Fig. 2) is important for a discussion of the photovoltaic effects or the effect of contact materials:

a) Fermi Levels

The Fermi energy E_F is the limit of the energy levels of a solid up to which a filling with electrons occurs at the absolute zero of temperature, and is identical with the electrochemical potential of the electrons. Since the probability f(E) of filling a level having energy E is given by the Fermi-Dirac relationship

$$f(E) = \frac{1}{1 + \exp[(E - E_F)/kT]} \qquad (17)$$

it is clear that only at higher temperatures is there a significant probability for the energy levels $E > E_F$ to be occupied.

Whereas E_F for metals lies in the middle of the conductivity band, it falls inside the forbidden energy zone in the case of non-conductors and intrinsic semiconductors. For n-conductors the Fermi level is displaced towards the conduction band because of the electron-filled (donor) energy level lying in the forbidden zone; in p-conductors it is displaced towards the ground-state band (see Fig. 1).

Illumination produces an increase in the number of electrons in the conduction band, and their concentration n_L and that of the vacant sites in the conduction band (effective density of state) N_c obey the general relationship

$$n_L/N_c = \exp[-(E_L - E_F)/kT] \qquad (18)$$

when $n_L \ll N_c$. Hence, E_F on illumination must be higher than the Fermi level in the dark [$(E_L - E_F)$ decreases]. The new position of the Fermi level is called the quasi-Fermi level. For illuminated p-conductors the quasi-Fermi level lies below the dark value E_F (see Section C. I. 3.).

The significance of the Fermi level in solids – in addition to providing data concerning the filling of the levels – is above all that E_F provides exact information about systems in contact (*e.g.* metal/semiconductor). An interchange of electrons must constantly take place on the contact surface, so that in the equilibrium state E_F has the same value in the linked systems, *i.e.* the Fermi edge E_F runs horizontally.

Since transfer of electrons from one solid to the other must take place to balance the different Fermi levels, an electrical double layer is formed on each contact surface producing a space charge in semiconductors and dyes (see Section G). Among other phenomena, this space charge produces the photovoltaic effects. Applied to the band model, it causes the bands to curve to an extent which is identical for all terms (see Fig. 2).

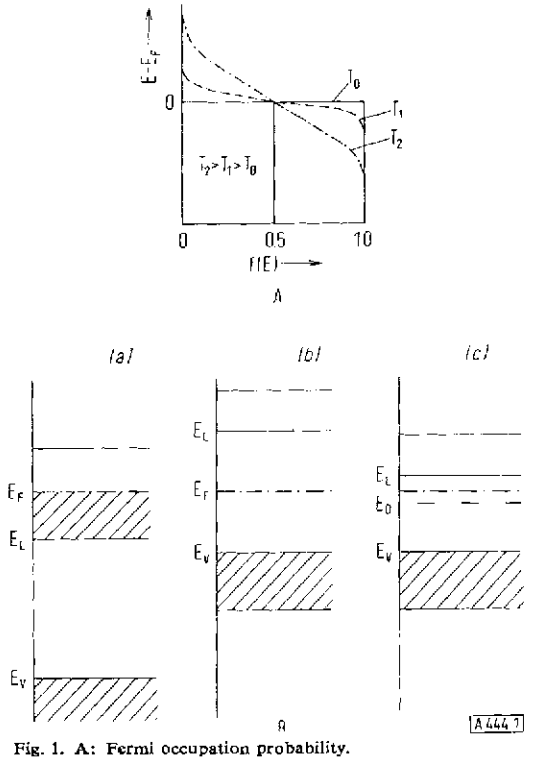


Fig. 1. A: Fermi occupation probability.
B: Position of the Fermi levels in metals (a), intrinsic semiconductors (b), and semiconductors (n-type) (c).

b) Thermal Work Function

The thermal work function ψ is the thermal energy required to remove an electron from a solid. ψ is the difference in energy between the electrostatic surface potential, possibly influenced by a double layer potential jump, and the Fermi level.

The magnitude of the work function can be determined from the contact potential (ex Volta potential) K [see Equation (19)] of two substances in vacuum if the work function of one of the solids is known.

$$K = \psi_1 - \psi_2 \qquad (19)$$

The contact potential is determined by two methods: (1) the Thomson vibration method [21], in which the Volta potential generated on a vibrating condenser is balanced by a counter-EMF; (2) by plotting a current-

[24] *A. F. Joffe:* Physik der Halbleiter. Akademie-Verlag, Berlin 1958.

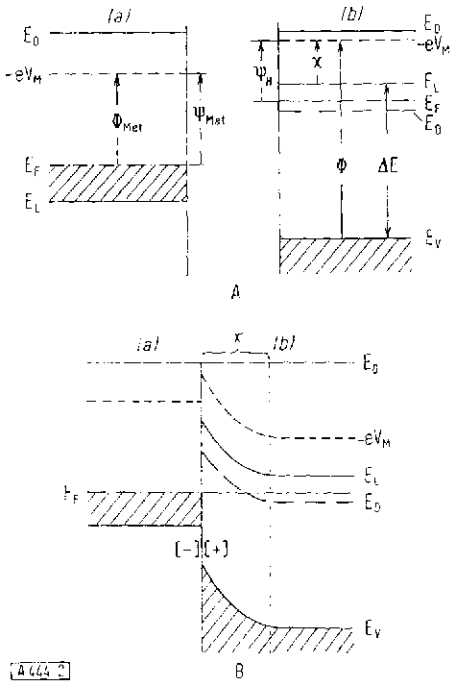


Fig. 2. Energy levels in a metal (a) and an n-type semiconductor (b). A separately; B in contact (x denotes the space charge zone). The crystal energy or the chemical bond energy of the electrons (E_L, E_D, *etc.*) is measured relative to the electrostatic energy $-eV_M$ (V_M = macroscopic electrostatic potential, possibly due to macroscopic space charges).

potential curve for the photoelectric or thermal emission of electrons (for measurements on dyes, cf. [26–28]). It should be noted that when interference by adsorbed gases is eliminated, ψ is equal to the Fermi energy E_F.

c) Photoelectric Activation Energy

The photoelectric activation energy Φ is the energy required for the photoelectric emission of an electron, and can be determined from the long-wavelength limit of the external photoelectric effect. For metals, Φ and ψ are identical, but for semiconductors this is not the case, since here photoelectric emission emanates from impurity levels or from fully occupied valence bands and not from Fermi levels [*]. For photoemission from the valence band, Φ is identical with the ionization potential, and hence can be used to determine the position of this band.

d) Energy Band Spacing

The distance between the valence band and the conduction band $\Delta E = (E_L - E_V)$ (see Section B. 1.) can be determined from the absorption spectrum by measurement of the limiting wavelength λ_g or from the threshold wavelength λ_g^* for photoconductivity, provided no excitation by lattice defects takes place.

e) Electron Affinity and the Position of the Conduction Band

The electron affinity χ is defined as the negative work necessary to transform an electron from outside the solid into the conducting state, and is equal to the energy E_L of the lower edge of the conduction band of a semiconductor. For dyes, χ was calculated from measurements of Φ and ΔE [29], using the relationship

$$\chi = \Phi - \Delta E \qquad (20)$$

Other possible methods of determining χ are the measurement of the redox potential or of the polarographic half-wave potential [30, 31].

In this connection, it should be stated that Scheibe's rule [32] indicates that the first excited state of many organic molecules lies about 3.4 eV below the zero level E_0. The conduction band in dyes therefore lies about 3.4 eV below the macropotential. It is worth noting that measurements of χ from photoelectric activation energies Φ and the bandwidth ΔE in thin photoconducting layers of dyes, using Equation (20), lead to values [26] of the same order of magnitude as that indicated by Scheibe's rule (cf. Section D.X). This result demonstrates that the rule, which was intended for single molecules, holds also for dye layers, and that the characteristic energy functions of the semiconductors and the methods worked out for their determination can be applied to organic solids [33].

C. Measurement of Photoconduction in Dyes

I. Methods of Measurement

In principle, the photoelectric behavior of a dye can be studied similarly to that of an inorganic system. However, the high resistance of the solid dyes, their high extinction coefficients, the difficult preparation of single crystals, and the possibility of interference by photochemical reactions often make it necessary to modify the procedure used for inorganic materials.

1. *Photoresistance*

The decrease in resistance on illumination is determined by the change in the current at a given external EMF. The current increase recorded by a galvanometer or electrometer can be converted to the increase in conductivity using the dimensions of the layers of dye between the electrodes (see Section B. III. 1.).

[25] *H. Meier*: Die Photochemie der organischen Farbstoffe. Springer, Berlin 1963.

[26] *B. L. Kurbatov* and *F. I. Vilesov*, Dokl. Akad. Nauk SSSR *141*, 1343 (1961); Soviet Physics Dokl. *6*, 1091 (1962).

[27] *R. C. Nelson*, J. opt. Soc. America *46*, 1016 (1956).

[28] *G. Mönch*, Z. Physik *47*, 522 (1928).

[*] Disregarding *e.g.* the special case of an extrinsic semiconductor with filled donor centers, where the Fermi level – displaced towards the conduction band – can coincide with the position of the impurity levels [21].

[29] *A. Terenin* and *I. Akimov*, Z. physik. Chem. *217*, 317 (1961).

[30] *S. E. Sheppard*, *R. H. Lambert*, and *R. D. Walker*, J. physic. Chem. *50*, 201 (1946).

[31] *Shuji Umano*, J. chem. Soc. Japan *77*, 796 (1956).

[32] *G. Scheibe*, *D. Brück*, and *F. Dörr*, Chem. Ber. *85*, 867 (1952).

[33] *L. E. Lyons* and *J. C. Mackie*, Proc. chem. Soc. (London) *1962*, 71.

Sandwich and surface-type cells are used for the measurement (see Fig. 3). In surface cells the dye layers are deposited uniformly between two electrodes applied onto glass or quartz in the form of a screen (Fig. 3 A) (suitable distance apart <0.1 mm); in sandwich cells the layer is packed between a lower metal electrode and an upper semitransparent electrode evaporated on the dye [15, 25, 34–36].

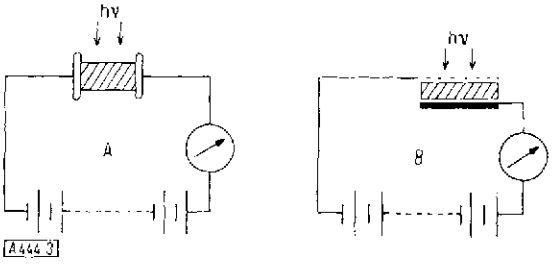


Fig. 3. Scheme of the Surface (A) and Sandwich (B) arrangement.

2. *The Condenser Method (Dember Effect)*

This method was initially developed by *Bergmann* [37] for the testing of powdered inorganic semiconductors. The dye is placed between two partly transmitting, insulated plates of a condenser charged by the charge carriers liberated by the changing illumination (photoelectric EMF about 0.01–0.1 mV/mW light energy [38–42]). Since the charge carriers follow the concentration gradient produced by the absorption of light, the sign of the EMF produced indicates the type of majority carrier [40, 43–47]. This procedure does not permit the determination of the photoelectric sensitivity when the illumination generates positive and negative charge carriers in approximately equal concentrations. Because of the insulation between dye and condenser, only the induced charge is determined and no current flows.

3. *Photocontact Potential*

Terenin et al. [40, 44, 48, 49] have used the change occurring on illumination in the contact potential between palladium and the dye for the study of the photoelectric sensitivity of various compounds. The change in potential was measured by the Thomson vibration method. The sign of the change (which is of the order of ±0.5 mV) provides information about the nature of the majority carriers formed. The differential displacement of the Fermi level on illumination of n- or p-type conductors, however, is likely to play a bigger part than the diffusion of the majority carriers into the semiconductor [44] (cf. Section B. VI. 2. a)).

4. *Short-Term Photoconductivity*

In addition to photoconductivity induced by prolonged illumination, flash-induced photocurrents are also of interest. The current produced provides information about the response times, and hence about possible photochemical reactions, and allows the measurement of μ and T.

a) Measurement of the Response Time

Response times of the order of milliseconds can be conveniently measured, for example by *Hauffe's* method [50], by a comparison of the oscilloscope trace of the burning of a flash bulb and the variation of the generated photocurrent with time. Using intermittent illumination (50–500 c.p.s.) it is likewise possible to measure photocurrent relaxation times of 5×10^{-6} to 1×10^{-2} sec on dyes [51–53].

b) Pulse Technique

In the pulse measurement technique proposed by *Kepler* and *Le Blanc* [54, 55], the migration of the charge carrier produced by a flash of 1–2 μsec duration is recorded oscillographically. The current pulse is a direct measure of the transit time T. A knowledge of this value permits the calculation of the mobility μ, when the EMF V and the electrode spacing L are known, using Equation (7) as follows:

$$\mu = L^2/VT \qquad (21)$$

[34] *H. Meier*, Z. wiss. Photogr., Photophysik Photochem. *53*, 1 (1958).

[35] *H. Meier* and *A. Haus*, Mitteilungsbl. chem. Ges. DDR *6*, 69 (1959).

[36] *W. Noddack*, *H. Meier*, and *A. Haus*, Z. wiss. Photogr., Photophysik Photochem. *55*, 7 (1961).

[37] *L. Bergmann*, Physik. Z. *33*, 209 (1932); Naturwissenschaften *20*, 15 (1932).

[38] *E. Putzeiko*, Dokl. Akad. Nauk SSSR *59*, 471 (1948); *67*, 1009 (1949).

[39] *E. Putzeiko* and *A. Terenin*, Zh. fiz. Khim. *30*, 1019 (1956).

[40] *A. Terenin*, *E. Putzeiko*, and *I. Akimov*, Disc. Faraday Soc. *27*, 83 (1959).

[41] *E. Putzeiko*, Soviet Physics Dokl. *1*, 63 (1951); Dokl. Akad. Nauk SSSR *124*, 796 (1959).

[42] *F. Dörr* and *A. Kleinle*, Z. Naturforsch. *13b*, 257 (1958).

[43] *A. Terenin*, *E. Putzeiko*, and *A. Akimov*, J. Chim. physique Physico-Chim. biol. *54*, 717 (1957).

[44] *A. Terenin* and *I. Akimov*: Ergebnisse der Internationalen Konferenz über wissenschaftl. Photographie, Köln 1956. Verlag Helwich, Darmstadt 1958, p. 117.

[45] *I. Akimov* and *E. Putzeiko*: Photoelectric and Optical Phenomena in Semiconductors. Published by Akad. Nauk. Ukrain. SSR, Kiew 1959, p. 301.

[46] *V. P. Juse* and *S. M. Riwkin*, Dokl. Akad. Nauk SSSR *62*, 55 (1948).

[47] *L. Bergmann* and *J. Häusler*, Z. Physik *100*, 50 (1936).

[48] *I. Akimov*, Dokl. Akad. Nauk SSSR *128*, 691 (1959).

[49] *A. Terenin*: Proceedings of the Conference on Electrical Conductivity in Organic Solids. Interscience, New York 1961, pp. 39–59; Proc. chem. Soc. (London) *1961*, 321.

[50] *K. Hauffe* and *J. Kaufhold*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *66*, 316 (1962).

[51] *H. Meier*, Angew. Chem. *68*, 525 (1956).

[52] *E. Putzeiko*, Dokl. Akad. Nauk SSSR *132*, 1299 (1960).

[53] *N. A. Tolstoi* and *R. P. Feofilov*, Izv. Akad. Nauk SSSR, Ser. Fiz. *15*, 712 (1950).

[54] *R. G. Kepler* in *J. J. Brophy* and *J. W. Buttrey*: Organic Semiconductors. The Macmillian Comp., New York 1962, pp. 1–20; Physic. Rev. *119*, 1226 (1960).

[55] *O. H. Le Blanc jr.* in *J. J. Brophy* and *J. W. Buttrey*: Organic Semiconductors. The Macmillan Comp., New York 1962, pp. 21–26; J. chem. Physics *33*, 626 (1960).

5. *Photovoltaic Effects*

Photovoltaic effects, which are characterized by the appearance of photoelectric potentials and currents in the absence of applied potentials, are measured analogously to those in inorganic photoelectric elements. Both the open-circuit EMF V_∞ and the short-circuit current I_0 (current in a very low external resistance) are measured. Fig. 4 shows the arrangement used for the measurement of the photovoltaic effect of both inorganic and organic systems.

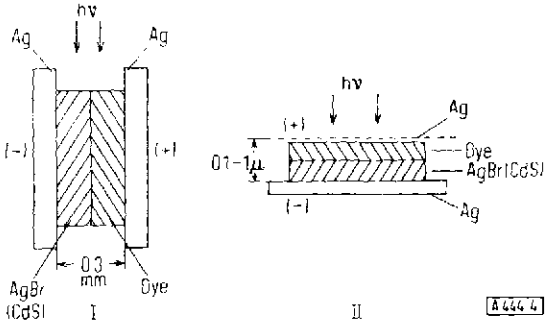


Fig. 4. Arrangement for determining the photovoltaic effects in inorganic/organic systems. Illuminated area 1 cm².

6. *Electrophotographic Methods of Measurement*

In this method the photoconductor properties are determined by measurements of the light-induced decay of the corona discharge-generated electrostatic charge on an organic layer. Although this process, taken from electrophotographic practice, has so far been employed predominantly for the study of organic high polymers [56], it seems fundamentally suitable for the study of photoconducting dye layers. The difficulties associated with the deposition of electrodes could well be avoided in this way.

7. *The Becquerel Method*

In the Becquerel arrangement the change in the potential of an illuminated dye electrode immersed in an electrolyte is measured [13, 59]. Although this effect can be used in some cases for the measurement of the photoelectric sensitivity [13, 59], its principal application lies in the investigation of the mechanism of photochemical bleaching processes in dyes. A positive or negative charge on the electrode will, for example, provide information as to whether the bleaching is due to photochemical reduction or oxidation of the dye [25, 60–62].

[56] *H. Hoegl*, ref. [56a].

[56a] Lecture at the Conference on semiconductor chemistry in München (Germany), October 12th–13th, 1964. For a summary, see Angew. Chem. *77*, 177 (1965); Angew. Chem. internat. Edit. *4*, 163 (1965).

[57] *E. Thomson*, Physic. Rev. *5*, 43 (1915).

[58] *C. Stora*, J. Chim. physique *29*, 168 (1932).

[59] *G. Eckert*, Z. wiss. Photogr. Photophysik Photochem. *49*, 220 (1954).

[60] *P. J. Hillson* and *E. K. Rideal*, Proc. Roy. Soc. (London), Ser. A *216*, 458 (1953).

[61] *A. W. Copeland, O. D. Black*, and *A. B. Garrett*, Chem. Reviews *31*, 177 (1942).

[62] *H. Mauser* and *U. Sproesser*, Angew. Chem. *75*, 299 (1963); Angew. Chem. internat. Edit. *2*, 262 (1963).

II. Preparation of the Photoconducting Dye Cells

1. *General*

Dyes are generally studied in thin layers obtained either by rapid precipitation from a volatile solvent or by sublimation in high vacuum, *e.g.* for merocyanines. Use of the correct technique for the preparation of the samples (control of crystal structure) improves the photoconducting properties of the product [63–64, 67–70]. The different modifications of the phthalocyanines do in fact possess different electrical and thermoelectric properties [65, 66]. It is noteworthy that the results obtained on single crystals of dyes, including tests of the directional dependence of conductivity [71 to 73], are quite unambiguous (for the case of phthalocyanines see [71, 74–79]).

2. *Purification*

Purification of the dyes by chromatography [64] or sublimation in high vacuum [80] does not reduce the photoconductivity, and may even increase it. This fact once again denies the frequent suggestion that impurities are responsible for the photoconduction. For example, the specific conductivity of Nacrosol Black B [*] increases from 10^{-11} to 10^{-7} ohm^{-1} cm^{-1} on purification [81]. Similarly, purification by zone melting does not eliminate the conductivity of heterocyclic compounds [82].

D. Properties of the Dye Photoconductors

I. Dark Conductivity

The dark conductivity of dyes is of the order of 10^{-10}–10^{-14} ohm^{-1} cm^{-1} and, in analogy with inorganic semiconductors, it increases with temperature in ac-

[63] *R. C. Nelson*, J. molecular Spectroscopy *7*, 449 (1961).

[64] *W. Noddack, H. Meier*, and *A. Haus*, Z. physik. Chem. N. F. *20*, 233 (1959).

[65] *C. Hamann* and *I. Storbeck*, Naturwissenschaften *50*, 327 (1963).

[66] *C. Hamann* and *M. Starke*, Physica Status solidi *4*, 509 (1964).

[67] *D. D. Eley, G. D. Parfitt, M. J. Perry*, and *D. H. Taysum*, Trans. Faraday Soc. *49*, 79 (1953).

[68] *K. Wihksne* and *A. E. Newkirk*, J. chem. Physics *34*, 2184 (1961).

[69] *C. Y. Liang* and *E. G. Scalco*, J. electrochem. Soc. *110*, 779 (1963).

[70] *M. J. Danzig, C. Y. Liang*, and *E. Passaglia*, J. Amer. chem. Soc. *85*, 668 (1963).

[71] *P. E. Fielding* and *F. Gutman*, J. chem. Physics *26*, 411 (1956).

[72] *H. Mette* and *H. Pick*, Z. Physik *134*, 566 (1953).

[73] *N. Riehl*, J. physic. Chem. *29*, 959 (1955).

[74] *G. H. Heilmeier, G. Warfield*, and *S. E. Harrison*, Physic. Rev. Letters *8*, 309 (1962).

[75] *G. H. Heilmeier* and *G. Warfield*, J. chem. Physics *38*, 163 (1963).

[76] *F. P. Bowden* and *L. T. Chadderton*, Proc. Roy. Soc. (London) Ser. A *269*, 143 (1962).

[77] *L. T. Chadderton*, J. physic. Chem. Solids *24*, 751 (1963).

[78] *L. E. Lyons, J. Walsh*, and *J. W. White*, J. chem. Soc. (London) *1960*, 167.

[79] *A. T. Vartanyan* and *I. A. Karpovitch*, Zh. fiz. Khim. *32*, 178 (1958).

[80] *H. Meier*, Photogr. Sci. Engng. *6*, 235 (1962).

[*] A dye of the Aniline Black type (National Aniline Div, Allied Chemical & Dye Corp., New York).

[81] *G. P. Brown* and *S. Aftergut* in: *J. J. Brophy* and *J. W. Buttrey*: Organic Semiconductors. The Macmillan Comp., New York 1962, pp. 89–99.

[82] *S. Aftergut* and *G. P. Brown*, ibid. pp. 79–88.

cordance with Equation (1) [50, 71, 83–89]. It is interesting to note that the thermal activation energy ΔE_{therm} determined from the slope of the linear plot of log σ_D against 1/T from Equation (1), is closely related to the structure of the organic solid. For example, ΔE_{therm} for linearly condensed hydrocarbons can be expressed as a function of the number of rings n by the relationship [90]:

$$\Delta E_{therm} = (17-n)^2/100 \quad (22)$$

In addition, it is found that ΔE_{therm} generally decreases with increasing number of electrons N, in accordance with the relationship given by the electron gas theory [89, 91]. If the relationship between ΔE and N for the open [Equation (23)] and cyclic [Equation (24)] π-electron systems is represented graphically, then the

$$\Delta E = 19.2(N+1)N^2 \quad [eV] \quad (23)$$

$$\Delta E = 38/N \quad [eV] \quad (24)$$

ΔE_{therm} value obtained from conductivity measurements on many organic compounds – including dyes [86] – lies between the two curves [89]. Deviations generally point to a perturbed conduction process [92]. The value of ΔE_{therm} = 1.7 eV [71, 93] measured for single crystals of phthalocyanine leads to the conclusion that the 18 π-electron system is responsible for light absorption and for conduction. The agreement of the ΔE_{therm} values with the ΔE_{opt} values obtainable from the upper wavelength limit of the photoconductivity is also worth noting (cf. Section B. I. and Table 1) [49].

Table 1. ΔE_{therm} and ΔE_{opt} of some dyes, calculated by means of Equations (1) and (2).

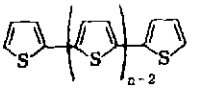
	Phenosafranine	Pinacyanol	Cu-phthalocyanine
ΔE_{therm} (eV)	2.08	1.8	1.7
ΔE_{opt} (eV)	2.07	1.77	1.63

II. Spectral Dependence of Photoconductivity

The results of numerous investigations [39, 41, 50, 77, 79, 94–98] have confirmed that the action spectra [*] of the photoconductivity measured on thin layers of dyes, including those of associated dye molecules, are in substantial agreement with the absorption spectra [42]. This proves that the energy absorbed by the molecule – and not absorption by lattice imperfections – is the cause of photoelectric conduction.

Deviations observed for thick layers [94, 96], which occur in surface-type cells (photocurrent minimum near the absorption maximum) are probably due to only a fraction of the charge carriers formed at the surface reaching the electrical field between the electrodes. With illumination through the gap between the electrodes, these deviations are eliminated [96]. With a sandwich-type cell of, *e.g.* phthalocyanine single crystals [77], the action and absorption spectra correspond. This behavior of single crystals of aromatic compounds can be used to determine the absorption spectrum [99].

Kuhn et al. [98] have found that in the case of polythienyl *(1)* built into a sandwich-type cell with barium stearate, the action spectrum of the photoconduction differs from the absorption



(1)
n=6

spectrum of the oriented dye in the layer but agrees with the spectrum in solution. It is assumed that the photoconduction is due to a small fraction of the molecules, which cannot be detected in the absorption spectrum, having the unperturbed planar structure, as in the solution.

III. Dependence on the Potential

In organic and inorganic conductors alike, Ohm's law is generally found to be valid up to field strengths of 10^3 V/cm [75, 88, 100], the maximum being 10^5 V/cm [101, 102] (cf. Fig. 5). At higher fields the current increases at a faster rate than the potential [25, 75, 90, 103] – the Wien-Poole effect – or saturation of the photocurrent occurs [15, 104]. It is not known to what extent the conditions mentioned in Section B. IV. 1. (blocking contacts, *etc.*) occur in the formation of saturation currents or to what extent currents limited by space charges must be assumed in the case of ohmic contacts ($T < \tau_R$) (cf. Section B. IV. 2. and [105, 106]). Significantly, if ohmic contacts which replenish charge carriers are present, Ohm's law ($I \propto V$) is replaced by

[83] *A. T. Vartanyan* and *I. A. Karpovitch*, Dokl. Akad. Nauk SSSR *111*, 561 (1956); *113*, 1020 (1957).

[84] *A. T. Vartanyan* and *C. D. Rosenstein*, *ibid. 124*, 195 (1959).

[85] *A. T. Vartanyan*, Izv. Akad. Nauk SSSR, Ser. Fiz *20*, 1541 (1956); *21*, 523 (1957).

[86] *H. Meier*, Z. physik. Chem. *208*, 325 (1958).

[87] *A. T. Vartanyan*, Soviet Physics Dokl. 7, 332 (1962).

[88] *D. Kleitman* and *G. J. Gouldsmith*, Physic. Rev. *98*, 1544 (1955).

[89] *D. D. Eley* and *G. D. Parfitt*, Trans. Faraday Soc. *51*, 1529 (1955).

[90] *M. Wilk*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *64*, 930 (1960).

[91] *H. Kuhn*, Angew. Chem. *71*, 93 (1959).

[92] *C. McPollock* and *A. R. Ubbelohde*, Trans. Faraday Soc. *52*, 1112 (1956).

[93] *G. H. Heilmeier*, *G. Warfield*, *S. E. Harrison*, and *J. Assour*, Program Abstracts of the Organic Crystal Symposium, Ottawa 1962, p. 133.

[94] *J. W. Weigl*, J. chem. Physics *24*, 883 (1956); J. molecular Spectroscopy *1*, 216 (1957).

[*] The action spectrum is the spectral distribution $\sigma_{phot} = f(\lambda)$ of photoconduction, normalized to equal input energies at all wavelengths.

[95] *R. C. Nelson*, J. opt. Soc. America *46*, 10 (1956).

[96] *G. Tollin*, *D. R. Kearns*, and *M. Calvin*, J. chem. Physics *32*, 1013 (1960).

[97] *P. Devaux*, *M. Schott*, and *M. Lazerges*, Physica Status solidi *4*, 43 (1964).

[98] *H. Kuhn*, Vortrag auf dem 2. Internationalen Farbensymposium, Elmau, April 1964.

[99] *D. J. Carswell*, J. chem. Physics *21*, 1890 (1953).

[100] *W. Noddack* and *H. Meier* in ref. [100a], pp. 515–531.

[100a] Scientific Photography, Proceedings of the International Colloquium held at Liège 1959. Pergamon Press, London 1962.

[101] *D. C. Northrop*, Proc. physic. Soc. Sect. B *74*, 756 (1959).

[102] *D. D. Eley*, Lecture, 2nd International Dye Symposium, Elmau (Germany), April 1964.

[103] *A. Rose*, Physic. Rev. *97*, 1538 (1955).

[104] *W. Noddack*, *H. Meier*, and *A. Haus*, Z. physik. Chem. *212*, 55 (1959).

[105] *F. Stöckmann*, Z. Physik *138*, 404 (1954).

[106] *M. Polke*, *G. Storch*, and *F. Stöckmann*, Z. Physik *55*, 7 (1961).

Childs' law ($I \propto V^2$) for space-charge-limited currents [102] above a limiting potential. Measurements on phthalocyanine [75] show this transition point.

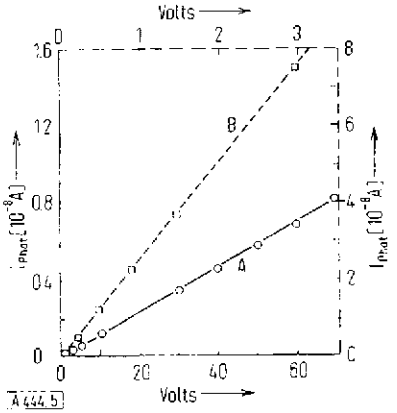


Fig. 5. Dependence of the photocurrent on the applied potential for A (lower abscissa, left-hand ordinate): Cu phthalocyanine (surface-type cell), and B: merocyanine A-10 (sandwich-type cell).
Illumination conditions: A. Unfiltered white light; 1.8 mW/cm².
B. λ = 6220 Å; 370×10^{13} quanta/(cm² sec).
Cell dimensions: Electrode spacing $\leqslant$0.01 cm (A) and 10^{-4} cm (B); illuminated area 1 cm².

To clarify numerous problems concerning the current-potential relation, it would be desirable to study metal/dye systems systematically, with special reference to the work function, the type of the majority carrier, the type of contact, and possible space-charge-limited currents [107, 108].

IV. The Intensity Dependence

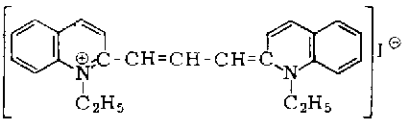
Numerous dyes exhibit a linear growth of the photocurrent in sandwich-type cells with increasing intensity of light B [36, 80, 109]. Measurements on phthalocyanine surface cells [96] show a proportionality between the photocurrent and $B^{1/2}$. Similar relationships between I_{phot} and B are known for many inorganic and organic photoconductors [110] and can be derived kinetically [17].

V. Quantum Yield

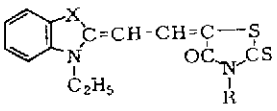
The quantum yield G (cf. Section B. III. 2.) is of the order of unity in several undoped dyes [25, 80, 104], *e.g.* in malachite green (G = 0.2), pinacyanol *(2)* (G = 0.37) and merocyanine A-10 *(3)* (G = 0.6).

These values conflict with the view that photoconduction is a result of a photochemical bleaching process, since the quantum yield for an oxidative bleaching process is of the order of 10^{-3} [25]. The quantum yield depends on the following factors:

1. G increases with decreasing layer thickness; *e.g.* for crystal violet it increases from 0.06 for a layer 1×10^{-5}cm



(2)



(3): X = S; R = C_2H_5
(4): X = O; R = CH_3

thick to 0.33 for a 3×10^{-6} cm layer. This rule was established by means of Becquerel cells [59] with a surface-type arrangement [104] and by means of the external photoelectric effect [111].

2. In agreement with Equation (15), the quantum yield increases with decreasing distance between the electrodes at constant field strength and layer thickness (cf. Table 2 [104]).

Table 2. Relation between the quantum yield and electrode spacing for crystal violet (λ = 5870 Å; $\mathfrak{E}$ = 7000 volts/cm; layer thickness 3×10^{-6} cm)

L [cm]	0.08	0.042	0.02	0.01	0.003
G	0.0009	0.0012	0.0026	0.0052	0.014

These figures prove that the general relationships of Section B. III. hold also for dye photosemiconductors.

3. According to measurements carried out to date, G varies with the dye structure as follows [25]:

In triphenylmethane dyes the photoconductivity is proportional to the degree of methylation of the amino groups [12, 64]; replacement of a methyl group by ethyl or by hydrogen has a sensitivity-reducing effect, *i.e.* $CH_3 \gg C_2H_5$, H, C_6H_5. The photoconductivity increases with the number of methine groups, *i.e.* with a growth in the conjugated chain length, as is demonstrated from studies of cyanines and merocyanines.

VI. The Rise and Decay Process

The photocurrent of dye semiconductors is established within 10^{-5} to 10^{-6} sec, as shown by measurements on metal-free and copper phthalocyanines [52, 96]. It is possible that the onset of current, detection of which is governed by instrumental limitations, occurs even more rapidly. At the end of illumination the current decays with time constants ranging between 10^{-3} sec and several seconds or more. It has been demonstrated that the current decay generally follows a second-order law in accordance with Equation (25) [11, 50, 96, 112, 113], *i.e.* it can be traced to a bimolecular charge-carrier recombination.

$$1/I(t) = Kt + \text{const.} \qquad (25)$$

With large photocurrents – corresponding to high charge-carrier concentrations – decay is slower than

[107] *W. Helfrich* and *P. Mark*, Z. Physik *166*, 370 (1962).
[108] *J. Adolph*, *E. Baldinger*, and *I. Grānacher*, Physics Letters *8*, 224 (1964).
[109] *V. A. Benderskii*, *B. Ya. Kogan*, *Yu. Abramov*, and *L. E. Kapranova*, Dokl. Akad. Nauk SSSR *156*, 897 (1964).
[110] *S. C. Ganguly* and *N. K. Chandhury*, Rev. mod. Physics *31*, 1013 (1959).
[111] *F. Hlucka*, Z. Physik *81*, 66, 516 (1933).
[112] *R. C. Nelson*, J. chem. Physics *22*, 885 (1954).

expected from Equation (25). *Tollin* [96] attempted to explain this anomaly by a concentration dependence of the charge-carrier mobility, possibly analogous to that found in ionic solutions [114]. Decay periods of several minutes are explained by a strongly diffusion-dependent bimolecular recombination [115].

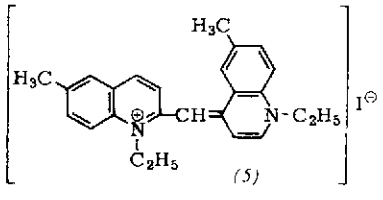
The analogy between inorganic and organic photoresistors points to the influence of trapping centers on the response times. As an example of this theory, dye cells, like inorganic systems [7], can be subdivided into slow and fast cells [25, 49, 116]. In addition, the response time can be markedly reduced by high field strengths and by the use of cells with small electrode spacings (sandwich-type cells) [25]. Moreover, the charge carriers present at the end of the illumination period can be thermally ejected by heating the photoconductor [113, 117], just like those in inorganic crystal phosphors containing numerous trapping centers (conductivity glow curves). The use of organic photoconductors for storing electrical energy (photoelectrets) is quite feasible [118].

VII. Dependence on Temperature

The photocurrent increases with temperature in accordance with Equation (26):

$$I_{phot} = A\exp(-\Delta E_H/kT) \qquad (26)$$

The plot of log I_{phot} against 1/T gives a straight line from the slope of which the thermal activation energy ΔE_H of the photoconduction can be calculated (0.4 to 0.6 eV) [49, 50, 109, 112, 113, 119]. ΔE_H ist not identical with ΔE_{therm} (*e.g.* for Orthochrome T *(5)*, $\Delta E_{H\,therm}$ = 1.5 eV; ΔE_H = 0.44 eV [86, 113]).



(5)

In analogy with inorganic crystalline phosphors [120–122], the temperature dependence of the photocurrent can probably be ascribed to trapping centers [108, 123–128] which are filled by a fraction of the charge-carriers formed during illumination. As the temperature increases, these centers become vacant, which produces an increase in the current. Experiments [*] carried out to determine the depth of the traps ΔE_H gave consistent results.

VIII. n- and p-Type Conduction in Dyes

Dyes can be divided into n- and p-type conductors according to the effect of oxygen [34, 129]. In some dyes, (triphenylmethane derivatives, rhodamines) the conductivity decreases when oxygen is adsorbed (n-type conduction); others (merocyanines, phthalocyanines) exhibit increased conductivity (p-type conduction) under these conditions. Hydrogen behaves in the reverse manner [130] (cf. Fig. 6).

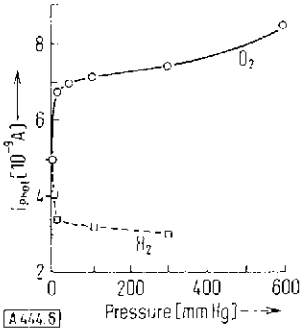


Fig. 6. Pressure-dependence of the photocurrent of a merocyanine A-10 surface cell in an oxygen and in a hydrogen atmosphere. In vacuum (5×10^{-6} mm Hg), the photocurrent is 5×10^{-9} A (applied potential 80 V; λ = 6000 Å, 12×10^{15} quanta/(cm² sec); illuminated area 1 cm², electrode separation 0.01 cm.

This classification of dyes presupposes:

1. an electron interaction between the gas and the solid dye analogous to that in inorganic semiconductors and metals [131–136], and

[113] *H. Meier*, Z. physik. Chem. *208*, 340 (1958).

[114] *W. J. Moore*: Physical Chemistry. Prentice-Hall, Englewood Cliffs, N. J., 1950, p. 451.

[115] *T. R. Waite*, Physic. Rev. *107*, 463 (1957).

[116] *W. Noddack* and *H. Meier*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *63*, 971 (1959).

[117] *W. Helfrich, N. Riehl*, and *P. Thoma*, Physics Letters *10*, 31 (1964).

[118] *H. Kallmann* and *B. Rosenberg*, Physic. Rev. *97*, 1596 (1955).

[119] *R. C. Nelson*, J. chem. Physics 22, 892 (1954).

[120] *H. Gobrecht, D. Hahn*, and *H. J. Kösel*, Z. Physik *136*, 285 (1953).

[121] *J. R. Cook*, Proc. physic. Soc. Sect. B *68*, 148 (1955).

[122] *H. Meier*, Z. wiss. Photogr., Photophysik Photochem. *51*, 208 (1957).

[123] *A. G. Chynoweth* and *W. G. Schneider*, J. chem. Physics *22*, 1021 (1954).

[124] *A. G. Chynoweth*, J. chem. Physics 22, 1029 (1954).

[125] *D. C. Hoesterey* and *G. M. Leston*, J. physic. Chem. Solids *24*, 1609 (1963).

[126] *S. Z. Weisz, R. C. Jarnagin, M. Silver, M. Simhony*, and *J. Balberg*, J. chem. Physics *40*, 3365 (1964).

[127] *J. Kommandeur* and *W. G. Schneider*, J. chem. Physics *28*, 252 (1958).

[128] *A. Bree, P. J. Reucroft*, and *W. G. Schneider* in: Symposium on Electrical Conductivity in Organic Solids. Interscience Publ., New York 1961, pp. 113–125.

[*] *E.g.* measurements of glow curves [128], of the change of the rate constant of current decay with temperature, or of logI_{phot} as a function of 1/T [25, 112, 113, 119].

[129] *H. Meier*, Angew. Chem. *69*, 730 (1957).

[130] *H. Meier*, Z. physik. Chem. *212*, 73 (1959).

[131] *C. Wagner* and *K. Hauffe*, Z. Elektrochem. angew. physik. Chem. *44*, 172 (1938).

[132] *K. Hauffe, R. Glang*, and *H. J. Engel*, Z. physik. Chem. *201*, 221 (1952).

[133] *G. M. Schwab* and *J. Block*, Z. physik. Chem. N. F. *1*, 42 (1954).

[134] *K. Hauffe*: Reaktionen in und an festen Stoffen. Springer, Berlin 1955.

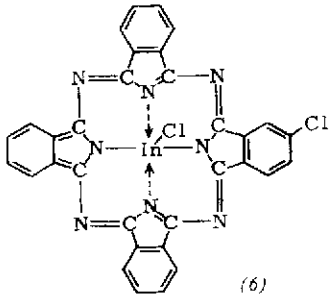
[135] *R. Suhrmann*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *60*, 804 (1956).

[136] *G. Rienäcker* and *N. Hansen*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *60*, 887 (1956).

2. the validity of *Heckelsberg's* method [137] for determining the type of majority charge carriers in organic systems.

Both assumptions are supported by overwhelming evidence. Gases such as NO, BF_3, and SO_2 produce the same changes in conductivity in organic and inorganic systems [*] [124, 138–143] and the n- and p-type conduction mechanisms are confirmed by Hall-effect measurements [74, 144, 145], thermoelectric power measurements [65, 71, 146–149], measurement of the sign of the diffusion EMF in a static condenser [40, 43, 44], and by studies of the changes in the contact potential using the vibration method [49]. In every case, dye single crystals exhibited the same type of conduction as layers. Further, dyes belonging to the same class exhibit the same conduction type; *e.g.* more than 40 merocyanine dyes showed p-type behavior.

The cause of the two types of conduction in the various dyes is not yet known [25]. Studies of systems in which the type of conduction changes, *e.g.* transition from p-type to n-type conduction of chloroindium chlorophthalocyanine *(6)* [65] or the behavior of mixtures [34], may possibly help to elucidate the problem.



(6)

[137] *L. F. Heckelsberg, G. Bailey,* and *H. Clark,* J. Amer. chem. Soc. *77,* 1373 (1955).

[*] Chemiesorption of gases having electron-donating properties (*e.g.* H_2O, NH_3, *etc.*) on thin metal films leads to an increase in conductivity, whereas electron acceptors (O_2, NO, BF_3, *etc.*) give rise to the reverse effect since they withdraw electrons from the substrate. In semiconductors the effect of chemisorption depends on the mechanism of conduction: thus electron donors increase the conductivity of electronic semiconduction (n-type) and decrease that of electron-defect semiconductors (p-type), and *vice versa* for electron acceptors. Since chemisorption affects the surface layers of the semiconductor, this effect ist most pronounced for thin films, in which the surface conductivity exceeds the bulk conductivity.

[138] *D. D. Eley* and *H. Inokuchi,* Z. Elektrochem., Ber. Bunsenges. phys. Chem. *63,* 29 (1959).

[139] *L. E. Lyons* and *G. C. Morris,* J. chem. Soc. (London) *1957,* 3648.

[140] *F. R. Lipsett, D. M. Compton,* and *T. C. Waddington,* J. chem. Physics *26,* 1444 (1957).

[141] *W. G. Schneider* and *T. C. Waddington,* J. chem. Physics *25,* 358 (1956).

[142] *D. M. Compton* and *T. C. Waddington,* J. chem. Physics *25,* 1075 (1956).

[143] *K. Hauffe,* ref. [56a].

[144] *A. Epstein* and *B. Wildi* in: Symposium on Electrical Conductivity in Organic Solids. Interscience, New York 1961, p. 337–357.

[145] *G. Delacote* and *M. Schott,* Physica Status solidi *2,* 14, 60. (1962).

[146] *N. Petruzella* and *R. C. Nelson,* J. chem. Physics *37,* 3010 (1961).

[147] *M. Labes, R. Sehr,* and *M. Bose*: Proceedings of the International Conference on Semiconductor Physics, Prague 1960. Academic Press, New York 1961, pp. 850–853.

[148] *F. H. Moser* and *A. L. Thomas*: Phthalocyanine Compounds. Reinhold, New York 1963, p. 75.

[149] *N. J. Juster,* J. chem. Educat. *40,* 547 (1963).

Both types of charge carriers are of course present in both p- and n-type conduction, but in different proportions [21, 54].

IX. Lifetime and Mobility

No precise information regarding the lifetime τ during which the charge carriers are freely mobile inside the solid dyes is as yet available. The decay curves, varying from 10^{-2} sec to several minutes, are probably subject to interference by the temporary residence of charge carriers in trapping centers. For example, crystal phosphors containing numerous trapping centers have a long decay time of the photocurrent; yet the lifetime characteristic for the free movement of charge carriers without capture on trapping centers is only about 5×10^{-8} sec [123].

The possibility that triplet states are the primary participants in the conductivity process and that a lifetime of 10^{-4} sec and longer [96] can therefore be expected, is excluded by short-duration measurements on phthalocyanines which permit the detection of charge carriers within 10^{-6} sec or less [150]. Since the life of the excited singlet states of the phthalocyanines is approximately 10^{-9} sec [151], lifetime values lying between 10^{-6} and 10^{-9} are quite feasible [152].

On the basis of Hall-effect measurements, *Delacote* and *Schott* [145] found a mobility of 100 $cm^2\ V^{-1}\ sec^{-1}$ for the charge carriers in phthalocyanines. This result raises the question as to what corrections must be applied to the mobilities determined from electron spin resonance [153], from the mean free path [25, 36], and from other measurements [25, 94, 154–156]. A comparison with germanium ($\mu_{\oplus}$ = 1700 $cm^2\ V^{-1}\ sec^{-1}$) is interesting, and seems to show that the mobilities in inorganic semiconductors and organic dyes are not very different.

X. Energy Levels

Data concerning the magnitude of the energy levels is available for only a few dyes [26, 27, 29, 44, 157–165]; see Table 3.

[150] *A. T. Vartanyan* and *I. D. Rosenstein,* Dokl. Akad. Nauk SSSR *131,* 279 (1960).

[151] *O. D. Dmietrievskii, V. L. Ermolaev,* and *A. N. Terenin, ibid. 114,* 751 (1957).

[152] *G. H. Heilmeier* and *G. Warfield,* J. chem. Physics *38,* 897 (1963).

[153] *B. Y. Cho, R. C. Nelson,* and *L. C. Brown,* J. chem. Physics *39,* 499 (1963).

[154] *L. E. Lyons* and *G. C. Morris,* J. chem. Soc. (London) *1957,* 3648.

[155] *S. H. Glarum,* J. physic. Chem. Solids *24,* 1577 (1963).

[156] *J. N. Murrell,* Molecular Physics *4,* 205 (1961).

[157] *D. Fox, M. Labes,* and *A. Weissberger*: Physics and Chemistry of the Organic Solid State, Vol. I. Interscience, New York 1963.

[158] *H. Meier,* J. physic. Chem. *69,* 719 (1965).

[159] *V. I. Vileskov* and *A. Terenin,* Dokl. Akad. Nauk SSSR *125,* 55 (1959); *133,* 1060 (1960); *134,* 71 (1960); Naturwissenschaften *46,* 167 (1959).

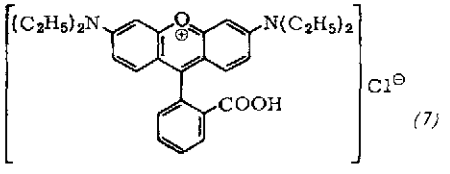
[160] *E. A. Taft, H. R. Philip,* and *L. Apker,* Physic. Rev. *110,* 876 (1958).

[161] *F. I. Vilesov,* Dokl. Akad. Nauk SSSR *132,* 632 (1960).

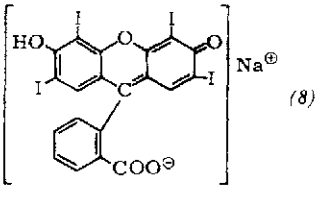
Table 3 shows that the first excitation level of the dye layers (governed by the electron affinity χ) is approximately 3.4 eV from the ionization limit, in accord with Scheibe's rule (see Section B. VI. 2. e)). The table demonstrates also that the values of the Fermi level E_F

Table 3. Energy constants of organic dyes and photosemiconductors (for explanation of the columns see Section B. VI. 2)

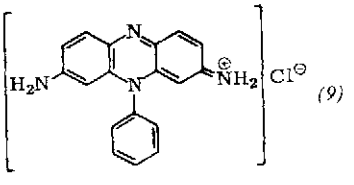
Dye	Conduction Type	$\Psi = E_F$ [eV]	Φ [eV]	χ [eV]	ΔE [eV]	Contact substance	K [mV]	Ref.
Rhodamine B *(7)*	n	4.45	5.2	3.2	2.0	Pd	+500	[29, 44]
		4.6	5.1	—	—			[26]
Erythrosin *(8)*	p	4.64	5.5	3.3	2.2	Pd	+310	[29]
		—	5.5	3.4	2.0			[26]
Malachite green	n	4.86	—	—	2.0	Pd	+90	[29]
		4.6	5.2	—	—			[26]
		—	5.2	3.2	1.6			[161]
Pinacyanol *(2)*	(n)	4.55	4.9	3.1	1.8	Pd	+400	[29]
		—	7.28	5.1	—			[29]
		3.1	4.6	3.0	1.6	CdS	+320	[27, 163]
Merocyanine	p	—	5.8	3.5	2.3			[29]
		—	7.35	4.8	—			[29]
		5.3	5.6	3.3	2.3			[26]
Crystal violet	n	3.32	5.1	3.0	1.7	CdS	+180	[27, 163]
		4.5	5.0	—	—			[27]
Phthalocyanine	p	—	6.0	4.3	1.7			[29]
Phenosafranine *(9)*	n	5.0	5.4	3.3	2.1			[26]
AgBr	p	5.33	6.0	3.5	2.5			[29, 44]
Palladium		4.95						[163]



(7)



(8)



(9)

(governed by the thermal work function) of the different dyes differ markedly, so that further measurements are necessary to establish the value of E_F precisely.

E. The Mechanism of Conduction in Dyes

The agreement between the electrical behavior of organic and inorganic semiconductors may be regarded as proof that photoconduction in solid organic dyes is not due to a photochemical decomposition reaction or an ionic mechanism but to the formation and migration of electronic charge carriers. This leads to the question of how the charges are transported through the solid dye. Whereas in inorganic crystals the lattice spacings are approximately 1.4 Å, molecular latticcs in organic molecules are relatively widely spaced (about 3.5 Å) [25, 166, 167].

I. The Tunnel Effect Mechanism

A possible explanation is the postulate that an excited electron (*e.g.* in the singlet state) reaches a vacant term of the neighboring molecules by tunneling through the potential barrier [50]. Since the probability for this transition $Dz \approx 10^{14}$ (where D is the transmission coefficient and z [sec^{-1}] is the number of impacts against the potential barrier) is greater than the probability $1/\tau \approx 10^9$ of return to the ground state, the transport of charges by the tunnel effect (hopping mechanism) from molecule to molecule seems feasible [90, 168], since $Dz/(1/\tau) \approx 10^{14}/10^9$.

Any increase in this ratio [126] leads to the participation of the longer-lived triplet state in photoconduction [90, 169, 170] and increases the likelihood of this mechanism.

II. Band Model Hypothesis

One objection to the tunnel effect mechanism, in which the charge carriers are localized at the lattice points for a certain time, is that the triplet states are not primary participants in the conduction [171]. Since, moreover, the boundary between the hopping mechanism and the quasi-free transport postulated by the band hypothesis

[162] *R. Fleischmann*, Ann. Physik *5*, 73 (1930).

[163] *R. C. Nelson*, J. opt. Soc. America *51*, 1186 (1961); J. molecular Spectroscopy *7*, 439 (1961).

[164] *R. C. Nelson*, J. chem. Physics *27*, 864 (1957).

[165] *A. Terenin* and *E. Putzeiko* in ref. [100a], pp. 532–543.

[166] *J. Robertson* and *L. A. Woodward*, J. chem. Soc. (London) *1940*, 36.

[167] *W. Hoppe*, Kolloid-*Z. 101*, 300 (1942); *109*, 21, 27 (1944).

[168] *R. C. Nelson*, J. chem. Physics *30*, 406 (1959).

[169] *B. Rosenberg*, J. chem. Physics *29*, 1108 (1958); *34*, 63 (1961).

[170] *A. Terenin*, Radiotekhn. i Elektron. *1*, 1127 (1956).

[171] *M. Y. Kleinermann* and *S. P. McGlynn* in *J. J. Brophy* and *J. W. Buttrey*: Organic Semiconductors. The Macmillan Comp., New York 1962, p. 108–114.

is a mobility of about 1 $cm^2/V^{-1}\,sec^{-1}$, and values of up to 100 $cm^2/V^{-1}\,sec^{-1}$ have been found for phthalocyanines [145], the energy band hypothesis is more probably correct. Additional evidence for the free movement of the electrons and positive holes in energy bands, which was already stated for dye photoconductors in 1954 [172], is provided by the observed decrease in the mobility with increasing temperature in organic single crystals [54, 55]. The tunnel effect mechnism requires the opposite to happen, because higher temperatures lead to an increase in z.

The relatively narrow energy bands in organic solids may well be due to the discrete energy levels of the molecules caused by electronic interaction (exchange degeneracy), as has been discussed in greater detail in Section B. VI. 1. Since ultimately the degree of overlap of the electron clouds is responsible for the bands, and hence for the mobility of the charge carriers, the relative orientation of the molecules, the distance between them, and their structure are very significant.

The directional character of the conduction is in accord with the band hypothesis [71, 173, 174]. Optical studies show that during crystallization the phthalocyanines show a transition from the sharp energy levels of the free molecules of the vapor state to wide, quasi-continuous bands [77].

III. The Exciton Hypothesis

Several authors [94, 175–178] have postulated the primary formation of excitons to explain the mechanism of photoconduction in organic compounds (cf. [25]). These diffuse to the surface, decompose, and contribute to the formation of electrons and positive holes. The migration of these secondary charge carriers is likewise interpreted by means of the band model. Naturally, the exciton theory offers no explanation for conduction in the dark. Dyes with good photoconductivity ($G \gg 1$) do not require the existence of additional excitons, which only partly decompose into charge carriers.

F. Doping

The addition of small quantities of organic compounds, *e.g.* *o*-chloranil, can increase both the dark and light conductivity of organic semiconductors by several orders of magnitude [179–188]. The following laws govern the doping effect in dyes:

1. The photoconductivity of p-type phthalocyanines [189, 190] and merocyanines [191] is increased by a factor of 5 to 10^4 by the addition of electron acceptors (iodine, *o*-chloranil, tetracyanoethylene) (cf. Fig. 7).

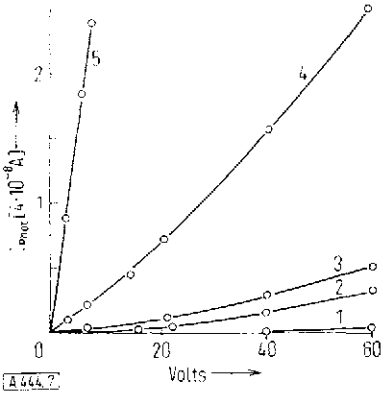


Fig. 7. Potential- and doping-dependence of a merocyanine FX-30 surface cell illuminated with white light at 1.8 mW/cm²; cell dimensions as in Fig. 6.
Curve 1: Undoped merocyanine FX-30. Curves 2, 3, 4, and 5: doped with dibromosuccinic acid (10^{-7} mole/cm² [*]), tetraiodophthalic anhydride (10^{-7} mole/cm²), *o*-chloranil (10^{-7} mole/cm²), and iodine (10^{-8} mole/cm²).

Specific dark conductivities up to $10^{-2}\,ohm^{-1}\,cm^{-1}$, *i.e.* values similar to those found in inorganic semiconductors, are possible.

2. No change occurs in the type of conduction.

3. Doping is effective at quantities of less than 10^{-7} mole on a photoconductive layer 1 cm² in area (Fig. 8).

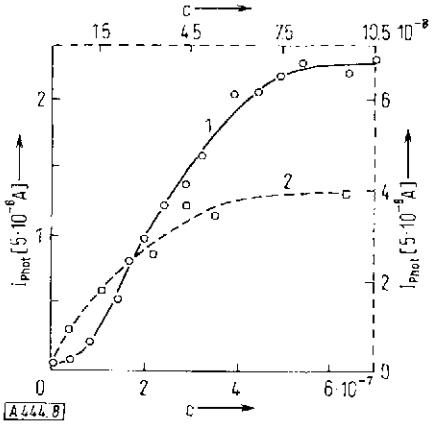


Fig. 8. Dependence of the photocurrent of a merocyanine FX-30 [(4)] surface cell on the concentration of doping agent (mole/cm²).
Curve 1: *o*-chloranil, λ = 5495 Å, 1.57×10^{15} quanta/(cm² sec); curve 2: iodine, white light, 1.8 mW/cm², 40 V. Cell dimensions as in Fig. 6.

[172] *H. Meier*, Doctorate Dissertation, Universität Mainz, 1954.
[173] *H. Mette* and *H. Pick*, Z. Physik *134*, 566 (1953).
[174] *G. Drehfahl* and *H. J. Henkels*, Naturwissenschaften *42*, 624 (1955).
[175] *O. H. Le Blanc*, ref. [56a].
[176] *J. Voitländer*, ref. [56a].
[177] *J. W. Steketee* and *J. de Jonge*, Proc. Kon. nederl. Akad. Wetensch., Ser. B *66*, 76 (1963).
[178] *L. E. Lyons*, J. chem. Soc. (London) *1957*, 5001; Austral. J. Chem. *10*, 365 (1957).
[179] Belg. Pat. 591164 (1960), inventor.: *H. Hoegl*, Kalle & Co.
[180] DBP. 1111935 (1961), inventor.: *H. Hoegl*, *O. Süs*, and *W. Neugebauer*, Kalle & Co.
[181] Belg. Pat. 589994–6 (1960), inventor.: *P. M. Cassiers*, Gevaert.
[182] *H. Akamatu*, *H. Inokuchi*, and *Y. Matsunaga*, Nature (London) *173*, 168 (1954); Bull. chem. Soc. Japan *29*, 213 (1956).
[183] *H. Akamatu* and *H. Inokuchi* in: Symposium on Electrical Conductivity in Organic Solids. Interscience, New York 1961, pp. 277–290.
[184] *G. Briegleb*: Elektronen-Donator-Acceptor-Komplexe. Springer, Berlin-Göttingen-Heidelberg 1961.
[185] *R. G. Kepler*, *E. Bierstedt*, and *P. E. Merified*, Physic. Rev. Letters *5*, 503 (1960).
[186] *N. J. Dunning*, Dielectrics *1 (4)*, 201 (1964).
[187] *S. Nishizaki* and *H. Kusakawa*, Bull. chem. Soc. Japan *36*, 1681 (1963).
[188] *H. Akamatu* and *H. Kuroda*, J. chem. Physics *39*, 3364 (1963).
[189] *D. R. Kearns*, *G. Tollin*, and *M. Calvin*, J. chem. Physics *32*, 1020 (1960).
[190] *D. R. Kearns* and *M. Calvin*, J. Amer. chem. Soc. *83*, 2110 (1961).
[191] *H. Meier* and *W. Albrecht*, Z. physik. Chem. N. F. *39*, 249 (1963).

[*] *I.e.* 10^{-7} mole deposited on a surface of 1 cm² area under standard conditions.

4. The quantum yield G is increased by several orders of magnitude and may exceed unity (for merocyanine A-10, G = 2.3).

The doping effect is probably due to a transfer of electrons from the donor dye to the acceptor molecule by a light-induced charge transfer process in the sense expressed by *Mulliken* [192] and the acceptor action of the impurities, similar to the effects observed in inorganic semiconductors [193].

Fig. 9 shows that the transfer causes acceptors to become negatively charged and increases the positive hole concentration in the ground-state band of the dye, and hence the p-type conductivity. This is confirmed by,

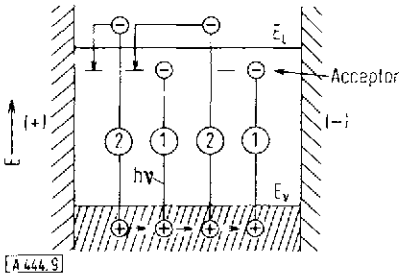


Fig. 9. Explanation of the doping effect.
1. Charge-transfer complex between the dye and the acceptor.
2. Trapping effect of the acceptor.

for example, electron spin resonance measurements [190], which show an increase in the conductivity with increasing number of electrons taken up by the acceptor molecules when the concentration of the doping agent is increased [194]. The reverse doping of n-type conductors (acceptors) with electron donors [56] is likewise in accord with this hypothesis.

A quantum yield G > 1 (see Section B. IV. 2.) may be explained in analogous manner to that in inorganic semiconductors, *e.g.* in CdS [195]. It means that the substantially immobile electrons shown in Fig. 9, which are taken up by the acceptors, build up a negative space charge on illumination. Positive holes are thereby injected from the anode just as in anthracene [196–198]. Owing to this replenishing effect, a positive hole exists even after its entry into the cathode. Since this is formally equivalent to an extension of the lifetime of the charge carrier, G (= τ/T) can exceed unity for $\tau > T$.

G. Photovoltaic Effects in Dyes

According to Section B. VI. 2. a), space charges are formed in the interface between two semiconductors in contact to give rise to photovoltaic effects. The observation of such effects in dyes confirms that the relationships which hold for "inorganic" boundary faces (*e.g.* postulation of the Fermi level) are also feasible for dye systems.

I. Dye/Metal Systems

Photocurrents (up to 10^{-8} A) and photopotentials (up to 10 mV) arise in dye/metal systems just as in Cu_2O and selenium photoelements [14–16, 199]. The slight rectifying action of the unilluminated arrangement indicates the probable presence of a barrier layer photoeffect (but cf. [200, 201]). Similar effects are also observed in metals (Pt, Au, Ag) in contact with polynuclear aromatic compounds (perylene, coronene) [202].

II. n-Type Dye/p-Type Dye Systems

Photocurrents of the order of 10^{-8} to 10^{-9} A and maximum photopotentials of 100 mV are found when n-type and p-type dyes are combined, *e.g.* rhodamine B (n)/merocyanine (p) [25, 36, 158, 203]. The currents rise in less than 10^{-2} sec (cf. *e.g.* Fig. 10) and grow with increasing illumination, indicating an electron transfer from the p-conductor to the n-conductor in the interior of the

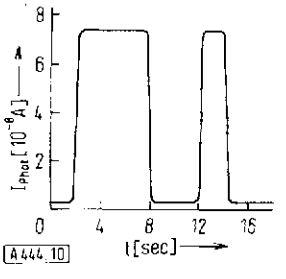


Fig. 10. Oscillogram of the photovoltaic sandwich cell of malachite green (n) and merocyanine A-10 (p). λ = 6220 Å, 3.7×10^{15} quanta/cm² sec); cell as in Fig. 4, II.

cell independent of the direction of illumination, similar to the case of inorganic systems. Analogous photovoltaic effects are obtained on coupling p-type aromatic amines with n-type dyes (crystal violet) [204] and in systems of magnesium phthalocyanine and air-oxidized *N,N,N',N'*-tetramethyl-*p*-phenylenediamine (maximum photopotential 200 mV [205]).

[192] *R.S.Mulliken*, J. Amer. chem. Soc. *72*, 600 (1950); *74*, 811 (1952).

[193] *H. Meier* and *W. Albrecht*, ref. [56a].

[194] *R. P. Kohin, K. A. Müller*, and *H. Hoegl*, Helv. physica Acta *35*, 255 (1962).

[195] *H. Meier* and *W. Albrecht*, Ber. Bunsenges. physik. Chem. *68*, 64 (1964).

[196] *H. Kallmann* and *M. Pope*, Nature (London) *186*, 31 (1960); J. chem. Physics *32*, 300 (1960); Symposium on Electrical Conductivity in Organic Solids. Interscience, New York 1961 pp. 1 to 25.

[197] *M. Silver* and *W. Moore*, J. chem. Physics *33*, 1671 (1960).

[198] *M. Silver* in *J. J. Brophy* and *J. W. Buttrey*: Organic Semiconductors. The Macmillan Comp., New York 1962, pp. 27–35.

[199] *H. Meier*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *59*, 1019 (1955).

[200] *H. Baba, K. Chitoku*, and *K. Nitta*, Nature (London) *177*, 672 (1956).

[201] *H. Amsler*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *57*, 801 (1953).

[202] *H. Inokuchi, Y. Maruyama*, and *H. Akamatu* in: Symposium on Electrical Conductivity in Organic Solids. Interscience, New York 1961, pp. 69–76; Bull. chem. Soc. Japan *34*, 1093 (1961).

[203] *H. Meier* and *A. Haus*, Angew. Chem. *72*, 631 (1960); Z. Elektrochem., Ber. Bunsenges. physik. Chem. *64*, 1105 (1960).

[204] *W. C. Needler*, International Conference on Photosensitization in Solids, Chicago, June 1964.

[205] *D. Kearns* and *M. Calvin*, J. chem. Physics *29*, 950 (1959)].

Photocurrents up to 10^{-8} A and photopotentials up to 300 mV arise [195, 207] in mixed organic/inorganic systems, where the components are arranged side by side [164, 206] or superposed in thin layers (cf. Fig. 4). This high value for the photopotential as compared to those found in dye/metal systems demonstrates that the interface between the inorganic semiconductor and the dye and not the metal/semiconductor contact is responsible for the photovoltaic effect.

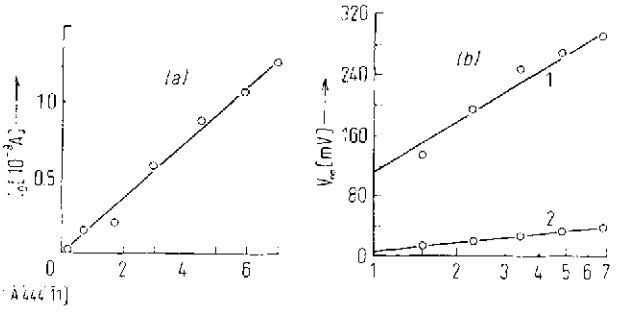


Fig. 11 *(a)*: Dependence of the short-circuit current on illumination (λ = 5580 Å; CdS/merocyanine A-10; Cell as in Fig. 4, I). *(b)*: Dependence of the open-circuit photopotential on the illumination [λ = 6000 Å; curve 1: AgI/Rhodamine B (arrangement I in Fig. 4). Curve 2: AgBr/Rhodamine B (arrangement II in Fig. 4).
Abscissae: Illumination (Hefner units).
Note: 1 Hefner unit = 94.7 μW/cm².

The arrangements behave substantially in the same way as purely inorganic pn-photovoltaic systems, as is shown by the dependence of the photocurrent on the light intensity (see Fig. 11), and by the facts that the current rises in less than $^1/_{50}$ sec, and the action and absorption spectra agree. The dependence of the photocurrent and the photopotential on the type of conduction of the combination (p or n) is significant, and agrees with the direction of travel of the electrons predicted by the p–n junction theory [19] (cf. Table 4).

Comparison of the energy levels (see Section D. X.) shows that, *e.g.* electron transfer is possible in the dark from an n-type dye to AgBr, since E_F (AgBr) lies below E_F (dye), to produce an internal electric field. The dye in the boundary layer becomes positive and the silver halide negative. The resulting field separates the electron-positive hole couples formed on illumination in the sense given by the p–n junction theory.

The photovoltaic effect of the inorganic/organic combinations can be increased by doping the p-type dye component; an example is shown in Fig. 12.

Table 4. The electric charge arising in combinations of dyes and inorganic photoconductors on illumination.

Inorganic photoconductor I	Dye II	Charge on Illumination Experiment I	II	pn-Theory I	II	Ref.
CdS (n)	Phthalocyanine (p)	−	+	−	+	[195]
CdSe (n)	Merocyanine A-10 (p)	−	+	−	+	[207]
ZnO (n)	Eosin (sodium salt) (p)	−	+	−	+	[208]
AgBr (p)	Rhodamine B *(7)* (n)	+	−	+	−	[207]
AgI (p)	Malachite green (n)	+	−	+	−	[207]
TlI (p)	Phenosafranine *(9)* (n)	+	−	+	−	[209]
Malachite green (n)	Merocyanine A-10 (p)	−	+	−	+	[203]

[206] *R. C. Nelson*, J. opt. Soc. America *46*, 13 (1956).

[207] *H. Meier* and *W. Albrecht*, Ber. Bunsenges. physik. Chem. *69*, 160 (1965).

[208] *S. J. Dudjowski* and *L. J. Grossweiner*, J. opt. Soc. America *54*, 486 (1964).

[209] *A. Terenin* and *I. Akimov*, International Conference on Photosensitization in Solids, Chicago, June 1964.

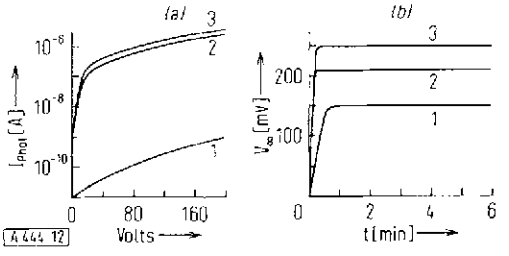


Fig. 12. Effect of doping on the photoconductivity *(a)* and the photovoltaic effect *(b)* in a CdS/merocyanine A-10 surface cell (dimensions: for *(a)* as in Fig. 6; for *(b)* as in Fig. 4, I).

Curve 1: Undoped Merocyanine A-10; curves 2 and 3: Merocyanine A-10 doped with tetraiodophthalic anhydride [10^{-7} mole/cm²]; or iodine [10^{-8} mole/cm²].

H. Significance and Applications of Dye Photosemiconductors

I. Photochemical and Biological Problems

The extent of the participation of electronic charge carriers in the primary process of photosynthesis is an interesting problem [25, 210–213]. Electronic charge carriers are indeed formed [13, 36, 41, 43, 164, 214–216], since chlorophyll and its analogues (chlorophyll a, b; methylchlorophyllide a + b; chlorophyll pigments with β-carotene, xanthophyll, neoxanthine, and violaxanthine) exhibit photoconductivity. Measurements of the dependence on oxygen pressure and of the crystal photoeffect have shown that positive holes are the majority carriers in these processes. It is feasible that these add to water molecules which then split into molecular oxygen and hydrogen, while the electrons are taken up by an acceptor (*e.g.* coenzyme Q) and participate in the CO_2 reduction process [25, 210, 211].

The similarity between the photocurrents of electroretinograms measured in the eye and dye photocurrents indicates that the primary reaction of the process of vision is electronic and not photochemical in nature [199, 217].

In agreement with the electroretinograms, certain dye photoelements [16, 172] alter the direction of the photocurrent when the wavelength of the incident monochromatic light changes [218–220], (Fig. 13).

[210] *M. Calvin*, Rev. mod. Physics *31*, 147 (1959).

[211] *G. Tollin*, Radiat. Res., Suppl. *2*, 407 (1960).

[212] *B. Rumberg* and *H. T. Witt*, Z. Naturforsch. *19b*, 693 (1964).

[213] *W. Arnold* and *H. Sherwood*, J. physic. Chem. *63*, 2 (1959).

[214] *E. Putzeiko*, Dokl. Akad. Nauk SSSR *138*, 1381 (1961).

[215] *A. Terenin* and *E. Putzeiko*, Angew. Chem. *70*, 508 (1958).

[216] *A. J. Vartanyan*, Soviet Physics Dokl. *8*, 29, 349 (1963); Akad. Dokl. Nauk SSSR *149*, 563 (1963).

[217] *H. Meier*, Z. wiss. Photogr., Photophysik Photochem. *53*, 117 (1959).

[218] *A. Kohlrausch*: Handbuch der normalen und pathologischen Physiologie. Receptionsorgane, Photoreceptoren. Teil 2. Springer, Berlin 1931, pp. 1394–1496.

[219] *R. Granit*, Proc. physic. Soc. (London) *57*, 447 (1945).

[220] *G. Svaetichin*, Acta physiol. scand. *39*, 17 (1956).

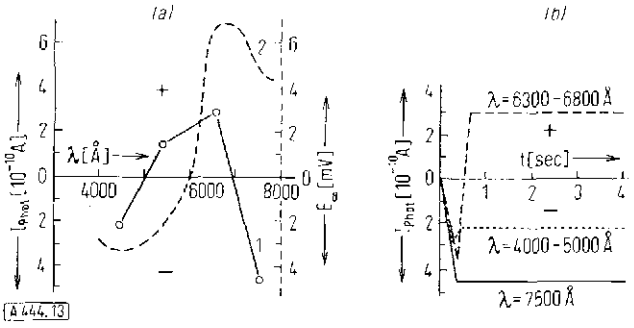


Fig. 13. *(a)*: Wavelength-dependence of the direction of the photovoltaic effect (photocurrent and photopotential). Curve 1: Orthochrome T, 1 mW/cm² [16, 172]; curve 2: β-carotene [221], 3.9×10^{15} quanta/(cm² sec).

(b): Variation of the photocurrent with time for Orthochrome T for different wavelengths [16, 172].

Similar behavior is shown by the receptors which are charged in dependence on the wavelength and transmit the stimuli [25, 217]. According to a recent study [221], the direction of the photocurrent in β-carotene, which is closely related to visual purple, is likewise wavelength-dependent. It may be noted that the photocurrents in β-carotene (which is p-conducting [25, 222]) depend on potential, intensity of illumination, gas atmosphere, *etc.* in the same way as those in other p-conducting dyes such as merocyanines and phthalocyanines [223—226]. The 15,15′-*cis* isomer of β-carotene which is formed in the eye exhibits a photoelectric sensitivity which is 1000 times greater than that of the (absent) all-*trans* isomer [227]. This fact also speaks in favor of an electronic mechanism of the process of vision.

II. Spectral Sensitization

An electron transfer mechanism for the spectral sensitization of the photographic process and the photoconductivity of semiconductors [13, 25, 158, 228—233] presupposes the formation and migration of electronic charge carriers in the sensitizing agent. As the photoelectric sensitivity of the various sensitizer dyes shows (pinacyanol *(2)*, infrared sensitizer S 916 [*], this is indeed the case [16, 80, 100, 229, 234].

Knowledge of the type of conduction of the sensitizing dyes and the positions of their energy levels, as well as the photovoltaic effects on sensitized system models (e.g. CdS/dye) leads to the interpretation of the sensitization as a type of p-n photoeffect [158, 207, 235]. Supersensitization [**] of photoconductivity is possibly related to the doping effect (see Sections F and G III) and can be explained in a similar manner [193, 207, 236, 237].

III. Dyes as Organic Photoconductor Models

The simple method of construction of photoconducting dye cells in comparison to other organic photoconductors (high polymers, aromatic compounds), giving relatively high, reproducible photocurrents in the visible spectral region makes dyes, and particularly the phthalocyanines [238—241], the preferred organic semiconductors for further study. Many results and hypotheses obtained with these substances can be applied to other types of organic semiconductors (cf. [8, 25, 54, 55, 102, 149, 242—246]).

IV. Technical Applications

The rectifying effect of metal/dye systems can reach substantial magnitudes in phthalocyanines placed between two different metals [247—250]. At 10 Kc/s, rectification in the ratio of 1000:1 is possible.

The electronic interaction mechanism between organic semiconductors and adsorbed gases, which is analogous to that in inorganic catalysts, leads to expected catalytic properties of the organic semiconductors. For example, the para → ortho conversion of hydrogen is catalysed by α,α′-diphenyl-β-picrylhydrazyl [138] and by polymeric and monomeric copper

[221] *B. Rosenberg, R. J. Heck,* and *K. Aziz,* J. opt. Soc. America *54*, 1018 (1964).

[222] *B. Rosenberg,* J. chem. Physics *31*, 238 (1959).

[223] *H. Meier,* lecture at Erlangen (Germany), July 10th, 1958.

[224] *B. Rosenberg,* J. opt. Soc. America *48*, 581 (1958); J. chem. Physics *34*, 63 (1961); Symposium on Electrical Conductivity in Organic Solids. Interscience, New York 1961, pp. 291—308.

[225] *B. Rosenberg, R. A. Orlando,* and *J. M. Orlando,* Arch. Biochemistry *93*, 395 (1961).

[226] *A. I. Burstein,* Fig. Tverd. Tela *5*, 1264 (1963).

[227] *B. Rosenberg,* J. opt. Soc. America *51*, 238 (1961).

[228] *R. W. Gurney* and *N. F. Mott,* Proc. Roy. Soc. (London) Ser. A *164*, 151 (1938).

[229] *W. Nodduk* and *H. Meier,* Z. Elektrochem., Ber. Bunsenges. physik. Chem. *63*, 971 (1959).

[230] *J. Eggert,* Ann. Physik [7], *4*, 140 (1959).

[231] *G. Scheibe* and *F. Dörr* in ref. [100a], pp. 511—513.

[232] *B. H. Carroll* in ref. [100a], pp. 427—439.

[233] *J. W. Weigl* in: Photographic Science Symposium, Zürich 1961. The Focal Press, London 1963, S. 345—370.

[*] Sensitization maximum 8100 Å; Farbwerke Hoechst AG.

[234] *H. Meier,* Kép-és Haugtechnika (Budapest) *1*, 1 (1962).

[235] *H. Meier,* Chimia *18*, 179 (1964).

[**] Supersensitizers are organic substances which are added in traces and produce an extraordinary spectral sensitization of the photographic layers without appreciable absorption of light.

[236] *E. Inoue, I. Maki,* and *T. Yamaguchi,* J. chem. Soc. Japan, ind. Chem. Sect. *66*, 428 (1963).

[237] *E. Inoue* and *T. Yamaguchi,* Bull. chem. Soc. Japan *36*, 1573 (1963).

[238] *P. E. Fielding* and *A. G. MacKay,* Austral. J. Chem. *17*, 750 (1964).

[239] *Ch. J. Hofmann,* Quart. Rev. (Chem. Soc., London) *18*, 113 (1964).

[240] *R. C. Bradley, J. D. Grace,* and *D. C. Munro,* J. physic. Chem. Solids *25*, 725 (1964).

[241] *G. H. Heilmeier* and *L. A. Zanoni,* J. physic. Chem. Solids *25*, 603 (1964).

[242] *C. G. B. Garrett* in *N. B. Hannay*: Semiconductors. Reinhold, New York 1959, pp. 662—673; Radiat. Res., Suppl. *2*, 340 (1960).

[243] *M. Pope* and *H. Kallmann* in: Symposium on Electrical Conductivity in Organic Solids. Interscience, New York 1961, pp. 83—104.

[244] *E. Clar*: Polycyclic Hydrocarbons, Vol. I. Academic Press, London, and Springer, Berlin-Göttingen-Heidelberg 1964.

[244a] *Y. Okamoto* and *W. Brenner*: Organic Semiconductors. Reinhold, New York 1964.

[245] *R. G. Kepler, P. E. Bierstedt,* and *R. E. Merrifield* in *J. J. Brophy* and *J. W. Buttrey*: Organic Semiconductors. The Macmillan Comp., New York 1962, pp. 45—48.

[246] *M. Y. Kleinermann* and *S. P. MacGlynn* in [245], pp. 108 to 114.

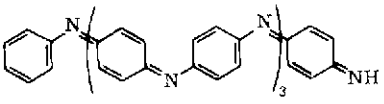
[247] *F. A. Haak* and *J. P. Nolte,* Conference on Semiconduction in Molecular Solids. Proceedings Princeton Univ., February 1960.

[248] *J. B. Rust, F. A. Haak,* and *J. P. Nolte,* WADD Techn. Report 60—111, Hughes Res. Lab., Culver City, Calif., October 1959.

[249] *H. A. Pohl* in *J. J. Brophy* and *J. W. Buttrey*: Organic Semiconductors. The Macmillan Comp., New York 1962, p. 139.

[250] *C. Hamann,* Physica Status solidi *4*, 97 (1964).

phthalocyanine [250a]. Conjugated polymers such as polybenzimidazole catalyse the decomposition of N_2O as well as the liberation of H_2 from alcohols and formic acid [251]. Dyes such as Aniline Black *(10)* and Paramine Brown [*] can also behave as catalysts [252]. In some instances, organic catalysts have proved to be more efficient than inorganic ones [253, 254].



(10)

The possible technical use of organic dyes as photoresistors or photoelements cannot yet be evaluated. It is not the magnitude of the attainable photocurrent (up to 10^{-4} A at an applied EMF of 100 volts) and photopotentials (up to 0.4 V) but rather the stability of the photoelectric cells which is likely to be decisive. Organic semiconductors possibly can be used as photosensitive electrets, electrode materials, *e.g.* for fuel cells [149, 249], semiconductor radioactivity detectors [255, 256], or as superconductors [257] (see Fig. 14).

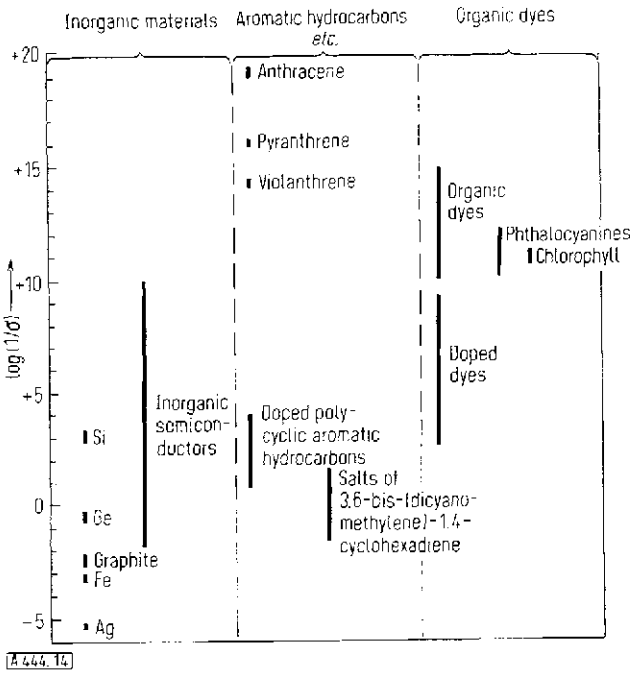


Fig. 14. Specific resistances $1/\sigma$ of inorganic and organic materials.

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German version: Angew. Chem. 77, 633 (1965)
Translated by Express Translation Service, London

[250a] *G. J. Acres* and *D. D. Eley*, Trans. Faraday Soc. *60*, 1157 (1964.)

[251] *Ph. Traynard*, ref. [56a].

[*] A dye similar to Aniline Black obtained analogously from *p*-phenylenediamine.

[252] Chem.-Ing.-Techn. *36*, A 1245 (1964).

[253] *H. Inoue, S. Hayashi*, and *E. Imoto*, Bull. chem. Soc. Japan *37*, 326 (1964).

[254] *J. Dokukina, S. Roginski, M. Ssacharow, A. Toptschijew, M. Geiderich, B. Dawydow*, and *B. Krenzel*, Dokl. Akad. Nauk SSSR *137*, 893 (1961).

[255] *H. K. Hartmann*, Z. angew. Physik *14*, 727 (1962).

[256] *S. E. Harrison* and *P. F. Proulx*, NASA Document N 63-18974 (1964); Sci. Tech. Aerospace Report *1*, 1434 (1963).

[257] *W. A. Little*, Physic. Rev. *134*, A 1416 (1964).

The Chemistry of Nitrous Acid and of its Derivatives in Liquid Hydrogen Fluoride

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The reaction of liquid hydrogen fluoride with nitrous acid, dinitrogen trioxide, dinitrogen tetroxide, and nitrosyl compounds leads to unexpectedly high-boiling liquids which contain nitrosyl fluoride in the form of remarkably stable, electrolytically dissociated hydrogen fluoride solvates. Nitrosyl fluoride solvated by pure hydrogen fluoride is a new reagent, valuable in fluorine chemistry since it reacts with many elements and compounds to form fluorine derivatives of preparative importance.

1. Introduction

Hydrogen fluoride is a liquid between −85 and +19.6 °C and can dissolve many inorganic and organic substances. Like water it can combine with saturated compounds, thus giving rise to solvates. In striking contrast to its aqueous solution, anhydrous *liquid* hydrogen fluoride is a very strong acid with respect to water; it forms salts even with very weakly basic nitrogen and oxygen compounds, and decomposes derivatives of weaker acids by solvolysis. These properties determine the chemistry of liquid hydrogen fluoride.

This interesting field of chemistry, full of experimental difficulties, was pioneered by *K. Fredenhagen* and his

school (1929–39) [1, 2], who investigated the behavior of numerous compounds in liquid hydrogen fluoride, but not that of nitrous acid and its derivatives. Owing to this surprising omission, the intriguing chapter of nitrous acid chemistry in liquid hydrogen fluoride could be opened up only recently.

2. The Reaction between Nitrous Acid and Hydrogen Fluoride

Fredenhagen reported that potassium nitrite dissolves in hydrogen fluoride with the evolution of nitrogen oxides [2]. The reaction was not further investigated, possibly because it was assumed that merely solutions of potassium fluoride were formed. However, when nitrite is cautiously added to hydrogen fluoride at a low temperature, practically no nitrogen oxides are evolved and the "trivalent nitrogen" content of the solution remains unchanged for a long time in vessels resistant to hydrogen fluoride. Obviously nitrous acid is stabilized under these conditions, as it is by the reaction with concentrated perchloric acid or sulfuric acid yielding nitrosyl perchlorate or nitrosylsulfuric acid (or their monohydrates). Ultraviolet spectroscopy reveals that the reactions of nitrous acid with strong oxyacids and with hydrogen fluoride are in fact of the same type. When nitrites are dissolved in perchloric acid [3] or sulfuric acid [4] of decreasing water content, the longest-wavelength band of nitrous acid is seen to transform progressively into the charge-transfer band of the hydrated nitrosyl cation $NO^+ \cdot OH_2$ [4]. The same phenomenon is observed in mixtures of hydrogen fluoride and water, containing 45 to 60 % by weight of HF [5] (cf. Fig. 1).

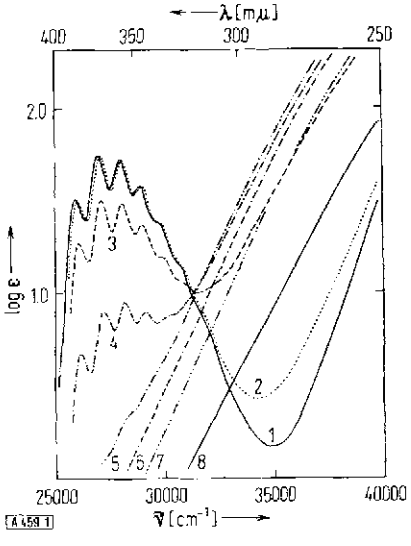

Fig. 1. Absorption of light by solutions of sodium nitrite in 30.8 to 70.5 % aqueous hydrofluoric acid.

Curve	1	2	3	4	5	6	7	8
HF [%]	30.8	45.2	50.2	52.5	54.6	57.0	59.8	70.5

Similarly to solutions of nitrous acid in aqueous perchloric acid or sulfuric acid, solutions in hydrogen fluoride do not show a sharp isosbestic point owing to the absorption shift caused by the solvent. The concentration of unchanged nitrous acid can however be determined from the height of the characteristic band maxima in the extinction diagram. If the logarithm of the ratio of the concentrations of $NO^+ \cdot OH_2$ and NO·OH is plotted against the acidity function H_0 [6] of the HF/H_2O mixture, a straight line is obtained, which is parallel to the corresponding straight lines for nitrous acid in aqueous $HClO_4$ and H_2SO_4. Since the slope of the straight lines in Fig. 2 is about 2, there cannot be a significant connection between H_0 and the position of the protolytic equilibrium. This is due to the fact that nitrous acid is not a proton-acceptor base, but a hydroxyl-donor base.

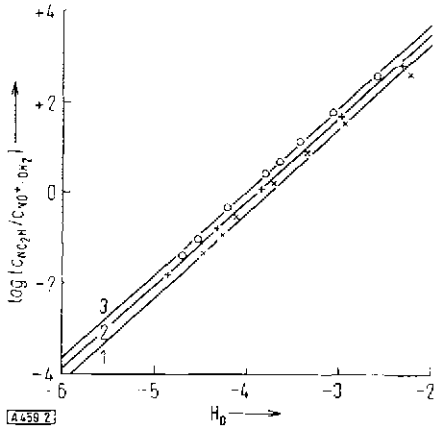

Fig. 2. Stability of nitrous acid and the hydrated nitric oxide cation as a function of H_0 in various strong acids [curve 1 (×): $HClO_4/H_2O$; curve 2 (+): HF/H_2O; curve 3(o): H_2SO_4/H_2O].

The solvent chemistry of hydrogen fluoride is seen here, as on other occasions, to be remarkably similar to that of perchloric acid and sulfuric acid. In all these strong acids, nitrous acid behaves as a base.

$$NO{\cdot}OH + HClO_4 \rightarrow NO^+ \cdot OH_2 + ClO_4^-$$
$$NO{\cdot}OH + H_2SO_4 \rightarrow NO^+ \cdot OH_2 + HSO_4^-$$
$$NO{\cdot}OH + HF \rightarrow NO^+ \cdot OH_2 + F^-$$

In anhydrous hydrogen fluoride, the molar conductivity of nitrous acid is twice as high as that of a 1:1 electrolyte (*i.e.* the molar conductivity of potassium nitrite is three times the value expected for a single electrolytic dissociation) [7]. Clearly a further protonation of the nitrous acid must take place, which has also been detected in solutions of nitrous acid in anhydrous sulfuric acid [8], and which consists of the complete separation of the hydroxyl group to form the oxonium ion:

$$NO^+ \cdot OH_2 + H_2SO_4 \rightarrow NO^+ + OH_3^+ + HSO_4^-$$
$$NO^+ \cdot OH_2 + HF \rightarrow NO^+ + OH_3^+ + F^-$$

[1] *K. Fredenhagen* and *G. Cadenbach*, Z. anorg. allg. Chem. *178*, 289 (1929); Z. Elektrochem. angew. physik. Chem. *37*, 684 (1931); Z. physik. Chem., Abt. A *146*, 245 (1930); *164*, 176 (1933); *K. Fredenhagen* and *J. Dahmlos*, Z. anorg. allg. Chem. *178*, 272 (1929); *K. Fredenhagen* and *H. Fredenhagen*, ibid. *243*, 39 (1939); Angew. Chem. *52*, 189 (1939); *W. Klatt*, Z. anorg. allg. Chem. *222*, 225 (1935); *232*, 393 (1937); *233*, 307 (1937); *234*, 189 (1937).

[2] *K. Fredenhagen*, Z. anorg. allg. Chem. *242*, 23 (1939).

[3] *K. Singer* and *P. A. Vamplew*, J. chem. Soc. (London) *1956*, 3971.

[4] *F. Seel* and *R. Winkler*, Z. physik. Chem. NF *25*, 217 (1960).

[5] *R. Winkler*, Doctorate Dissertation, Technische Hochschule Stuttgart, 1959.

[6] *H. H. Hyman*, *M. Kilpatrik*, and *J. J. Katz*, J. Amer. chem. Soc. *79*, 3668 (1957); see also *L. P. Hammet*, Chem. Rev. *13*, 61 (1935); *M. A. Paul* and *F. A. Long*, ibid. *57*, 1 (1957).

[7] *B. Medinger*, unpublished work.

[8] *R. J. Gillespie*, *T. Graham*, *E. D. Hughes*, *C. K. Ingold*, and *E. R. A. Peeling*, J. chem. Soc. (London) *1950*, 24.

Up to a molar ratio of 1:11, solutions of sodium nitrite in liquid hydrogen fluoride are colorless and no more nitrite can be dissolved without nitrous acid decomposing into nitrogen oxides. The solution of nitrous acid in hydrogen fluoride, which is colorless up to a molar ratio of 1:9, is decomposed by the addition of soluble fluorides. Evidently a solution of nitrous acid is stable only in the presence of sufficient hydrogen fluoride as a solvating agent.

Like solutions of nitrosylsulfuric acid in sulfuric acid, solutions of nitrous acid in hydrogen fluoride develop a deep indigo color when treated with nitric oxide or subjected to partial reduction with sulfur dioxide or methanol. On cooling these blue solutions exhibit the thermochromism which is characteristic of the nitrosyl-nitric oxide ion [9]:

$$NO^+ + NO \rightarrow N_2O_2^+$$

(*It was on addition of sodium nitrite to a solution of* sulfur dioxide in hydrogen fluoride that the "purple hydrogen fluoride" was discovered [10], and this stimulated the investigations described here.)

3. Reactions of Dinitrogen Trioxide with Hydrogen Fluoride

Solutions of dinitrogen trioxide in liquid hydrogen fluoride can be prepared by passing an equimolecular mixture of nitric oxide and nitrogen dioxide into the solvent, or by liquefying a gaseous mixture of NO, NO_2, and HF. Colorless solutions are again obtained if the amount of HF present is sufficient for a complete reaction. The colorless solution of composition $N_2O_3 \cdot 12.8$ HF or $NOF \cdot 5.4$ HF $\cdot 0.5$ H_2O can be distilled at 68 °C under atmospheric pressure without change in composition, and can also be separated by distillation from solutions of different composition. It can be shown by infrared spectroscopy that hydrogen fluoride, dinitrogen trioxide, and its decomposition products nitric oxide and nitrogen dioxide are present in the vapor of the "68 °C product". This indicates that distillation leads to reversible decomposition of the liquid. (Surprisingly the liquid turns only faintly brown, even when heated to its boiling point.)

The liquid boiling at 68 °C can also be distilled from solutions of metal nitrites ($NaNO_2$, KNO_2, $AgNO_2$) in hydrogen fluoride [11]. The ease of formation of the "68 °C product" is clearly due to the decomposition of nitrous acid into N_2O_3 (or NO + NO_2) and water, which is retained by the hydrogen fluoride. Solutions of nitrous acid obtained by passing N_2O_3 (or NO + NO_2) into aqueous hydrogen fluoride can be separated by fractional distillation into the "68 °C product" and the azeotropic mixture (b.p. 112 °C) of hydrogen fluoride and water [12].

The "68 °C product" can also be obtained by treating a mixture of nitric acid and hydrogen fluoride with nitric oxide, or by treating hydrogen fluoride alone with nitric oxide under pressure. In the presence of excess nitric oxide, the deeply colored "purple hydrogen fluoride" is formed first. These methods for preparing solutions of dinitrogen trioxide in HF are based on the well known reaction of nitric acid with nitric oxide to give nitrous acid and dinitrogen trioxide, and on the disproportionation of nitric oxide into dinitrogen trioxide and nitrous oxide.

On cooling to below −12 °C, the liquid of composition $N_2O_3 \cdot 12.8$ HF first becomes viscous and then solidifies into a glass melting between −17 and −23 °C [13]. It is extremely unlikely that we are dealing here with an azeotropic mixture of dinitrogen trioxide and hydrogen fluoride [14], or of HF and an N_2O_3-HF compound. If dinitrogen trioxide behaves towards HF as it does towards H_2SO_4 or $HClO_4$, then hydrogen fluoride first solvolyses dinitrogen trioxide into nitrosyl fluoride and nitrous acid:

$$N_2O_3 + HF \rightarrow NOF + HNO_2$$

and the nitrous acid subsequently reacts with HF to give $NO^+ \cdot OH_2$ or NO^+ and F^-.

That the solution contains an electrolyte is indicated by the electrical conductivity of the "68 °C product," which resembles that of a fused electrolyte (*e.g.* fused zinc chloride). The molar conductivity of a much more dilute (about 0.1 M) solution of N_2O_3 in liquid hydrogen fluoride is about three times as high as that of a potassium fluoride solution of the same concentration. This indicates the following overall reaction, neglecting solvation of the ions:

$$N_2O_3 + 3\ HF \rightarrow 2\ NO^+ + OH_3^+ + 3\ F^-$$

The infrared spectrum of the liquid "68 °C product" shows a band at 2350 cm^{-1}, which is characteristic of the nitrosyl cation [15] (cf. Fig. 3).

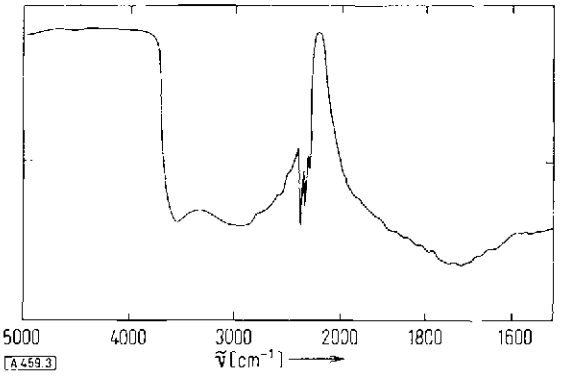

Fig. 3. The infrared spectrum of $N_2O_3 \cdot 12.8$ HF.

When a solution of dinitrogen trioxide in hydrogen fluoride is subjected to partial freezing, the solid phase is seen to contain not only HF and N_2O_3, but also NOF, while the liquid phase contains H_2O in addition to HF

[9] *F. Seel, B. Ficke*, and *E. Völkl*, Z. Naturforsch. *8b*, 607 (1953); *F. Seel*, Angew. Chem. *68*, 276 (1956); *F. Seel* and *H. Sauer*, Angew. Chem. *69*, 135 (1957); Z. anorg. allg. Chem. *292*, 1 (1957).

[10] *F. Seel* and *L. Riehl*, unpublished work, quoted in Angew. Chem. *69*, 135 (1957).

[11] *G. Fuchs*, Doctorate Dissertation, Universität Saarbrücken 1964.

[12] *B. Medinger*, Diploma Thesis, Universität Saarbrücken, 1965.

[13] *J. Schmidt*, Doctorate Dissertation, Universität Saarbrücken, 1965.

[14] *B. Fox, R. Siegel, S. I. Speirs*, and *R. H. Wiswall jr.*, Abstr. 144th Meeting Amer. chem. Soc. 1963, 9 K.

[15] *D. Werner*, unpublished work.

and N_2O_3, corresponding to an enrichment of nitrosyl-hydrogen fluoride in the solid phase and of oxonium-hydrogen fluoride in the liquid phase. These observations further indicate that the solution of dinitrogen trioxide in liquid hydrogen fluoride contains no undecomposed, HF-solvated N_2O_3 molecules.

Water can be removed from the "68 °C product" by treating the latter with sulfur tetrafluoride:

$$SF_4 + H_2O \rightarrow SOF_2 + 2\ HF$$

After the removal of thionyl fluoride, a pure solution of nitrosyl fluoride in hydrogen fluoride is obtained. Fractional distillation of this solution yields a product (b.p. 94 °C) of the composition NOF + 3 HF, which will be described in Section 5. The low volatility of the HF-solvated nitrosyl fluoride explains why NOF cannot be isolated by distilling a solution of solvolysed dinitrogen trioxide in hydrogen fluoride.

If sodium fluoride or potassium fluoride is added to $N_2O_3 \cdot 12.8$ HF, hydrogen fluoride is removed from the solution by the formation of metal hydrogen fluorides, and nitric oxide and nitrous oxide are liberated.

4. Reactions of Dinitrogen Tetroxide with Hydrogen Fluoride

Very little was previously known of the behavior of dinitrogen tetroxide towards hydrogen fluoride. The fact that colorless mixtures containing a maximum of 25 mole-% nitrogen dioxide can be prepared proves that NO_2 and HF do in fact react with each other. On the basis of the behavior of nitrogen dioxide towards concentrated perchloric and sulfuric acids, it seems reasonable to propose the solvolysis of the nitrosyl nitrate form of dinitrogen tetroxide:

$$(O_2N \cdot NO_2 \rightleftharpoons 2\ NO_2 \rightleftharpoons ON \cdot ONO_2) + HF \rightarrow NOF + HNO_3$$

Admittedly, an unfavorable value is obtained for the free energy of this reaction on substituting in the following equation the values for the energies of formation of the four gaseous participants [16]:

$$\Delta F°_{298} = -[\Delta F°(N_2O_4) + \Delta F°(HF)] + [\Delta F°(NOF) + \Delta F°(HNO_3)]$$
$$= -(24.8-64.7) + (-12.5-19.0) = +8.4\ \text{kcal/mole}$$

Possibly, however, the energy deficit is compensated by solvation in the condensed phase. This is indicated by the fact that the fractional distillation of a colorless mixture of nitrogen dioxide with excess hydrogen fluoride enables the separation into NOF·3 HF (b.p. 94 °C), mentioned above, and a constant-boiling liquid (b.p. 52 °C) of composition [17]

$$N_2O_4 + 7.0\ HF + 0.87\ HNO_3 = NOF + 6.0\ HF + 1.87\ HNO_3$$

The "52 °C product" is colorless at room temperature, but becomes golden yellow on boiling, which shows that on distillation it decomposes into N_2O_4 and HF. Evidently nitric acid, being more volatile than NOF·3 HF and less basic than nitrous acid, distils out of the solution of N_2O_4 in hydrogen fluoride during the evolution of NO_2 and HF. The constant-boiling products obtained by treating hydrogen fluoride with N_2O_3 and N_2O_4 are listed in Table 1.

Table 1. Constant-boiling products.

B.p. [°C]	Composition
52	N_2O_4 + 7.0 HF + 0.87 HNO_3 or NOF + 6.0 HF + 1.87 HNO_3
68	N_2O_3 + 12.8 HF or NOF + 5.4 HF + 0.5 H_2O
94	NOF + 3 HF

5. Hydrogen Fluoride Solvates of Nitrosyl Fluoride

a) Preparation and Properties

Whereas the reaction of nitrogen dioxide with hydrogen fluoride leads to the unexpectedly high-boiling liquid (b.p. 94 °C) of composition NOF·3 HF in a yield of only about 20 %, the distillation of a solution of nitrosyl fluoride in anhydrous hydrogen fluoride results in the "94 °C product" in quantitative yield (based on the nitrogen compound). It is worth noting that the NOF–HF solvate can also be prepared from nitrosyl chloride and hydrogen fluoride in the liquid or gaseous phase [18–25] (in the second case at somewhat higher temperatures [21]). The reaction

$$NOCl + HF \rightarrow NOF + HCl$$

is thermodynamically unexpected, since an unfavorable free energy is calculated from the energies of formation of the gaseous participants [16] (as in the case of N_2O_4 and HF):

$$\Delta F°_{298} = [\Delta F°(NOCl) + \Delta F°(HF)] + [\Delta F°(NOF) + \Delta F°(HCl)]$$
$$= (15.9-64.7) + (-12.5-22.8) = +13.5\ \text{kcal/mole}$$

It is obvious that the formation of a solvate between nitrosyl fluoride and hydrogen fluoride facilitates the reaction.

[16] Sources: *W. M. Latimer*: Oxidation Potentials. 2nd edit., Prentice-Hall, New York 1952. The value of $\Delta F°(NOF)$ was calculated from the heat of the reaction 2 NO + F_2 → 2 NOF, assuming that the entropy of formation is the same for NOF as for NOCl [*H. S. Johnston* and *H. J. Bertin*, J. Amer. chem. Soc. *81*, 6402 (1959)].

[17] *F. Seel, G. Fuchs*, and *D. Werner*, Chem. Ber. *96*, 179 (1963).

[18] *F. Seel* and *W. Birnkraut*, Angew. Chem. *73*, 531 (1961).

[19] German Patent 1123297 (Aug. 8th, 1960), inventor: *F. Seel*.

[20] *L. G. Anello, J. Gordon, H. R. Nychka*, and *C. Woolf*, Abstr. 140th Meeting Amer. chem. Soc. 1961, 18 M.

[21] *F. Seel, W. Birnkraut*, and *D. Werner*, Chem. Ber. *95*, 1264 (1962).

[22] Brit. Pat. 941537 (Dec. 4th, 1961); French Pat. 1310892 (Dec. 22nd, 1961); Belg. Pat. 611544 (Dec. 14th, 1961), Allied Chem. Corp., inventors: *L. G. Anello* and *C. Woolf*.

[23] U.S. Pat. 3062902 (Dec. 23rd, 1960), Allied Chem. Corp., inventors: *L. G. Anello, J. Gordon*, and *C. Woolf*.

[24] U.S. Pat. 3074781 (Dec. 23rd, 1960); French Pat. 1309590 (Dec. 22nd, 1961) Allied Chem. Corp., inventors: *L. G. Anello* and *C. Woolf*.

[25] German Published Patent Application 1160409 (Dec. 14th, 1961); French Pat. 1317920 (Dec. 22nd, 1961), Allied. Chem. Corp., inventors: *L. G. Anello* and *C. Woolf*.

Pure NOF·3 HF is a colorless, hygroscopic liquid. Its weakly yellowish color points to partial hydrolytic decomposition. The specific gravity of the substance is unexpectedly high (1.50) indicating that nitrosyl fluoride occupies only a very small space in the HF solution. The liquid is immiscible with hydrocarbons and with partially and fully chlorinated or fluorinated hydrocarbons. It can be stored in containers made of paraffin, Hostafion C (Kel F), Teflon, or pure nickel. In carbon tetrachloride, the solvate forms large floating drops which can be frozen out by cooling with ice. On the skin, NOF·3 HF produces painful wounds, but not as fast as liquid hydrogen fluoride.

In the vapor of the "94 °C product" free nitrosyl fluoride, hydrogen fluoride, and nitric oxide (originating from hydrolysis) can be detected [13]. The vapor density indicates that NOF and HF are associated in the gaseous phase as well.

Like $N_2O_3 \cdot 12.8$ HF, the solvate NOF·3 HF exhibits the electrical conductivity of a fused salt. Dilute (about 0.25 M) solutions of NOF in HF show the same molar conductivity as solutions of a 1:1 electrolyte [7]. Obviously nitrosyl fluoride in hydrogen fluoride dissociates into nitrosyl cations and fluoride anions.

When hydrogen fluoride is pumped off from the 94 °C product at room temperature, a liquid of composition NOF·2.67 HF is left behind, which melts sharply at 4.7 °C, whereas NOF·3 HF melts between 1 and 5.5 °C. Nitrosyl fluoride is given off on heating the melt of NOF·2.67 HF, and finally NOF·3 HF is obtained again by distillation at 94 °C. It appears therefore that several addition compounds of nitrosyl fluoride and hydrogen fluoride can coexist in equilibrium in the liquid and gaseous phase.

It emerges from the ^1H- and ^{19}F-NMR spectra [27] that the hydrogen and the fluorine atoms of the nitrosyl fluoride-hydrogen fluoride, and also of $N_2O_3 \cdot 12.8$ HF, participate in rapid exchange reactions between 0 and 5 °C. The liquids give only one signal (cf. Table 2) [27]. The positions of the fluorine signals show that the exchange of the fluorine atoms takes place not between undissociated molecules of nitrosyl fluoride and hydrogen fluoride but *via* an intermediate containing hydrogen

Table 2. Nuclear magnetic resonance spectra.

	Chemical shift [p.p.m.]	
	^1H (TMS = 0)	^{19}F ($CFCl_3$ = 0)
HF	− 7.6	+197.5
NOF		− 478
NOF·3.0 HF	−12.4	+155
NOF·2.67 HF	−12.6	+150
$N_2O_3 \cdot 12.8$ HF	−10.2	+173

fluoride and fluoride ions. This is further proof of the fact that salt-like hydrogen fluoride addition compounds are formed from nitrosyl fluoride and HF.

Solutions or compounds of nitrosyl fluoride and hydrogen fluoride can also be decomposed chemically in such a way that either one or the other component is set free.

Hydrogen fluoride is split off by alkali metal fluorides [20–22]. Nitrosyl fluoride is best prepared by passing the vapors from NOF/HF solutions obtained from nitrosyl chloride and hydrogen fluoride into a KF melt [22]. Nitrosyl fluoride can be separated with metal fluorides and non-metal fluorides, which form stable nitrosyl salts of complex fluoro acids.

$$NOF(HF)_m + BF_3 \rightarrow NOBF_4 + m\ HF$$
$$NOF(HF)_m + As(Sb)F_5 \rightarrow NO[As(Sb)F_6] + m\ HF$$

Conversely, less stable nitrosyl salts, *e.g.* $(NO)_2SiF_6$, are decomposed by hydrogen fluoride into the nitrosyl fluoride-hydrogen fluoride addition compound:

$$(NO)_2SiF_6 + 2m\ HF \rightarrow 2\ NOF(HF)_m + SiF_4$$

b) The Reaction with Water

Whereas NOF-rich NOF/HF solutions are immediately hydrolysed by water with the evolution of nitrogen oxides, solutions rich in HF can take up water without liberating nitrogen oxides, which is undoubtedly due to the fact that nitrous acid is stabilized by a sufficient quantity of hydrogen fluoride. It is understandable that the 68 °C product of composition

$$N_2O_3 + 12.8\ HF = 2\ NOF + 10.8\ HF + H_2O$$

can also be obtained from NOF·3 HF, hydrogen fluoride, and water, and that the addition of 0.5 mole of water per mole of nitrosyl fluoride to NOF·3 HF, followed by distillation, leads to nitrous fumes in addition to the 68 °C product. Hydrogen fluoride solutions containing nitrosyl fluoride and dinitrogen trioxide, or more than 2 moles of nitrosyl fluoride per mole of water, can be separated by distillation into pure solutions of NOF and of N_2O_3. (Such solutions are formed in the reaction of aqueous hydrogen fluoride or nitrosyl chloride containing nitric oxide.) This separation appears to be a distillation of two immiscible liquids (cf. Fig. 4). This is undoubtedly due to the fact that volatilization

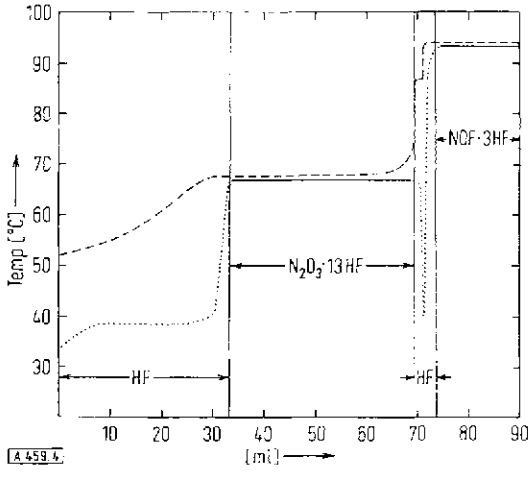

Fig. 4. Temperature changes observed in the distillation of a solution of dinitrogen trioxide and nitrosyl fluoride (or nitrous acid and excess nitrosyl fluoride) in liquid hydrogen fluoride.

– Condensate in the vapor zone; .... vapor; ---- boiling liquid

[26] U.S. Patent 3160623 (Dec. 23rd, 1960); Brit. Pat. 963823 (Dec. 4th, 1961); French Pat. 1310192 (Dec. 22nd, 1961), Allied Chem. Corp., inventors: *L. G. Anello* and *C. Woolf*.

[27] For these investigations, the author wishes to thank Dr. *W. Brügel*, Badische Anilin- & Soda-Fabrik, Ludwigshafen (Germany).

and condensation of the product to distil first are based on chemical reactions:

$$2\ NO^+ + OH_3^+ + 3\ F^- \rightleftharpoons NO + NO_2 + 3\ HF$$

The 68 °C product obtained by the distillation of aqueous hydrogen fluoride with nitrosyl chloride or of anhydrous hydrogen fluoride with nitrosyl chloride containing dinitrogen trioxide was first regarded as pure nitrosyl fluoride-hydrogen fluoride [20, 21]. The compound corresponding to NOF·6 HF, claimed in addition to NOF·3 HF in many patents [20–24], certainly does not exist as a pure substance, although it may be present as a component in a mixture of liquid HF-solvates of nitrosyl fluoride. The correct composition of the 68 °C product was first determined independently by *B. Fox, R. Siegel, S. L. Speirs*, and *R. H. Wiswall jr.* [14] and by *G. Fuchs* [11].

c) Reactions with Alcohols and Amines

The reaction of nitrosyl fluoride-hydrogen fluoride with alcohols was investigated with amyl and benzyl alcohol. Similarly to amyl and benzyl nitrite, the alcohols are dehydrogenated to the aldehydes, so that the following two-step reaction appears probable:

$$R{-}CH_2OH + NOF \rightarrow R{-}CH_2O{-}NO + HF$$
$$R{-}CH_2O{-}NO + NOF \rightarrow R{-}CHO + 2\ NO + HF$$

(The solvation of the nitrosyl fluoride is neglected here and in the following equations.) Both anhydrous and water-containing solutions of nitrosyl fluoride in hydrogen fluoride are capable of diazotizing aromatic amines [21, 26]:

$$C_6H_5NH_2 + NOF \rightarrow H_2O + C_6H_5N_2F \rightarrow C_6H_5F + N_2$$

The resulting diazonium fluorides decompose with evolution of nitrogen, even at low temperatures, yielding the fluorinated compound corresponding to the amine used. Diazotizations with solutions of nitrosyl chloride and sodium nitrite in liquid hydrogen fluoride have been described earlier [28, 29].

d) Chlorine-Fluorine Exchange

Numerous chlorine-fluorine exchange reactions can be carried out with solutions of nitrosyl fluoride in hydrogen fluoride, as with pure hydrogen fluoride [21, 23]. One of the advantages of the new process is that open vessels can be used, at higher temperatures and lower vapor pressures. When hydrogen chloride is passed into boiling NOF·3 HF, nitrosyl chloride and hydrogen fluoride are obtained. These exchange reactions proceed very fast when the chlorine compound is of the nature of an acid chloride. In the reactions of the trichlorides of phosphorus, arsenic, and antimony, the valence of these elements is increased, and the well known nitrosyl fluoride addition compounds of the pentafluorides are obtained:

$$6\ NOF + P(As,Sb)Cl_3 \rightarrow NOP(As,Sb)F_6 + 5\ NO + 1.5\ Cl_2$$

[28] U.S. Pat. 2563796 (May 26th, 1948), Harshaw Chem. Comp., inventors: *W. I. Shenk* and *G. R. Pellon*.

[29] German Patent 600706 (March 23rd, 1933), I.-G. Farbenindustrie, inventors: *Ph. Osswald* and *O. Scherer*.

The preparation of thionyl fluoride from sulfur dichloride and a mixture of the 68 °C product and the 94 °C product, ascribed to the action of nitrosyl fluoride-hydrogen fluoride [24], may be attributed to a reaction with the 68 °C product only:

$$SCl_2 + N_2O_3 \rightarrow SOCl_2 + 2\ NO$$
$$SOCl_2 + 2\ HF \rightarrow SOF_2 + 2\ HCl$$

When iodine trichloride is treated with nitrosyl fluoride-hydrogen fluoride, iodine trifluoride seems to be formed first. It disproportionates into iodine and iodine pentafluoride, and the latter finally adds onto nitrosyl fluoride to form $NOIF_6$ [30].

Chloro compounds, such as carbon tetrachloride or chloroform, remain unreactive until the temperature of NOF·3 HF exceeds its boiling point. For this reason, reactions of this type offer no advantage over fluorinations with pure hydrogen fluoride [23].

e) Reactions with Oxides and Oxyacids

Oxides also react with the nitrosyl fluoride-hydrogen fluoride solvate, giving rise chiefly to fluorides (and oxide fluorides). These reactions are of particular interest to the analyst. Difficultly soluble silicates, in fact even quartz, are dissolved by the 94 °C product within a few minutes. The solubilization of natural beryl may be of industrial importance; the reaction gives gaseous silicon fluoride, HF-soluble nitrosyl fluoroberyllate, and insoluble aluminum fluoride.

The preparation of sulfuryl fluoride from sulfur dioxide is based on the reaction of the latter with nitrosyl fluoride [25]:

$$2\ NOF + SO_2 \rightarrow SO_2F_2 + 2\ NO$$

Perchloric acid and fluorosulfonic acid precipitate nitrosyl perchlorate and nitrosyl fluorosulfate. When 3 moles of nitrosyl fluoride-hydrogen fluoride are distilled with 1 mole of anhydrous sulfuric acid, the 68 °C product distills off, leaving behind a residue of nitrosyl fluorosulfate. The 94 °C product is converted into the 68 °C product also by distillation with conc. sulfuric acid and, surprisingly, with fuming sulfuric acid. Since nitrosylsulfuric acid reacts with NOF·3 HF to give nitrosyl fluorosulfate, the reaction of $NOF(HF)_m$ with sulfuric acid can probably be explained by the following series of reactions:

$$NOF(HF)_m + SO_4H_2 \rightarrow NOSO_4H + (m+1)\ HF$$
$$NOF(HF)_m + NOSO_4H \rightarrow NOSO_3F + NO{\cdot}OH + m\ HF$$
$$NOF(HF)_m + NO{\cdot}OH \rightarrow N_2O_3 + (m+1)\ HF$$

f) Reactions with Elements

The reactions of nitrosyl fluoride-hydrogen fluoride with the elements themselves are of even greater importance in preparative chemistry than are the chlorine-fluorine exchange reactions [21] (cf. Table 3). In this respect, the nitrosyl fluoride-hydrogen fluoride solvate surpasses pure hydrogen fluoride, since nitrosyl fluoride splits more easily into nitric oxide and fluorine than does hydrogen fluoride into hydrogen and fluorine. Thus even red phosphorus is attacked. In principle, both the nitrosyl fluoride and the hydrogen fluoride moiety can react.

[30] Experiments carried out by *A. B. Ray*.

The nitrosyl fluoride adducts of pentafluorides (or the nitrosyl salts of the hexafluoro acids) are formed by elements whose maximum valence is five. If nitrosyl fluoride-hydrogen fluoride contains some nitrogen dioxide (formed by hydrolysis), nitrosyl salts of oxyfluoro acids, such as $NOTeOF_5$ and $NOMoOF_5$, can also be formed. Many interesting compounds are to be found among the reaction products with various elements, for example: $CrF_3 \cdot 3\,NOF \cdot 3\,HF$, which decomposes stepwise into $(NO)_2CrF_5$ and CrF_3 [11], or nitrosyl hexafluorouranate(V) $NOUF_6$, prepared by treating metallic uranium, as well as UF_4, UO_2F_2, and UO_3 with the 94 °C, 68 °C, or 52 °C products [9]. Nitrosyl hexafluorouranate(V) can be converted into UF_6 or UF_7NO with fluorine or chlorine trifluoride, respectively. Mercury(II) fluoride, which is a particularly effective reagent in chlorine-fluorine exchange reactions, is now readily available through its preparation from $NOF \cdot 3\,HF$ and mercury(I) fluoride, which can be precipitated from aqueous solutions. A purely chemical route leads from hydrogen fluoride to fluorine *via* nitrosyl fluoride-hydrogen fluoride, mercury(II) fluoride, and potassium fluoroplatinate(IV), which can be decomposed pyrolytically above 500 °C [31]:

$$HF + NOCl \rightarrow NOF + HCl$$
$$2\,NOF + Hg_2F_2 \rightarrow 2\,HgF_2 + 2\,NO$$
$$3\,HgF_2 + K_2PtCl_6 \rightarrow 3HgCl_2 + K_2PtF_6$$
$$K_2PtF_6 \rightarrow 2\,KF + Pt + 2\,F_2$$

[31] *M. Brill*, Doctorate Dissertation, Universität Saarbrücken, 1965.

Table 3. Reactions of $NOF \cdot 3\,HF$ in the liquid phase with various elements (+++ very fast; ++ fast; + slow; (+) surface reaction; – no reaction up to 94 °C; [+] reaction above 94 °C)

		Products			Products
Be	++	$BeF_2 \cdot 2\,NOF$	Ti, Zr	++	$Ti(Zr)F_4 + Ti(Zr)F_4 \cdot 2\,NOF$
Mg	(+)	MgF_2			
B	[+]	$BF_3 \cdot NOF$	V	[+]	$VF_4 \cdot 2\,NOF$
Al	(+)	AlF_3	Nb, Ta	[+]	$Nb(Ta)F_5 \cdot NOF$
Ga	+	GaF_3	Mo	++	$MoF_5 \cdot NOF$
C Graphite	–		Cr	[+]	$CrF_3 \cdot 3\,NOF \cdot 3\,HF$
Si, Ge, Sn	++	$Si(Ge, Sn)F_4 + Ge(Sn)F_4 \cdot 2\,NOF$	W	+	$WF_6 \cdot NOF$
			U	++	$UF_5 \cdot NOF$
Pb	(+)	PbF_2	Mn	+	MnF_3
P, As red	+++	$PF_5 \cdot NOF$	Fe	++	$FeF_3 \cdot NOF$
As, Sb	+++	$As(Sb)F_5 \cdot NOF$	Co, Ni	–	
Bi	++	BiF_3	Pt	–	
S	–		Cu	+	Cu_2
Se, Te	++	$Se(Te)F_4 \cdot NOF$	Ag	+	AgFF
			Au	–	
Cl, Br, I	–		Zn, Cd	+	$Zn(Cd)F_2$
			Hg	+++	Hg_2F_2, HgF_2

Nitrosyl fluoride dissolved in hydrogen fluoride can also be decomposed electrolytically into fluorine and nitric oxide.

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Fluorosulfuric Acid as a Reaction Medium and Fluorinating Agent in Inorganic Chemistry

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Fluorosulfuric acid is known both in aqueous solution and as the anhydrous compound. The anhydrous acid exhibits electrical conductivity which indicates its autodissociation. Even strong acids such as H_2SO_4 or $HClO_4$ behave as proton acceptors, i.e. as bases, in fluorosulfuric acid. Volatile inorganic acid fluorides can be readily prepared using fluorosulfuric acid as fluorinating agent.

1. Fluorosulfuric Acid in Aqueous Solution

Fluorosulfuric acid was first prepared in 1892 by *Thorpe* and *Kirman* [1] from sulfur trioxide and anhydrous hydrogen fluoride:

$$SO_3 + HF \rightleftharpoons HSO_3F$$

[1] *T. E. Thorpe* and *W. Kirman*, J. chem. Soc. (London) *1892*, 921.

Since it reacts very vigorously with water, the compound was at first assumed to be hydrolysed instantaneously and completely in this medium:

$$HSO_3F + H_2O \rightleftharpoons H_2SO_4 + HF$$

Many years elapsed before *Traube* [2] found salts of fluorosulfuric acid to be fairly stable in aqueous solution and the acid to be incompletely hydrolysed on slow addition to water accompanied by cooling.

[2] *W. Traube*, Ber. dtsch. chem. Ges. *46*, 2513 (1913).

Woolf [3] subsequently prepared pure aqueous solutions of fluorosulfuric acid from its salts with the aid of a strongly acidic ion exchanger. *Hayek* and *Czaloun* [4] succeeded in preparing pure dilute aqueous solutions of the acid from its anhydride, pyrosulfuryl fluoride $S_2O_5F_2$.

The stability of the aqueous acid is comparable to that of aqueous tetrafluoroboric acid, but is greater than that of the complex fluoro acids of Group Va elements [3]. Conductivity measurements in very dilute solutions indicate the dissociation

$$HSO_3F + H_2O \rightleftharpoons SO_3F^- + H_3O^+$$

When only limited amounts of water are present, it is found that fluorosulfuric acid and water are in equilibrium with sulfuric acid and hydrogen fluoride.

The similarities between perchlorates and fluorosulfates in respect to solubility and crystallographic properties suggest that the ionic radii of the anions are comparable and that solvation is analogous in both cases. This is supported by a comparison of their ionic mobilities which can be derived from the equivalent conductivities. The latter are 69 $cm^2 \cdot ohm^{-1}$ for ClO_4^- and 71 $cm^2 \cdot ohm^{-1}$ for SO_3F^-, both at 25 °C.

The conductometric titration curve [3] of aqueous fluorosulfuric acid is practically identical with the neutralization curve for sulfuric acid, *i.e.* the two acids have approximately the same strength in water.

2. Anhydrous Fluorosulfuric Acid

The special properties of anhydrous fluorosulfuric acid are best shown by a comparison with sulfuric acid. The relatively low viscosity and low freezing point of anhydrous HSO_3F are particularly conspicuous. These properties are undoubtedly due to the presence of a smaller number of hydrogen bonds.

Table 1. Comparison of fluorosulfuric and sulfuric acids.

	HSO_3F	H_2SO_4
Boiling point [°C]	162.7	290—317
Freezing point [°C]	−89.0	10.37
Density at 25 °C [g/ml³]	1.7264	1.8267
Viscosity at 25 °C [cp]	1.56	24.54
Dielectric constant at 25 °C	*ca.* 120	100
Heat of formation (liq.), [kcal/mole]	184	194
Specific conductivity at 25 °C [ohm^{-1} cm^{-1}]	1.085×10^{-4}	1.03×10^{-2}

Auto-dissociation of the fluorosulfuric acid must be assumed to explain its conductivity which cannot be further decreased by repeated purification [5, 8]:

$$2\ HSO_3F \rightleftharpoons H_2SO_3F^+ + SO_3F^- \quad (a)$$

Woolf [3] has also considered the following dissociations:

$$HSO_3F \rightleftharpoons HSO_3^+ + F^- \quad (b)$$

$$2\ HSO_3F \rightleftharpoons H_2F^+ + S_2O_6F^- \quad (c)$$

but, on the evidence of electrolysis experiments, concludes that they are at most of minor importance.

Hydrogen is the only gas evolved at the cathode during electrolysis of fluorosulfuric acid, and the amount given off is in agreement with that expected from Equation (a) or (c). The observed fluorine migration towards the anode can be reconciled only with Equation (a) or (b), since for dissociation (c), the relative ionic mobilities would lead to a movement of fluorine towards the cathode. In addition, the electrolyte acts as an oxidizing agent at the anode, in virtue, presumably, of the formation of peroxodifluorosulfate ions:

$$2\ SO_3F^- - e^- \rightarrow S_2O_6F_2^-$$

This postulate has recently been confirmed by *Dudley* [6], who succeeded in preparing peroxopyrosulfuryl difluoride by electrolysis of solutions of alkali metal fluorosulfates in fluorosulfuric acid:

$$2\ SO_3F^- - 2\ e^- \rightarrow S_2O_6F_2$$

In order to avoid reduction of the peroxopyrosulfuryl difluoride by the cathodic gases, the experiment was carried out in vacuum diaphragm cells. This reaction can be regarded as analogous to the formation of peroxodisulfates during the anodic oxidation of sulfuric acid.

The equivalent conductivities of alkali metal and alkaline earth metal fluorosulfates [5] are very similar. This observation shows that the current is carried mainly by the fluorosulfate ions. The values indicate that solvation increases in the sequence:

$$NH_4^+ < Rb^+ = K^+ < Na^+ = Li^+ < Ba^{2+} < Sr^{2+}$$

This series is more or less the one expected from the size and charge of the cations and agrees with their solvation in sulfuric acid [7].

The abnormally high mobility of the SO_3F^- ion is probably due to a proton transfer mechanism of the Grotthus type, as postulated for water and sulfuric acid. The $H_2SO_3F^+$ ion likewise seems to obey this mechanism [5].

3. Acid-Base Reactions in Fluorosulfuric Acid

According to Equation (a), acids and bases in the fluorosulfuric acid system can be defined as substances which increase the relative concentration of the fluorosulfate acidium ion $H_2SO_3F^+$ or of the fluorosulfate ion, respectively.

The relative concentration of the fluorosulfate ion can be increased by adding either a dissociating alkali metal fluorosulfate or substances which act as proton acceptors and therefore decrease the concentration of the fluorosulfate acidium ion.

Since even substances which are strong acids in water, *e.g.* H_2SO_4 or $HClO_4$, act as proton acceptors in fluorosulfuric acid, it must be assumed that true acids do not

[3] *A. A. Woolf*, J. chem. Soc. (London) *1954*, 2840.

[4] *E. Hayek* and *A. Czaloun*, Mh. Chem. *87*, 790 (1956).

[5] *J. Barr*, *R. J. Gillespie*, and *R. C. Thompson*, Inorg. Chem. *3*, 1149 (1964).

[6] *F. B. Dudley*, J. chem. Soc. (London) *1963*, 3407.

exist in this medium. Acid behavior is to be expected only from substances such as SbF_5 which combine with the SO_3F^- anion and therefore increase the relative concentration of the fluorosulfate acidium ion (see Table 2).

Table 2. Acids and bases in fluorosulfuric acid.

Bases	Acids
Alkali and alkaline earth fluorosulfates	SbF_5
AsF_3	AuF_3
SbF_3	BF_3
IF_5	TaF_5
$HClO_4$	PtF_4
H_2SO_4	SO_3
HF	

Conductometric titrations with potassium fluorosulfate or antimony pentafluoride make it possible to determine whether a compound acts as an acid or as a base in fluorosulfuric acid. Potassium fluorosulfate (in HSO_3F) is added to a solution of the compound to be investigated (in HSO_3F) and the change in conductivity is recorded. If the substance acts as an acid, the latter is neutralized by the fluorosulfate and the conductivity falls to a minimum. Neutralization, naturally, represents the reverse of autoprotolysis:

$$H_2SO_3F^+ + SO_3F^- \rightleftharpoons 2\ HSO_3F$$

The behavior of H_2SO_4, HF, $HClO_4$, and their salts in fluorosulfuric acid gives an indication of the strength of the latter. On dissolution of potassium sulfate in fluorosulfuric acid, the conductivity observed is almost exactly twice that of an equimolar solution of potassium fluorosulfate [5]. It follows that potassium sulfate is completely solvolysed in this medium:

$$K_2SO_4 + 2\ HSO_3F \rightleftharpoons 2\ K^+ + 2\ SO_3F^- + H_2SO_4$$

Conductometric investigations point to a weakly basic behavior of sulfuric acid in fluorosulfuric acid, characterized by a base constant $K_b = 10^{-4}$, *i.e.* the following equilibrium can be postulated:

$$H_2SO_4 + HSO_3F \rightleftharpoons H_3SO_4^+ + SO_3F^-$$

During electrolysis of a solution of hydrogen fluoride in fluorosulfuric acid, *Woolf* [8] observed a migration of fluorine towards the cathode. This result and quantitative conductivity measurements are best explained by the formation of H_2F^+ ions, even if only to a very small extent, according to the following basic dissociation:

$$HF + HSO_3F \rightleftharpoons H_2F^+ + SO_3F^-$$

The interpretation of the behavior of perchloric acid or potassium perchlorate in fluorosulfuric acid involves some difficulty. *Woolf* [8] titrated a solution of perchloric acid in HSO_3F with antimony pentafluoride and with potassium fluorosulfate, and obtained a minimum in the first but not in the second case. Nevertheless, he assumed equilibrium (d), corresponding to the well-known reaction of $KClO_4$ with HSO_3F which leads to perchloryl fluoride [9].

$$2\ HSO_3F + HClO_4 \rightleftharpoons ClO_3^+ + H_3O^+ + 2\ SO_3F^- \qquad (d)$$

On the other hand, *Barr et al.* [5] concluded from measurements of the conductivity of potassium perchlorate in fluorosulfuric acid that perchloric acid must be a very weak basic electrolyte in accordance with Equation (e):

$$HClO_4 + HSO_3F \rightleftharpoons H_2ClO_4^+ + SO_3F^- \qquad (e)$$

while the conductivity expected from Equation (d) would be substantially higher than the observed value.

On dissolution of AsF_3 in fluorosulfuric acid, the conductivity increases gradually to reach a constant value in about four days [5]. Titration of such solutions with SbF_5 in HSO_3F has shown that AsF_3 dissolves as a weak base in accordance with equilibrium (f) proposed by *Barr et al.* The increase in conductivity can then be explained by the secondary reactions (g) and (h) leading to a fluorosulfate capable of dissociating.

$$AsF_3 + HSO_3F \rightleftharpoons HAsF_3^+ + SO_3F^- \qquad (f)$$

$$AsF_3 + HSO_3F \rightleftharpoons AsF_2(SO_3F) + HF \qquad (g)$$

$$AsF_2(SO_3F) \rightleftharpoons AsF_2^+ + SO_3F^- \qquad (h)$$

Solutions of antimony trifluoride in HSO_3F have considerably higher conductivities and are even less stable than solutions of AsF_3 [5]. Antimony trifluoride also behaves as a base, but forms secondary products relatively quickly even at room temperature. These secondary products then dissociate, probably in the same way as postulated for AsF_3.

4. Fluorosulfuric Acid as a Fluorinating Agent

Fluorosulfuric acid is an excellent fluorinating agent for the preparation of volatile inorganic acid fluorides and fluorosulfates. Some acid fluorides prepared in this manner are listed in Table 3.

Table 3. Preparation of acid fluorides with HSO_3F.

Starting material	Fluoride	B.p. [°C]	Ref.
$KMnO_4$	$FMnO_3$	60	[10]
K_2CrO_4 (CrO_3, $K_2Cr_2O_7$)	F_2CrO_2	30	[11]
P_4O_{10}	F_3PO	−39	[12]
$BaSeO_4$	F_2SeO_2	− 8	[13]
As_2O_5 ($BaHAsO_4$)	AsF_5, ($OAsF_3$)	−53 (+24)	[12]
As_2O_3	AsF_3	63	[14]
$BaTeO_4$	F_5TeOH	60	[15]
$KClO_4$	$FClO_3$	−46	[9]

When an alkali metal or alkaline earth metal salt of the acid, or the acid anhydride, is introduced into fluorosulfuric acid, the fluoride is formed either instantaneously in the cold or gradually on heating or boiling. For example, no perchloryl fluoride can be detected by NMR spectroscopy in a cold solution of potassium perchlorate in fluorosulfuric acid [16]. However, between 50 and 85 °C the product distils over in very good yield [9].

$$KClO_4 + 2\ HSO_3F \rightarrow ClO_3F + H_2SO_4 + KSO_3F$$

[7] *J. Barr, R. J. Gillespie,* and *E. A. Robinson,* Canad. J. Chem. *39,* 1266 (1961).

[8] *A. A. Woolf,* J. chem. Soc. (London) *1955,* 433.

[9] *G. Barth-Wehrenalp,* J. inorg. nucl. Chem. *2,* 266 (1956).

[10] *A. Engelbrecht* and *A. v. Grosse,* J. Amer. chem. Soc. *76,* 2042 (1954).

[11] *H. Atzwanger,* Dissertation, Universität Innsbruck, 1953.

[12] *E. Hayek, A. Aignesberger,* and *A. Engelbrecht,* Mh. Chem. *86,* 735 (1955).

[13] *A. Engelbrecht* and *B. Stoll,* Z. anorg. allg. Chem. *292,* 20 (1957).

[14] *A. Engelbrecht, A. Aignesberger,* and *E. Hayek,* Mh. Chem. *86,* 470 (1955).

[15] *A. Engelbrecht* and *F. Sladky,* a) Angew. Chem. *76,* 379, (1964); Angew. Chem. internat. Edit. *3,* 383 (1964); b) Mh. Chem. *96,* 159 (1965).

[16] *J. Bacon, R. J. Gillespie,* and *J. W. Quail,* Canad. J. Chem. *41,* 3063 (1963).

Woolf [8] has postulated the following reactions:

$$3\ HSO_3F + KClO_4 \rightleftharpoons ClO_3^+ + 3\ SO_3F^- + H_3O + K^+$$
$$ClO_3^+ + SO_3F^- \rightleftharpoons ClO_3F + SO_3$$

according to which perchloryl fluoride is formed by the thermal decomposition of the ion pair $ClO_3^+\ SO_3F^-$.

The analogous reactions which lead to MnO_3F and CrO_2F_2 [10,11] are instantaneous, and formation of the oxide fluorides is accompanied by the evolution of a considerable amount of heat.

It is worth noting that all the compounds prepared in this manner are highly volatile, and complete conversion is generally obtained only by removal of the acid fluorides already formed. This indicates equilibria which may be intrinsically unfavorable for the formation of acid fluorides, but which can be displaced by the volatility and the relatively low solubility of the reaction products in fluorosulfuric acid.

The preparation of SeO_2F_2 from barium selenate and fluorosulfuric acid involves complete solvolysis (i) as the primary stage, followed by the protolysis (k) of the selenic acid, which probably behaves as a base towards to fluorosulfuric acid:

$$BaSeO_4 + 2\ HSO_3F \rightleftharpoons H_2SeO_4 + Ba^{2+} + 2\ SO_3F^- \quad (i)$$
$$H_2SeO_4 + HSO_3F \rightleftharpoons H_3SeO_4^+ + SO_3F^- \quad (k)$$

Elimination of water from the selenate acidium ion may represent the rate-determining reaction which is strongly temperature-dependent.

$$H_3SeO_4^+ \rightleftharpoons H_2O + HSeO_3^+ \quad (l)$$

The last step is then probably the decomposition of the resulting ion pair $HSeO_3^+\ SO_3F^-$, leading to formation of SO_3, which combines with the water formed in Eq. (l) to give sulfuric acid:

$$HSeO_3^+\ SO_3F^- \rightleftharpoons HSeO_3F + SO_3$$

An analogous repetition of this reaction sequence then leads to the formation of selenium dioxide difluoride:

$$HSeO_3F + HSO_3F \rightleftharpoons H_2SeO_3F^+ + SO_3F^-$$
$$H_2SeO_3F^+ \rightleftharpoons H_2O + SeO_2F^+$$
$$SeO_2F^+\ SO_3F^- \rightleftharpoons SeO_2F_2 + SO_3$$

All reactions listed in Table 3 formally represent the replacement of a hydroxy group by fluorine. A thermally unstable fluorosulfate is indeed formed as an intermediate in addition to the acidium ion:

$$O_nX{-}OH + HSO_3F \rightleftharpoons O_{n-1}X(OH)^{2+} + SO_3F^- \quad (m)$$
$$O_{n-1}X(OH)_2^+ \rightleftharpoons H_2O + O_nX^+ \quad (n)$$
$$O_nX^+ + SO_3F^- \rightleftharpoons O_nXOSO_2F \quad (o)$$

Its thermal decomposition then leads to formation of the acid fluoride. Evidently the elimination of water from the acidium ion in accordance with Eq. (n) determines the rate of formation of the acid fluoride, since MnO_3F and CrO_2F_2 are formed by very fast reactions. It is well known that the acids H_2CrO_4 and $HMnO_4$ likewise form anhydrides relatively easily.

In some cases, the fluorosulfate itself is volatile and thermally sufficiently stable to distil without decomposition. One example is the reaction of As_2O_5 with fluorosulfuric acid, which leads not only to varying amounts of AsF_5 and probably $AsOF_3$, but also to a mixture of $AsF_2(SO_3F)_3$ and $AsF_3(SO_3F)_2$ [12]. The reaction of H_4BaTeO_6 with HSO_3F shows that the fluorosulfates of metals in high oxidation states can be relatively stable: the compound F_5TeOSO_2F is obtained in very good yield [15b].

5. Salts of Fluorosulfuric Acid

Alkali, alkaline earth, and ammonium fluorosulfates have been known for a long time [2]. A much used general method of preparation is the reaction between metal fluorides and sulfur trioxide [3,17–20]:

$$MF + SO_3 \rightleftharpoons MOSO_2F$$

An alternative procedure is based on the reaction of fluorides [21] or chlorides [19,22,23] with fluorosulfuric acid, and is accompanied by liberation of HF or HCl. However, chloride-, fluoride- and oxide fluorosulfates are sometimes formed during these reactions [19,23].

$$MCl_x + yHSO_3F \rightarrow MCl_{x-y}(SO_3F)_y + (x{-}y)HCl$$
$$M = Ti^{4+},\ Sn^{4+},\ Ta^{5+},\ Sb^{5+}$$

$$M(SO_3F)x \rightarrow MO(SO_3F)_{x-2} + S_2O_5F_2$$
$$M = Al^{3+},\ Sb^{3+},\ Nb^{5+},\ W^{6+}$$

$$MCl_x + xHSO_3F \rightarrow MF_{x-y}(SO_3F)y + (x{-}y)HCl + yHSO_3Cl$$
$$M = Th^{4+},\ Zr^{4+}$$

6. Thermal Decomposition of Fluorosulfates

Unlike the thermally stable fluorosulfuric acid, many fluorosulfates decompose at relatively low temperatures, *via* the following types of reactions [12,19,20,24–26]:

$$OMSO_2F \rightleftharpoons MF + SO_3$$
$$M(OSO_2F)_2 \rightleftharpoons MSO_4 + SO_2F_2$$
$$M(OSO_2F)_2 \rightleftharpoons M{-}O + S_2O_5F_2$$
$$M(OSO_2F)_3 \rightleftharpoons {-}M(F)O{-} + S_3O_8F_2$$

[17] *W. Lange*, Ber. dtsch. chem. Ges. *60*, 962 (1927).

[18] *R. K. Iler*, U.S.-Pat. 2 312 413 (March 2nd, 1943).

[19] *E. Hayek, A. Czaloun*, and *B. Krismer*, Mh. Chem. *87*, 741 (1956).

[20] *E. L. Muetterties* and *D. D. Coffman*, J. Amer. chem. Soc. *80*, 5914 (1958).

[21] *A. Engelbrecht*, unpublished work.

[22] *O. Ruff*, Ber. dtsch. chem. Ges. *47*, 656 (1914).

[23] *E. Hayek, J. Puschmann*, and *A. Czaloun*, Mh. Chem. *85*, 359 (1954).

[24] *H. Jonas*, Leverkusen (Germany), personal communication.

[25] *H. A. Lehmann* and *L. Kolditz*, Z. anorg. allg. Chem. *272*, 69 (1953).

[26] *G. C. Kleinkopf* and *J. M. Schreeve*, Inorg. Chem. *3*, 607 (1964).

Pyrosulfuryl fluoride $S_2O_5F_2$ [27], the anhydride of fluorosulfuric acid, is formed at low temperatures. Sulfuryl fluoride is obtained by decomposition of $S_2O_5F_2$ above 350 °C:

$$S_2O_5F_2 \rightleftharpoons SO_3 + SO_2F_2$$

Decomposition of fluorosulfates into SO_3 and metal fluorides occurs when fluoride formation is favored by a particularly stable crystal lattice.

[27] *E. Hayek* u. *W. Koller*, Mh. Chem. *82*, 940 (1951).

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New Methods in Preparative Organic Chemistry IV [*]

New Reactions of Alkylidenephosphoranes and their Preparative Uses

Part II. Alkylidenephosphoranes and Halogen Compounds [**]

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The reactions of alkylidenephosphoranes with compounds containing halogens can be used to prepare ylides, which can be converted into useful products, e.g. by hydrolysis, by thermal decomposition, or by other reactions. Examples of such products are ketones (including cyclic, unsaturated, and branched-chain ketones), carboxylic esters (including those of unsaturated, branched-chain, polyenecarboxylic, acetylenecarboxylic, and allenecarboxylic acids), and aldehydes.

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A. Introduction

The basic nature of alkylidenephosphoranes is shown not only by the reactions discussed in Part I, but also by the ability of these compounds to react with methyl iodide [1, 2]. The first step in this reaction [1] is methylation of the ylide *(1)* to the phosphonium salt *(2)*, R = CH_3.

$$(C_6H_5)_3P{=}CH_2 + R\text{-}I \rightarrow [(C_6H_5)_3\overset{\oplus}{P}\text{-}CH_2\text{-}R]\,I^{\ominus}$$
(1) *(3)* *(2)*

$$[(C_6H_5)_3\overset{\oplus}{P}\text{-}CH_2\text{-}R]\,I^{\ominus} \xrightarrow{H_2C=P(C_6H_5)_3\ (1)} (C_6H_5)_3P{=}CH\text{-}R + [H_3C\text{-}\overset{\oplus}{P}(C_6H_5)_3]\,I^{\ominus}$$
(4) *(5)*

After the recognition of the principle of transylidation, however, it was necessary to assume that halogen compounds *(3)* containing an electron-attracting group R give a salt *(2)* which is a strong acid, and which immediately enters into a transylidation reaction with a second molecule of the ylide *(1)*. The products in this case should be an alkylated ylide *(4)* and the phosphonium salt *(5)*.

Other reactions have also been observed besides the formation of the salt *(2)* or the immediate transylidation to form *(4)*. Thus whilst *(4)* results from attack by a second ylide molecule in the α position relative to the phosphorus atom of the salt *(2)*, the reaction with the second ylide can lead to a Hofmann degradation if the β position of *(2)* is activated. γ-Eliminations (with respect to the P atom) have also been observed. All these reactions open up new preparative methods, which will be discussed below.

B. Reactions Involving Transylidation

1. C-Acylation of Alkylidenephosphoranes

a) Reaction with Acyl Chlorides

Alkylidenephosphoranes *(6)* react with acyl chlorides *(7)* in accordance with Scheme 1 [3a, 3b].

The H atom on the α carbon of the initially formed phosphonium chloride *(8)* is strongly acidic, owing to the influence of the adjacent carbonyl group. Compound *(8)* therefore immediately enters into a transylidation reaction with a second molecule of the ylide *(6)*, to

$$(C_6H_5)_3P{=}\overset{H}{\underset{}{C}}\text{-}R^1 + R^2\text{-}CO\text{-}Cl \rightarrow \left[(C_6H_5)_3\overset{\oplus}{P}\text{-}\overset{H}{\underset{O=C\text{-}R^2}{C}}\text{-}R^1\right] Cl^{\ominus}$$
(6) *(7)* *(8)*

$$\xrightarrow{(6)} (C_6H_5)_3P{=}\underset{O=C\text{-}R^2}{\overset{}{C}}\text{-}R^1 + [(C_6H_5)_3\overset{\oplus}{P}\text{-}CH_2\text{-}R^1]\,Cl^{\ominus}$$
(9) *(10)*

Scheme 1

form an acylated alkylidenephosphorane *(9)* and the phosphonium salt *(10)* [4]. The stoichiometry of the reaction can be represented as 2 *(6)* + *(7)* → *(9)* + *(10)*.

The reaction with the acyl chlorides is carried out in a boiling benzene solution of the ylide containing no lithium salts. The salt *(10)* precipitates and can be used to prepare fresh *(6)*; the acylated alkylidenephosphoranes *(9)* remain in solution. It is essential to avoid an excess of acyl chloride, since these compounds can also attack *(9)*. Acylalkylidenetriphenylphosphoranes prepared by this method are listed in Table 1.

Table 1. Acylalkylidenetriphenylphosphoranes $R^2\text{—}CO\text{—}CR^1{=}P(C_6H_5)_3$ *(9)*.

	R^1	R^2	M.p. [°C]	Yield [%] with acyl chloride	Yield [%] with thioester
(11)	H	CH_3	200—202 [a]	51	78
(12)	H	C_6H_5	178 · 180 [a]	71	80
(13)	H	$C_6H_5\text{—}CH_2\text{—}CH_2$	148—150 [a]	49	80
(14)	H	p-$NO_2\text{—}C_6H_4$	159—161 [b] 176—178	93	—
(15)	H	$C_6H_5\text{—}CH_2$	147—148 [e]	0	42
(16)	CH_3	C_6H_5	170—172 [a]	71	93
(17)	CH_3	$C_6H_5\text{—}CH{=}CH$	205—208 [c]	73	70
(18)	CH_3	$C_6H_5\text{—}CH_2\text{—}CH_2$	164—166 [d]	50	76
(19)	CH_3	C_5H_{11}	oil	63	—
(20)	CH_3	C_3H_7	129—131 [e]	0	54
(21)	C_3H_7	CH_3	143 · 145 [e]	25	62
(22)	C_3H_7	$C_6H_5\text{—}CH_2\text{—}CH_2$	147—149 [e]	36	63
(23)	C_6H_5	CH_3	166—168 [a]	73	68
(24)	C_6H_5	C_6H_5	192—194 [a]	64	58
(25)	CO_2CH_3	C_6H_5	133—135 [a,f]	83	—

[a] Colorless or pale yellow crystals from ethyl acetate.

[b] Yellow needles, which rearrange on melting (159—161 °C) to form a red modification with m.p. 176—178 °C.

[c] Yellow crystals from a large volume of ethyl acetate; darkens on melting.

[d] Yellow crystals from ethyl acetate.

[e] Colorless to pale yellow crystals from ethyl acetate/petroleum ether.

[f] Obtained in ethyl acetate without protection by nitrogen.

The lowest yields are obtained from the reactions of strongly basic alkylidenephosphoranes with acyl chlorides having an activated H atom close to the carbonyl group. In these cases (*e.g.* with phenylacetyl chloride), the reaction yields dark resinous products from which triphenylphosphine oxide can be isolated.

[*] The contributions in the previous three series have been published collectively in three volumes by Verlag Chemie, Weinheim/Bergstr. (Germany). English edition: Academic Press, New York-London.

[**] For Part I see Angew. Chem. *77*, 609 (1965), Angew. Chem. internat. Edit. *4*, 583 (1965). Part III will appear shortly in this journal.

[1] *G. Wittig* and *M. Rieber*, Liebigs Ann. Chem. *562*, 177 (1949).

[2] *G. Wittig, H. D. Weigmann*, and *M. Schlosser*, Chem. Ber. *94*, 676 (1961).

[3a] *H. J. Bestmann*, Tetrahedron Letters *1960*, No. 4, p. 7.

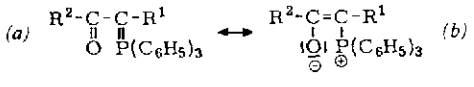
[3b] *H. J. Bestmann* and *B. Arnason*, Tetrahedron Letters *1961*, 455; Chem. Ber. *95*, 1513 (1962).

[4] *S. Trippett* and *D. M. Walker*, J. chem. Soc. (London) *1961*, 1266, have also reported reactions of alkylidenephosphoranes with acid chlorides. They used ylide solutions containing lithium salts. These authors did not, however, recognize the principle of C-acylation with simultaneous transylidation, and state that the reaction stops at the stage of the salt *(8)*; cf. [3b]. *P. L. Pauson* and *W. E. Watts*, J. chem. Soc. (London) *1963*, 2990 isolated a salt of the structure *(8)* after reaction of benzoyl chloride with an ylide of the ferrocene series, prepared with an organolithium compound.

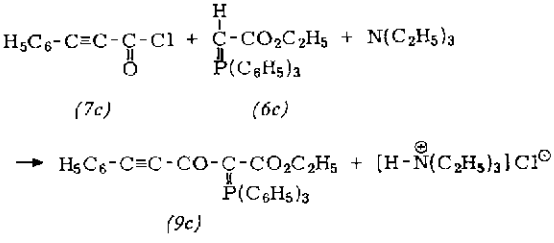
These disadvantages are avoided if thiol esters are used instead of acyl chlorides (cf. Section B 1b).

All the compounds listed in Table 1, with the exception of α-caproylethylidenetriphenylphosphorane *(19)*, are crystalline. They can be recrystallized from ethyl acetate or ethyl acetate/petroleum ether, and retain the solvent extremely tenaciously. However, drying need not be as thorough before further reactions as for melting-point determinations. The compounds are not attacked by atmospheric oxygen and cold water.

The CO band in the infrared spectra of all acylalkylidenetriphenylphosphoranes is displaced to 6.5–6.7 μ, as was observed earlier by *Wittig* [5] and *Ramirez* [6] for compounds *(23)* and *(24)*. *Ramirez* attributed the shifts to resonance between forms *(a)* and *(b)*.



This explanation agrees with the fact that the O atom is attacked in the reactions of acylalkylidenetriphenylphosphoranes *(9c)* with halogen compounds [6]. *Gough* and *Trippett* [7] have shown that when the alkylidenephosphorane *(6c)* used contains a strongly electron-attracting group R, so that the phosphonium salt intermediate *(8c)* (see Scheme 1) is a strong acid, the second molecule of ylide can be replaced by triethylamine.



Reactions of this type proceed only when the amine is a stronger base than the ylide [8].

Procedure:

Acylation of Alkylidenetriphenylphosphoranes with Acyl Chlorides [3]

A salt-free solution of 0.022 mole of an alkylidenetriphenylphosphorane in 100 ml of anhydrous benzene is heated to boiling under nitrogen in a Schlenk tube with a Claisen head fitted with a mercury-sealed reflux condenser and a dropping funnel. A solution of 0.01 mole of the acyl chloride in 50 ml of benzene is added dropwise to the boiling, red solution. The phosphonium chloride precipitates. The addition of acyl chloride is stopped when the ylide has been exhausted, as shown by decoloration of the solution. (An excess of acyl chloride must be avoided, since this compound also attacks the acylated ylide). When the reaction is complete, the inert atmosphere can be dispensed with. The phosphonium chloride is filtered off and washed with benzene, and the solution is concentrated in vacuum. The residue is mixed with 20 ml of ethyl acetate, cooled for a short time in ice/salt, and filtered.

A second fraction can be obtained by concentration of the mother liquor. Evaporation of the solvent frequently leaves behind an oily residue, but this generally dissolves in ethyl acetate and crystallizes after 24 h in a refrigerator.

Most acylalkylidenetriphenylphosphoranes can be recrystallized from ethyl acetate. The solubility of the compounds in this solvent increases with the number of methylene groups they contain. The crystallization is frequently slow, and can be accelerated by a few ml of ether. Many acylalkylidenetriphenylphosphoranes tenaciously retain the solvent.

It is not absolutely necessary to isolate the acyl compound in preparation for further reactions; it can be hydrolysed or made to react with aldehydes directly after concentration of the benzene solution. If benzene is to be used as the solvent for the reaction with aldehydes, the acylation solution can be used directly after the phosphonium salt has been filtered off.

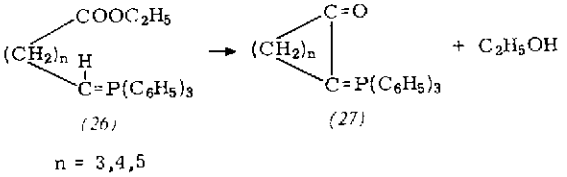
The phosphonium chlorides are formed in yields of 80 to 100%, and can be used to prepare fresh ylide after a single reprecipitation from chloroform with ether, followed by careful drying. The chlorides are occasionally obtained in the form of oils, but these can be crystallized by friction.

b) Reaction with Esters, Thiol Esters, and Acylimidazoles

Acylalkylidenetriphenylphosphoranes can be used for the synthesis of ketones, as will be shown in Section B 1c. Since the preparation of acyl ylides starting from α-bromoketones proceeds smoothly in only a few cases [9], the C-alkylation of alkylidenephosphoranes is of considerable practical importance.

Acylation with acyl chlorides has the disadvantage that one mole of the ylide used is lost as the triphenylalkylphosphonium chloride *(10)*, although the compound *(6)* can be recovered from this salt. A method of acylation which avoids this disadvantage is the reaction of alkylidenephosphoranes with esters.

Ylide solutions generally do not react with ethyl or methyl esters in the absence of salts [3, 10]. However, the ω-ethoxycarbonylalkylidenetriphenylphosphoranes *(26)* have been observed to undergo an intramolecular C-alkylation to form cyclic ylides *(27)* [11a, 11b]. This reaction presents new possibilities for the synthesis of cyclic carbonyl compounds.



n = 3,4,5

Surprisingly, however, the alkyl esters react with alkylidenephosphoranes in the presence of lithium salts [4, 5]. These reactions also proceed by transylidation [3]. The products obtained are the acylalkylidenetriphenylphosphoranes *(9)* and

[5] *G. Wittig* and *U. Schöllkopf*, Chem. Ber. *87*, 1318 (1954).

[6] *F. Ramirez* and *S. Dershowitz*, J. org. Chemistry *22*, 41 (1957).

[7] *S. T. D. Gough* and *S. Trippett*, J. chem. Soc. (London) *1964*, 543.

[8] *H. J. Bestmann*, unpublished work.

[9] *H. Hoffmann* and *H. J. Diehr*, Tetrahedron Letters *1962*, 583; *I. J. Borowitz* and *L. I. Grossmann*, ibid. *1962*, 471; *I. J. Borowitz* and *R. Virkhaus*, J. Amer. chem. Soc. *85*, 2183 (1963); *S. Trippett*, J. chem. Soc. (London) *1962*, 2337; *A. J. Speziale* and *R. D. Partos*, J. Amer. chem. Soc. *85*, 3312 (1963).

[10] *H. Behringer* and *K. Fulkenberg*, Chem. Ber. *96*, 1428 (1963), report the reaction of a vinylogous ester with ethoxycarbonylmethylidenetriphenylphosphorane.

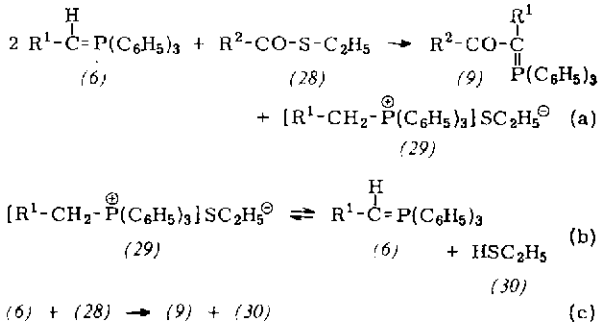
[11a] *H. O. House* and *H. Babad*, J. org. Chemistry *28*, 90 (1963).

[11b] *L. D. Bergelson*, *V. A. Vaver*, *L. I. Barsukov*, and *M. M. Schemyakin*, Izv. Akad. Nauk SSSR, Otd. Khim. Nauk *1963*, 1134; Chem. Abstr. *59*, 8607d (1963).

the triphenylalkylphosphonium bromides [*(10)*, with $Br^{\ominus}$ in place of $Cl^{\ominus}$], the latter resulting from reaction of the initially formed alkoxides [*(10)*, with $OC_2H_5^{\ominus}$ in place of $Cl^{\ominus}$] with the LiBr present in the solution. Thus the starting materials react in a molar ratio of 2:1; however, the yields of acylated ylide *(9)* are poor.

Better results are obtained in the reaction of salt-free solutions of alkylidenephosphoranes with activated esters, such as phenyl esters and thiophenyl esters [3], or with acylimidazoles [12]. These reactions again proceed by transylidation, and present important methods of formylation [8, 13].

A particularly useful group of acylating agents is formed by the *S*-ethyl esters of thiocarboxylic acids *(28)* [3].



The first step in this reaction is the formation of the acylalkylidenephosphorane *(9)* and the phosphonium ethylthiolate *(29)*, which precipitates out [Equation (a)]. Like the phosphonium alkoxides [14], *(29)* loses ethyl mercaptan on heating to form the ylide *(6)* [Equation (b)]. This can then react with further thiol ester *(28)*, and is removed in this way from the equilibrium, as is shown by the slow dissolution of the precipitated salt *(29)*, which is frequently in the form of an oil. The overall reaction is represented by Equation (c). This method requires one mole of ylide less than the acyl chloride method. The yields are noted in Table 1.

Procedures:

Acylation of Alkylidenetriphenylphosphoranes with S-Ethyl Esters of Thiocarboxylic Acids [3]

The reaction should be carried out in a Schlenk tube, and it is advisable to close the top of the reflux condenser with a mercury valve. 0.02 mole of the S-ethyl thiocarboxylate is added to a boiling solution of 0.022 mole of an alkylidenephosphorane (salt-free) in absolute toluene (the solution need not be filtered). The mixture is boiled for 18 hours, during which time the oily phosphonium thiolate which initially precipitates is slowly redissolved. If an unfiltered ylide solution is used, it is now necessary to remove the sodium halide by hot filtration (a protective nitrogen atmosphere is not required). Evaporation of the solution leaves the acylalkylidene triphenylphosphorane, which can be crystallized by friction. The yields and the solvents used for recrystallization are given in Table 1. The excess of phosphonium salt required increases with the length of the residue R in the triphenylalkylphosphonium salts $[R-CH_2-P^{\oplus}(C_6H_5)_3]X^{\ominus}$ (*e.g.* triphenylbutylphosphonium bromide: 35% excess).

[12] *H. J. Bestmann, N. Sommer*, and *H. A. Staab*, Angew. Chem. *74*, 293 (1962); Angew. Chem. internat. Edit. *1*, 270 (1962).

[13] *H. A. Staab* and *N. Sommer*, Angew. Chem. *74*, 294 (1962); Angew. Chem. internat. Edit. *1*, 270 (1962).

[14] *G. Wittig* and *W. Haag*, Chem. Ber. *88*, 1654 (1955).

The S-ethyl esters of thiocarboxylic acids are generally prepared from the acyl chlorides and $NaSC_2H_5$ [15].

α-Oxocyclohexylidenetriphenylphosphorane [11a]

Triphenyl-ω-ethoxycarbonylamylphosphonium iodide *(42g)* is added to a solution of 3.4 g of potassium in 300 ml of t-butanol. The mixture is refluxed for 12 hours and concentrated in vacuum, and the residue is shaken with chloroform/water. The chloroform solution is dried and the ylide *(27)*, n = 4, is precipitated with ethyl acetate; yield 22.1 g (79%); m.p. 243–245 °C.

c) Preparation of Ketones by Cleavage of Acylalkylidene Triphenylphosphoranes

Acylalkylidenetriphenylphosphoranes *(9)* are weak bases, and are therefore stable towards cold water. On boiling with water, however, they break down to form ketones *(31)* and triphenylphosphine oxide [6, 3].

Some examples are given in Table 2.

Table 2. Ketones $R^1-CO-CH_2-R^2$, *(31)*, obtained by hydrolysis of acylalkylidenetriphenylphosphoranes *(9)*.

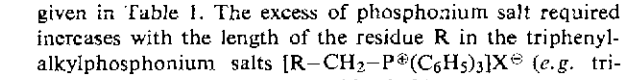
R^1	R^2	Yield [%]
CH_3	H	83 [a]
C_6H_5	H	93 [a]
$C_6H_5-CH_2-CH_2$	H	78
C_6H_5	CH_3	84 [a]
$C_6H_5-CH=CH$	CH_3	74
C_5H_{11}	CH_3	95

[a] Yield determined *via* the 2,4-dinitrophenylhydrazone.

The hydrolysis is carried out in aqueous alcohol. The reaction is accelerated by the addition of a little alkali metal hydroxide. The acylbenzylidenetriphenylphosphoranes *(23)* and *(24)*, *p*-nitrobenzoylmethylidenetriphenylphosphorane *(14)*, and benzoylmethoxycarbonylmethylidenetriphenylphosphorane *(25)* cannot be hydrolysed, probably owing to the proximity of resonance-stabilizing groups which interact with the C–P double bond. This interaction reduces the basicity of the carbon atom to such an extent that the phosphonium hydroxide can no longer be formed.

The cyclic ylides *(27)* are hydrolysed only on heating in *o*-dichlorobenzene/water/ethanol (1:3:5) in a pressure tube at 150 °C; the products are cyclic ketones and triphenylphosphine oxide [11a].

Ketones are also obtained by reductive cleavage of acylalkylidenetriphenylphosphoranes *(9)* with zinc in glacial acetic acid [4].

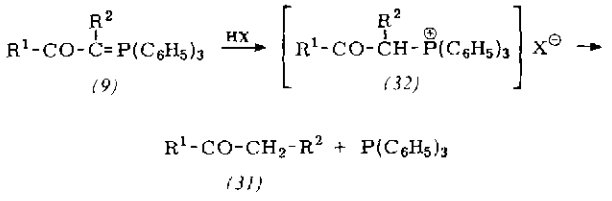


This reaction proceeds particularly well when the residue R^1 is aromatic (yields > 90%). With aliphatic residues R^1, the yields of ketone are much poorer than

[15] Cf. *H. J. Bestmann* and *H. Schulz*, Chem. Ber. *92*, 530 (1959).

those obtained by hydrolysis, and in some cases this method fails completely.

Another preparatively important reaction is the electrolytic cleavage of quaternary phosphonium salts [16]. The acylalkylidenetriphenylphosphorane is dissolved in the stoichiometric quantity of mineral acid, and the resulting solution of the salt *(32)* is electrolysed in a closed vessel fitted with a reflux condenser, using a lead cathode which is bent around the diaphragm of the carbon anode, a short distance away. The ketone *(31)* and triphenylphosphine are obtained in yields of 60–80 % [3b].



$$R^1\text{-}CO\text{-}\underset{\textit{(9)}}{\overset{R^2}{\overset{|}{C}}}\text{=}P(C_6H_5)_3 \xrightarrow{HX} \left[R^1\text{-}CO\text{-}\underset{\textit{(32)}}{\overset{R^2}{\overset{|}{C}}}\text{-}\overset{\oplus}{P}(C_6H_5)_3\right] X^{\ominus} \rightarrow$$

$$R^1\text{-}CO\text{-}CH_2\text{-}R^2 + P(C_6H_5)_3$$

(31)

This method fails with aromatic residues R^1, since in this case the ylides *(9)* are regenerated. The same is true when R^1 is C_6H_5–CH=CH–. On the other hand, the method is recommended for aliphatic residues R^1. Thus the electrolytic method supplements the method of reductive cleavage with zinc and glacial acetic acid, and *vice versa*. The advantage of these methods is the regeneration of the triphenylphosphine.

Procedures:

Preparation of Ketones by Hydrolysis [3]

The acylalkylidenetriphenylphosphorane (the unpurified product of the acylation can be used) is dissolved in 50–80 ml of 80% aqueous methanol, 1–2 ml of 2N NaOH is added, and the mixture is refluxed for 12 h. After addition of 3 ml of glacial acetic acid, the ketone formed is steam-distilled. The distillate is extracted with ether, the ether solution dried, and the ketone is distilled or recrystallized after the solvent has been driven off.

All the ketones listed in Table 2 can be isolated. If the product is not steam-volatile, the solution must be concentrated after addition of the glacial acetic acid, and the ketone is then separated from the triphenylphosphine oxide by treatment of the residue with petroleum ether. This separation can also be conveniently carried out by the zinc chloride method [17]. The yields are noted in Table 2.

Preparation of Ketones by Reductive Cleavage [3]

The acylalkylidenetriphenylphosphorane (0.005 mole) is dissolved in 25 ml of chloroform. Zinc powder is added (12 g), and 50 ml of glacial acetic acid is added to the boiling mixture over a period of 1 h. After boiling for a further hour, the reaction solution is steam-distilled, and the ketone is extracted from the distillate with ether. The residue from the steam-distillation is extracted with ether, and the ether phase is washed with 2N NaOH and dried over magnesium sulfate. The solvent is distilled off in vacuum, leaving behind triphenylphosphine, which can be recrystallized from methanol (m.p. and mixed m.p. 81 °C).

[16] *L. Horner* and *A. Mentrup*, Liebigs Ann. Chem. *646*, 65 (1961).

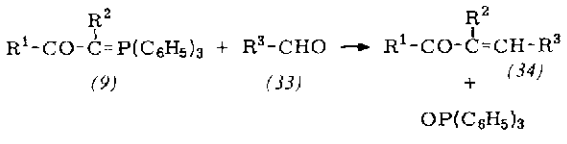
[17] *H. J. Bestmann, H. Buckschewski*, and *H. Leube*, Chem. Ber. *92*, 1345 (1959).

Preparation of Ketones by Electrolysis

The electrolysis is carried out in a three-neck flask (≈ 250 ml) with a wide middle neck, through which the diaphragm is introduced and fixed with a rubber collar. The lead cathode is bent around the diaphragm at a distance of 2–3 cm. A wire fused into a stopper which is fitted in one of the necks is connected to the cathode through a terminal. The third neck should be fitted with a reflux condenser, since the electrolysis is accompanied by a large increase in temperature. The acylalkylidenetriphenylphosphorane (0.01 mole) is dissolved in the stoichiometric quantity of HCl. The solution is diluted to 50–100 ml, and electrolysed at 24–30 volts. The current increases to 2–3 amp within 15 min, and slowly falls off again towards the end of the reaction. Many ketones can be steam-distilled directly from the reaction solution. The residue is triphenylphosphine. If the ketone is not steam-volatile, the electrolysed solution is extracted with ether and the solution is dried. After the ether has been driven off, the residue is distilled in a rotating bulb tube, or methanol is poured over it (0 °C) to remove triphenylphosphine. (For the experimental arrangement, see [16]).

d) Synthesis of α-Branched α,β-Unsaturated Ketones

Acylalkylidenetriphenylphosphoranes *(9)* can react with aldehydes *(33)* in a Wittig reaction to form α,β-unsaturated ketones, particularly with chain branching in the α position *(34)* [3, 6].



$$R^1\text{-}CO\text{-}\underset{\textit{(9)}}{\overset{R^2}{\overset{|}{C}}}\text{=}P(C_6H_5)_3 + \underset{\textit{(33)}}{R^3\text{-}CHO} \rightarrow R^1\text{-}CO\text{-}\underset{\textit{(34)}}{\overset{R^2}{\overset{|}{C}}}\text{=}CH\text{-}R^3 + OP(C_6H_5)_3$$

A number of compounds obtained by reaction with benzaldehyde are shown in Table 3.

Table 3. α-Branched α,β-unsaturated ketones C_6H_5–CH=CR^2–CO–R^1 obtained from acylalkylidenetriphenylphosphoranes $(C_6H_5)_3P$=CR^2–CO–R^1 and benzaldehyde.

Compound	R^1	R^2	Time [days]	Yield [%]
(35)	CH_3	H	3	76 [a]
(36)	C_6H_5	H	3	70 [a]
(37)	C_6H_5–CH_2–CH_2	CH_3	3	64
(38)	C_6H_5–CH=CH	CH_3	4	81
(39)	C_5H_{11}	CH_3	1	40
(40)	C_6H_5–CH_2–CH_2	C_3H_7	3	60 [a]

[a] Yield determined *via* the 2,4-dinitrophenylhydazone.

The reactions take much longer than the normal Wittig reaction. In order to obtain good yields, it is necessary in most cases to boil for 3 to 4 days in anhydrous benzene. Ketones do not react in this way [18]. The acylalkylidenetriphenylphosphoranes which are resistant to hydrolysis are also unable to undergo Wittig reactions with aldehydes.

Since triphenylalkylphosphonium salts can be prepared from alkyl halides or alcohols, the C-acylation of alkylidenephosphoranes provides a new method of synthesizing ketones from alkyl halides or alcohols and derivatives of carboxylic acids.

[18] Cf. the acid-catalysed reactions of the stable alkoxycarbonylethylidenetriphenylphosphoranes: *Ch. Rüchardt, S. Eichler*, and *P. Panse*, Angew. Chem. *75*, 858 (1963); Angew. Chem. internat. Edit. *2*, 619 (1963); *S. Fliszar, R. F. Hudson*, and *G. Salvadori*, Helv. chim. Acta *47*, 159 (1964).

Procedure:

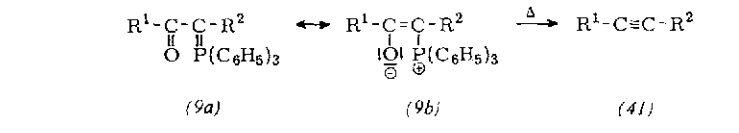
2-Methyl-1,5-diphenyl-1,4-pentadien-3-one (38)

Cinnamoylethylidenetriphenylphosphorane (8.4 g) *(17)* and 2.12 g of benzaldehyde are refluxed for 4 days in anhydrous toluene, in the absence of oxygen and moisture. The solvent is evaporated in vacuum, and the residue is mixed with 10–20 ml of ether at −40 °C and filtered (insoluble component: 4.5 g of triphenylphosphine oxide; m.p. and mixed m.p. 153 °C; yield 80 %). The filtrate is evaporated to dryness. The residue crystallizes on trituration with a little petroleum ether, and can be recrystallized from isopropanol at −40 to −60 °C; m.p. 62 °C, yield 4.0 g (81 %).

e) Synthesis of Acetylene Derivatives

Acylalkylidenetriphenylphosphoranes *(9)* can be represented by two resonance structures (cf. Section B 1a). The reactions with alkyl halides and acyl chlorides are formulated as passing through *(9b)*, since the attack takes place on the O atom [3, 6, 19].

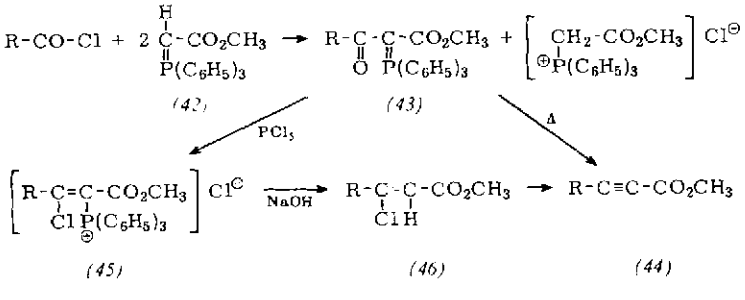
The thermal decomposition of the acylated ylides to form acetylenic compounds *(41)* probably also proceeds *via (9b)* [19, 20].



(9a) *(9b)* *(41)*

This reaction occurs only if R^1 or R^2 is an aromatic group, and if neither R^1 nor R^2 is hydrogen. The yields are around 50 %. If R^1 = C_6H_5 and R^2 = alkyl, the products include allenes as well as acetylenes [21].

The C-acylation of methoxycarbonylmethylidenetriphenylphosphorane *(42)* with acyl chlorides, which proceeds by transylidation, provides an easy route to the α-acyl-α-methoxycarbonylmethylidenetriphenylphosphoranes *(43)*. The thermal decomposition of these compounds leads to very high yields of esters of acetylenecarboxylic acids *(44)* (see Table 4), as was shown by *Märkl* [22] and independently by *Gough* and *Trippett* [19].



(42) *(43)* *(45)* *(46)* *(44)*

It is also possible in this way to obtain esters of bis-acetylenecarboxylic acids [7]. The place of the ester group may also be taken by a cyano group [20].

[19] *S. T. D. Gough* and *S. Trippett*, J. chem. Soc. (London) *1962*, 2333.

[20] Cf. also *S. Trippett* and *D. M. Walker*, J. chem. Soc. (London) *1959*, 3874.

[21] *H. J. Bestmann* and *F. Seng*, unpublished work.

[22] *G. Märkl*, Chem. Ber. *94*, 3005 (1961).

Table 4. Acetylenecarboxylic acids R−C≡C−CO_2H *(47)* obtained by thermal decomposition of acylmethoxycarbonylmethylidenetriphenylphosphoranes *(43)* followed by hydrolysis.

R	Yield [%]	M.p. [°C]
CH_3	77	147 [a]
C_6H_5	73	135–136
p-CH_3–C_6H_4	81	147–149
α-Naphthyl	81	138
m-NO_2–C_6H_4	66	107–108
o-CH_3O–C_6H_4	79	124
o-Cl–C_6H_4	66	130–131
	75	107–110 (decomp.)

[a] Amide.

The reaction of the ylides *(43)* with PCl_5 or Vilsmeier reagents leads to phosphonium salts *(45)*, which react with NaOH, without first being isolated, to form the esters of acetylenecarboxylic acids *(44)* *via* the compound *(46)* [23].

Procedure:

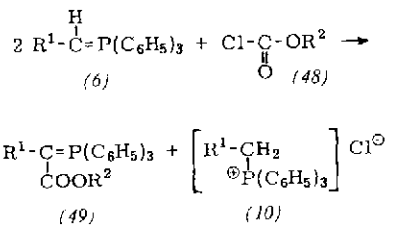
Acetylenecarboxylic Acids [22]

One gram of the ylide *(43)* [22] is placed in a sausage flask or a flask with a descending air-condenser running to a suction tube which acts as both an adaptor and a flask. Depending on the boiling point of the ester expected, the pressure is reduced to between 12 and 0.05 mm Hg, and the ylide is heated slowly to 220–260 °C. The greater part of the triphenylphosphine oxide as well as the ester distils over within about 15 min at 0.05 mm Hg. The distillate is taken up in methanol, and 3 ml of concentrated sodium hydroxide solution is added. The mixture is allowed to stand for 24 h at room temperature, the methanol is evaporated in vacuum, and 30 ml of water is added. Triphenylphosphine separates as an oil at first, but rapidly crystallizes in the cold. The crystals are filtered off, and the filtrate is acidified with a little concentrated hydrochloric acid. The acid which precipitates is subsequently recrystallized from a suitable solvent, depending on its properties.

2. Reaction of Alkylidenephosphoranes with Esters of Chloroformic Acid. Synthesis of Carboxylic Acids

a) Alkoxycarbonylation of Alkylidenephosphoranes

Alkylidenephosphoranes *(6)* react with esters of chloroformic acid *(48)* by transylidation. The reaction allows the alkoxycarbonylation of ylides *(6)* to the esters *(49)* (cf. Table 5).



(6) *(48)* *(49)* *(10)*

The ester carbonyl band in the infrared spectrum of the alkoxycarbonylalkylidenetriphenylphosphoranes

[23] *G. Märkl*, Angew. Chem. *74*, 217 (1962); Angew. Chem. internat. Edit. *1*, 160 (1962).

Table 5. Methoxycarbonylmethylidenetriphenylphosphoranes $(C_6H_5)_3P{=}CR^1{-}CO_2CH_3$ *(49)*, $R^2 = CH_3$, obtained from alkylidenetriphenylphosphoranes *(6)* and methyl chloroformate *(48)*, $R^2 = CH_3$.

	R^1	M.p. [°C]	[%]
(50)	H	164 [a]	80
(51)	CH_3	145 [a]	95
(52)	C_2H_5	125 [b]	88
(53)	C_3H_7	105 [c]	96
(54)	C_6H_5	155 [a]	80
(55)	Cyclohexyl	oil	75

[a] From ethyl acetate.
[b] From ethyl acetate/petroleum ether.
[c] From benzene/petroleum ether.

(49) is displaced to 6.15 μ [24,25], indicating the strongly "open" character of the carbonyl C–O bond.

Procedure:

Methoxycarbonylation of Alkylidenetriphenylphosphoranes [24]

Methyl chloroformate (0.1 mole) in 50 ml of benzene is added dropwise, in an atmosphere of nitrogen, to a boiling salt-free solution of 0.22 mole of an alkylidenetriphenylphosphorane in anhydrous benzene. The phosphonium chloride *(10)* precipitates. The dropwise addition is stopped immediately the ylide has been consumed, as shown by decoloration of the red solution. An excess of methyl chloroformate must be avoided, since this also attacks the alkoxycarbonylated ylide *(49)*. The nitrogen atmosphere is unnecessary when the reaction is complete. The phosphonium chloride is filtered off and washed with benzene, and the solution is concentrated in vacuum. The residue can be recrystallized from ethyl acetate or from mixtures of ethyl acetate or benzene with petroleum ether. The yields are shown in Table 5. It is not essential to isolate the alkoxycarbonylated ylide prior to further reactions. The benzene solution can be treated with aldehydes directly after removal of the phosphonium chloride, or the crude product can be hydrolysed after the benzene has been driven off.

The phosphonium chlorides are obtained in 80 to 100% yields. They can be used for regeneration of the ylide after a single reprecipitation from chloroform with ether, followed by careful drying. Chlorides which are initially oily can be crystallized by friction.

b) Carboxylic Acids from Methoxycarbonylalkylidenetriphenylphosphoranes

The alkoxycarbonylalkylidenetriphenylphosphoranes *(49)*, which are easily obtained by the above method, can be used for the synthesis of carboxylic acids [24,26]. Hydrolysis of the ylides *(49a)* results in the formation of esters of carboxylic acids *(56)*.

$$R\text{-}\underset{\underset{P(C_6H_5)_3}{\|}}{C}\text{-}CO_2CH_3 + H_2O \rightarrow R\text{-}CH_2\text{-}CO_2CH_3 + OP(C_6H_5)_3$$

(49a) *(56)*

Thus compound *(54)* yields phenylacetic acid (97% yield on boiling in alkaline solution; *(55)* gives cyclohexylacetic acid (75%).

Wittig reaction of compounds *(49a)* with aldehydes *(57)* leads to esters of α-branched α,β-unsaturated carboxylic acids *(58)* [24,26–28].

$$R^1\text{-}\underset{\underset{P(C_6H_5)_3}{\|}}{C}\text{-}CO_2CH_3 + R^2\text{-}CHO \rightarrow R^1\text{-}\overset{OP(C_6H_5)_3}{\overset{+}{\underset{\underset{R^2\text{-}CH}{\|}}{C}}}\text{-}CO_2CH_3$$

(49a) *(57)* *(58)*

Thus α-*trans*-alkylcinnamic acids were obtained by reaction of *(52)* and *(53)* with benzaldehyde [29], and 4-phenyl-1-n-propyl-1,3-butadienecarboxylic acid has been prepared from *(53)* by reaction with cinnamaldehyde.

Ketones generally do not react with the ylides *(49)*. *Fodor* and *Tömösközi* [30], however, were able to carry out reactions of this type in a pressure tube at 100 to 170 °C. Similar reactions can be effected in solution by acid catalysis [18].

Procedures:

Preparation of Carboxylic Acids by Hydrolysis of Methoxycarbonylalkylidenetriphenylphosphoranes (49a)

The ylide *(49a)* is refluxed for 1 h with a 10% solution of potassium hydroxide in aqueous methanol ($H_2O:CH_3OH \approx 1:1$). After cooling, the contents of the flask are mixed with ten times their volume of water, whereupon precipitation of the greater part of the triphenylphosphine oxide occurs. The mixture is filtered, and the filtrate is concentrated to 50–100 ml, cooled, and brought to pH 1 to 3 by addition of sulfuric acid. The subsequent working up is carried out in accordance with the properties of the carboxylic acid formed.

Preparation of α-Branched α,β-Unsaturated Carboxylic Acids by the Wittig Reaction

A solution containing the alkylmethoxycarbonylmethylidenetriphenylphosphorane *(49a)* and the aldehyde *(57)* in benzene is heated for several hours in a Schlenk tube which is fitted with a reflux condenser closed by a mercury valve. The solvent is evaporated in vacuum, and the residue extracted with petroleum ether or with a little ether. Some of the triphenylphosphine oxide remains undissolved. After filtration, the petroleum ether or ether is driven off, and the residue is hydrolysed as described above. Dilution of the reaction mixture with water results in the precipitation of the remaining triphenylphosphine oxide, and the subsequent working up depends on the properties of the carboxylic acid.

3. Reaction with Organic Halides and Carbonium Salts

a) Synthesis of Carboxylic Acids from Organic Halides and Methoxycarbonylmethylidenetriphenylphosphoranes [26]

The reaction of methoxycarbonylmethylidenetriphenylphosphoranes *(42)* with halides *(59)* leads first to the phosphonium salts *(60)*. If the residue R is a ligand with

[24] *H. J. Bestmann* and *H. Schulz*, Angew. Chem. *73*, 27 (1961); Liebigs Ann. Chem. *674*, 11 (1964).

[25] Cf. also *G. Aksnes*, Acta chem. scand. *15*, 692 (1961).

[26] *H. J. Bestmann* and *H. Schulz*, Chem. Ber. *95*, 2921 (1962).

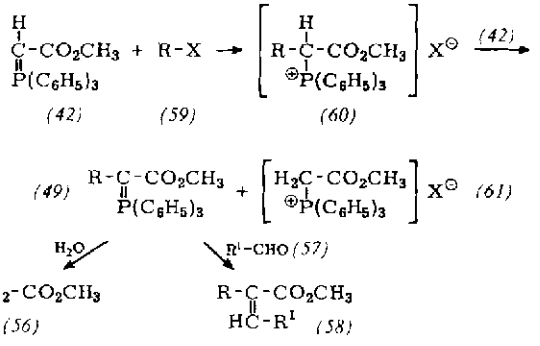
[27] *O. Isler, H. Gutmann, M. Montavon, R. Rüegg, G. Ryser*, and *P. Zeller*, Helv. chim. Acta *40*, 1242 (1957).

[28] *H. O. House* and *G. Rasmusson*, J. org. Chemistry *26*, 4278 (1961).

[29] The *cis*-compounds were not found; cf. [28].

[30] *G. Fodor* and *I. Tömösközi*, Tetrahedron Letters *1961*, 579.

a (−I)-effect, *(60)* will be a strong acid, and will immediately react with a second molecule of ylide *(42)* by transylidation. The resulting products are a substituted methoxycarbonylmethylidenetriphenylphosphorane and the phosphonium salt *(61)*, from which the starting ylide *(42)* can be easily recovered by treatment with a base.



When *(42)* is treated with alkyl iodides, the reaction in anhydrous ethyl acetate stops at the stage of the alkylated phosphonium salt *(60)*, since *(60)* is a weaker acid than the salt *(61)* which would result from transylidation, owing to the (+I)-effect of the aliphatic residue R. However, the yield of the salt *(60)* decreases rapidly with increasing length of the aliphatic group R, owing to the lower polarity of the C-halogen bond. Since the acid-base equilibrium (see Part I) gives rise to partial transylidation between alkylidenephosphoranes and phosphonium salts with equal acid and base strengths, unwanted by-products can be formed [26].

There is no doubt, however, about the course of reactions in which the inductive effect of the substituent R leads to complete transylidation (Table 6).

Table 6. Alkylmethoxycarbonylmethylidenetriphenylphosphoranes $(C_6H_5)_3P{=}CR{-}CO_2CH_3$ *(49a)* obtained from organic bromides *(59)* and methoxycarbonylmethylidenetriphenylphosphorane *(42)*.

R	Yield [%]	M.p. [°C]
$CH_2{-}CH{=}CH_2$	93	oil
$CH_2{-}CO_2CH_3$	98	157–158
$CH_2{-}CN$	89	138–139
$C_6H_5{-}CH_2$	75	186–187
$C_6H_5{-}CH{=}CH{-}CH_2$	81	oil

Anhydrous ethyl acetate is generally used as solvent. The triphenylmethoxycarbonylmethylphosphonium halide *(61)* precipitates (80 to 95% yield). The alkylmethoxycarbonylmethylidenetriphenylphosphoranes *(49a)* are obtained by concentration of the reaction solution. The compounds *(49a)* can be used to prepare the most diverse carboxylic acids *(56)*, *(58)* [26].

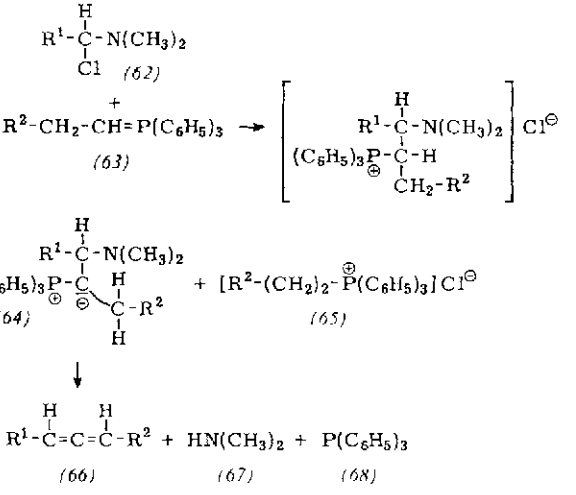
Procedure:

Alkylation of Methoxycarbonylmethylidenetriphenylphosphorane [26]

The alkyl halide *(59)* (0.2 mole) is added to a boiling solution of 0.4 mole of methoxycarbonylmethylidenetriphenylphosphorane *(42)* in anhydrous ethyl acetate, and the mixture is refluxed for 2 hours. The methoxycarbonylmethyltriphenylphosphonium halide *(61)* which precipitates is filtered off (yield 80–95%), and the filtrate is concentrated. The residue consists of the alkylated ylide *(49a)*, which is often obtained as an oil, but which can generally be crystallized by friction and recrystallized from ethyl acetate. The yields are noted in Table 6.

b) Allenes from Alkylidenephosphoranes and 1-Chloro-1-dimethylamino Compounds

The reaction of the readily obtainable dimethylaminochloro compounds *(62)* [31] with alkylidenephosphoranes *(63)* surprisingly yields allenes *(66)* [32].



Scheme 2

Investigations on the mechanism and stoichiometry of the reaction are still in progress [33]. It may be assumed that the reaction proceeds as shown in Scheme 2. From the compound *(62)* and the alkylidenephosphorane *(63)* a salt is formed at first, which undergoes transylidation with a second molecule of *(63)* to give the phosphonium salt *(65)* and the nitrogen-containing alkylidenephosphorane *(64)*. The latter decomposes by an intramolecular β-elimination into the allene *(66)*, dimethylamine *(67)*, and triphenylphosphine *(68)*. This decomposition may be regarded as an intramolecular Hofmann degradation. The amine *(67)* liberated can react with unchanged *(62)* to form *(69)*. The hydrochloric acid formed is bound by the ylide *(63)*.

$$HN(CH_3)_2 + R^1{-}CHCl{-}N(CH_3)_2 \rightarrow R^1{-}CH[N(CH_3)_2]_2 + HCl$$
(67) *(62)* *(69)*

Procedure:

Phenylallene [33]

α-Chlorodimethylbenzylamine (40 mmole) (prepared from benzylidenebisdimethylamine [31]) is added to a salt-free solution of 60 mmole of ethylidenetriphenylphosphorane [*(63)*, $R^2 = H$] in anhydrous tetrahydrofuran under N_2; the light yellow solution is stirred until it is decolorized. The triphenylethylphosphonium chloride which precipitates is filtered off.

[31] *H. Böhme, E. Mundlos*, and *O. E. Herboth*, Chem. Ber. *90*, 2003 (1957); *H. Böhme* and *K. Hartke*, Chem.Ber. *93*, 1305 (1960).

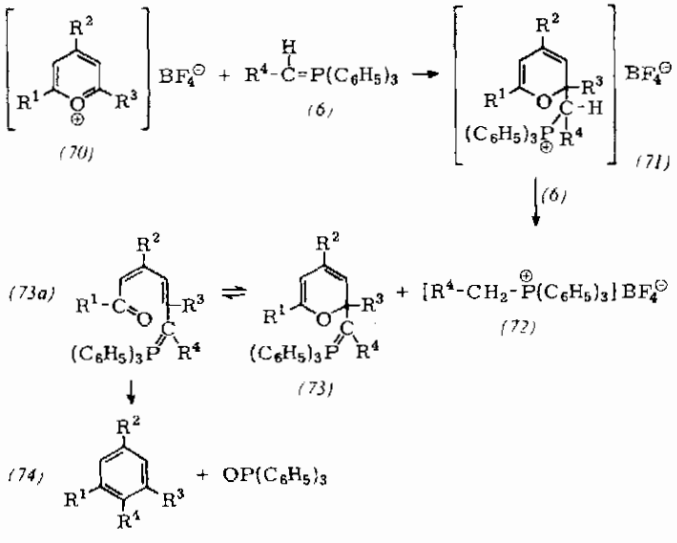
[32] *H. J. Bestmann, F. Seng* and *J. Berthold*, unpublished work; cf. also *H. J. Bestmann* and *F. Seng*, Angew. Chem. *75*, 1117 (1963); Angew. Chem. internat. Edit. *3*, 140 (1964).

[33] *H. J. Bestmann, F. Seng*, and *J. Popp*, unpublished work.

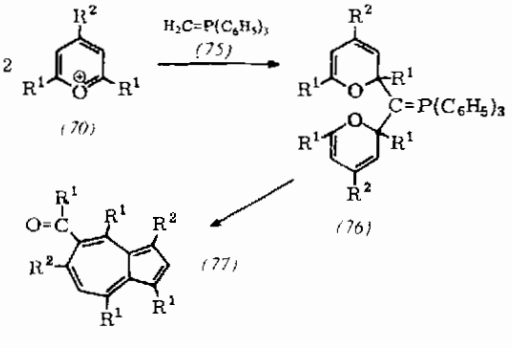
The filtrate is mixed with 20 g of methyl iodide and refluxed for 3 h to precipitate the triphenylphosphine and the compound *(69)*, $R^1 = C_6H_5$, formed in the secondary reaction. After removal of the precipitate, the solvent is distilled off over a small column and the residue is fractionated in vacuum. Phenylallene is obtained in 60% yield; b.p. 70 °C/20 mm Hg.

c) Aromatic Compounds and Azulenes from Alkylidenephosphoranes and Pyrylium Salts

The discovery of transylidation [34], and of the reaction of alkylidenephosphoranes and halogen compounds with simultaneous transylidation [3, 24, 26], has opened the way to new syntheses. Thus the salts *(71)*, which are the initial products of the reaction of pyrylium salts *(70)* and alkylidenephosphoranes *(6)*, react (by transylidation) with a second molecule of ylide *(6)* to form the phosphonium salt *(72)* and a new ylide *(73)*. This ylide undergoes an intramolecular Wittig reaction in its tautomeric form *(73a)* to form the aromatic compound *(74)* [35].



The reaction of pyrylium salts *(70)* with excess methylidenetriphenylphosphorane *(75)* leads to the formation of azulenes *(77)* [36]. It may be assumed that the ylide [*(73)*, R^4 = H] again undergoes transylidation with another molecule of pyrylium salt *(70)* to form the compound *(76)*, from which the azulene *(77)* is formed. The mechanism of the last reaction is not yet known.



[34] *H. J. Bestmann*, Chem. Ber. *95*, 58 (1962).

[35] *G. Märkl*, Angew. Chem. *74*, 696 (1962); Angew. Chem. internat. Edit. *1*, 511 (1962).

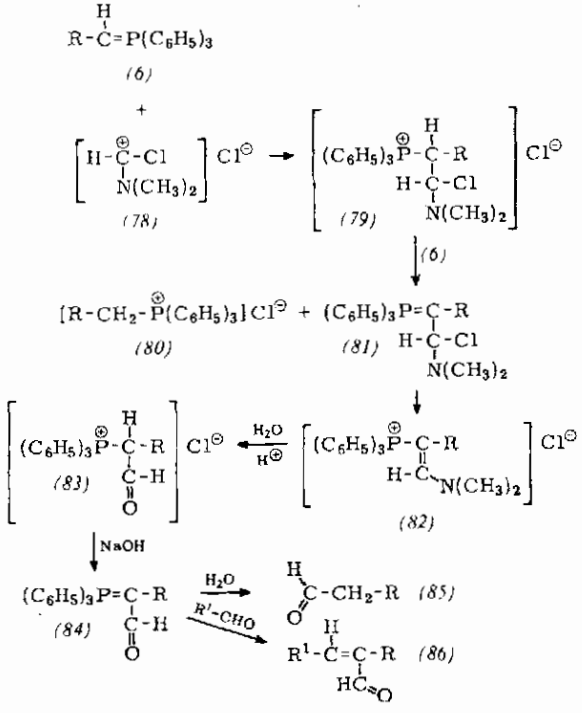
Procedure:

1,3,5-Triphenylbenzene [35]

Ten millimoles of 1,3,5-triphenylpyrylium tetrafluoroborate in a little acetonitrile is added over a period of 1 h to 20 mmole of methylidenetriphenylphosphorane *(75)* in 100 ml of boiling toluene. The violet color produced at the point of addition disappears instantaneously. When the addition is complete, the brown solution is boiled for a further 30 min and concentrated to 30 ml; precipitation is completed by addition of 100 ml of ether. The filtrate is evaporated to dryness, the residue is mixed with a little methanol, and the 1,3,5-triphenylbenzene is filtered off after some time; m.p. 170–172 °C, yield 59%.

d) Reaction of Alkylidenephosphoranes with Dimethylformamide Chloride. Synthesis of Aldehydes

The reaction of the ylide [*(6)*, R = C_6H_5 or CO_2CH_3] and the formamide chloride *(78)* yields the salt *(79)*, which undergoes transylidation with *(6)* to form the phosphonium chloride *(80)* and the alkylidenephosphorane *(81)* [37]. The compound isomerizes to the



phosphonium salt *(82)*, which reacts as an enamien with dilute hydrochloric acid to form the salt *(83)*. The action of sodium hydroxide on this salt gives the ylide *(84)*, which decomposes on hydrolysis into triphenylphosphine oxide and an aldehyde *(85)* [4, 13], and can undergo a Wittig reaction to form α-branched α,β-unsaturated aldehydes *(86)*.

The thermal decomposition of the 1-formyl-1-methoxycarbonylmethylidenetriphenylphosphorane [*(84)*, R = CO_2CH_3] yields methyl propiolate. Reactions of strongly basic ylides with formamide chlorides have not yet been studied.

[36] *K. Dimroth, K. H. Wolf*, and *H. Wache*, Angew. Chem. *75*, 860 (1963); Angew. Chem. internat. Edit. *2*, 621 (1963).

[37] *G. Märkl*, Tetrahedron Letters *1962*, 1027.

Procedure:

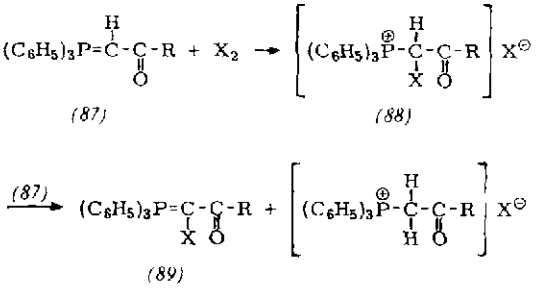
Triphenyl-1-formylbenzylphosphonium Chloride and 1-Formylbenzylidenetriphenylphosphorane

Benzylidenetriphenylphosphorane [*(86)*, R=C_6H_5] (30 mmole) in 150 ml of toluene is added at −5 °C to 20 mmole of dimethylformamide chloride in a little chloroform, acetonitrile, or dimethylformamide. The red solution is immediately decolorized, and the precipitate *(80)* is filtered off after a few hours. After the solvent has been driven off, the enaminephosphonium salt *(82)* is dissolved in a little water. The phosphonium chloride [*(83)*, R = C_6H_5] crystallizes on addition of a little concentrated hydrochloric acid (m.p. = 223 °C, yield 72%); the ylide *(84)*, R = C_6H_5, m.p. 124 to 126 °C (monohydrate), is obtained directly with dilute sodium hydroxide solution (yield 80%).

4. Reaction of Alkylidenephosphoranes with Halogens

a) Halogenation of Alkylidenephosphoranes

Stable alkylidenephosphoranes *(87)* react with free halogens at room temperature by transylidation [38a, 38b].



The second molecule of ylide can be saved by carrying out the halogenation in the presence of triethylamine [38b, 39], since the latter is a stronger base than the ylide *(87)*. At −70 °C, the reaction stops at the stage of the salt *(88)*. The ylide *(89)* can then be obtained from *(88)* with bases [39, 40]. Phenyl iodide chloride, $C_6H_5ICl_2$, is a particularly suitable chlorinating agent [38a, 38b]. Iodinations are best carried out in methanol, and brominations in glacial acetic acid [38b]. The reaction of strongly basic alkylidenetriphenylphosphoranes with halogens is accompanied by side reactions [41].

Procedures:

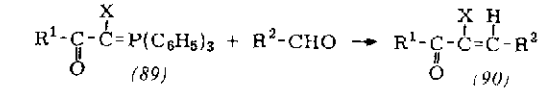
Bromoacylmethylidenetriphenylphosphoranes [(89), X = Br]

α) *In glacial acetic acid:* 10 mmole of *(87)* and 12.5 mmole of anhydrous sodium acetate are dissolved in 25 ml of glacial acetic acid, and 10 mmole of bromine in 10 ml of glacial acetic acid are added with stirring. After addition of 5 ml of concentrated hydrochloric acid, the solvent is evaporated in vacuum (thin layer evaporator); the residue is dissolved in water or water/methanol, and the ylide *(89)* is precipitated with dilute sodium hydroxide solution and recrystallized from ethyl acetate/petroleum ether or methanol/water.

β) *In chloroform:* 10 mmole of bromine in 10 ml of chloroform is added dropwise at 10 °C to a solution of 10 mmole of ylide *(87)* and 11 mmole of freshly distilled triethylamine in 25 ml of chloroform. The reaction mixture is washed twice with water to eliminate the triethylammonium chloride. After drying, the solvent is distilled off and the residue [the ylide *(89)*] is recrystallized as in α.

b) Preparation of α-Halogenated α,β-Unsaturated Carboxylic Acid Esters and Ketones

The halogenoylides *(89)* react with aldehydes.



The halogenated alkoxycarbonylmethylidenetriphenylphosphoranes [*(89)*, $R^1 = OR^2$] react much more readily than the acyl compounds [*(89)*, R^1 = alkyl or aryl]. The reaction leads to α-halogenated α,β-unsaturated ketones and carboxylic acid esters *(90)*, which are very difficult or impossible to obtain by other methods. Since compounds *(90)* react with bases to form acetylenes, this provides a possible synthesis of acetylenic ketones and esters of acetylenecarboxylic acids [38a].

C. Reactions Involving β-Elimination

1. The Mechanism of the Hofmann Degradation of Quaternary Phosphonium Salts

Ammonium salts of the type $[R^1-CH_2-CH_2N^{\oplus}R^2_3]X^{\ominus}$ are preferentially broken down by the action of bases into olefins and amines (Hofmann degradation) [42–44]. The analogous phosphonium salts, on the other hand, are decomposed by $OH^{\ominus}$ ions into a phosphine oxide and a hydrocarbon, whilst reaction with other bases, such as sodamides, organolithium compounds, and sodium alkoxides, leads to the formation of the alkylidenephosphoranes. Decomposition of phosphonium salts into an olefin and a phosphine occur in only a few cases, where the hydrogens in the β position with respect to the P atom are strongly activated [45–47].

[38a] *G. Märkl*, Chem. Ber. *94*, 2996 (1961).

[38b] *G. Märkl*, Chem. Ber. *95*, 3003 (1962).

[39] *D. B. Denney* and *St. T. Ross*, J. org. Chemistry *27*, 998 (1962).

[40] Cf. also *A. J. Speziale* and *C. C. Tung*, J. org. Chemistry *28*, 1353 (1963).

[41] *H. J. Bestmann*, unpublished work.

[42] *A. W. Hofmann*, LiebigsAnn. Chem. *78*, 253 (1851); *79*, 11 (1851).

[43] *G. Wittig, H. Tenhaeff, W. Schoch*, and *G. Koenig*, Liebigs Ann. Chem. *572*, 1 (1951); *G. Wittig, G. Koenig*, and *K. Clauss*, ibid. *593*, 127 (1955).

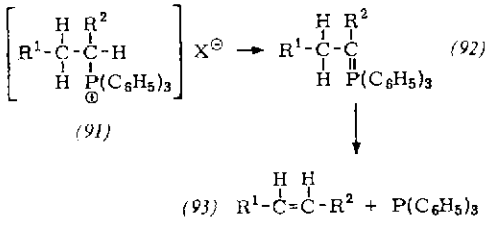
[44] *G. Wittig* and *R. Polster*, Liebigs Ann. Chem. *599*, 13 (1956); *J. Rabiant* and *G. Wittig*, Bull. Soc. chim. France *1957*, 798; *G. Wittig* and *R. Polster*, Liebigs Ann. Chem. *612*, 102 (1958); *G. Wittig* and *T. F. Burger*, ibid. *632*, 85 (1960).

[45] *H. Hoffmann*, Chem. Ber. *94*, 1331 (1961).

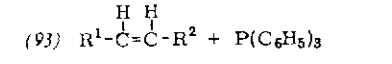
[46] *L. Hey* and *C. K. Ingold*, J. chem. Soc. (London) *1933*, 531; *M. Grayson, P. T. Keough*, and *G. A. Johnson*, J. Amer. chem. Soc. *81*, 4803 (1959); *R. P. Welcher* and *N. E. Day*, J. org. Chemistry *27*, 1824 (1962).

The Hofmann degradation of quaternary ammonium salts proceeds either by β-elimination or by α',β-elimination [44, 48]. Primary α-elimination following in intramolecular or intermolecular proton shift from the β position to the α position of the same ligand of the N atom has not been observed [49]. However, since α protons in phosphonium salts are split off 10^5 times more rapidly than in ammonium salts [50], the primary α-elimination should be preferred in the decomposition of triphenylphosphonium salts.

It has been shown, using compounds labeled with tritium, that when organolithium compounds or sodamide are used for the Hofmann degradation of phosphonium salts *(91)* in which the residue R^1 is strongly electron-attracting, the primary reaction is α-elimination to form the ylide *(92)* [51].



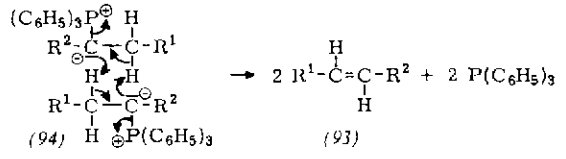
(91) *(92)*



(93)

Reactions with completely deuterated compounds have shown that the alkylidenephosphorane *(92)* then decomposes by intermolecular hydrogen shift to an olefin *(93)* and triphenylphosphine [51].

It is assumed that two molecules of the ylide come together to form a transition state *(94)*, which under-



(94) *(93)*

goes a reciprocal β-elimination, with simultaneous loss of triphenylphosphine. This means that the Hofmann degradation of phosphonium salts, which begins with an α-elimination from the same ligand, is induced by an intermolecular β-elimination. The ylide formation can therefore be regarded as an "interfering reaction" in the Hofmann degradation.

The rate of the intermolecular hydrogen shift (reciprocal β-elimination) is determined by the residues R^1 and R^2 in the ylide *(92)*. Electronegative residues R^1 increase the rate by increasing the mobility of the β protons, whilst electronegative residues R^2 retard the reaction by decreasing the basicity of the ylides (as proton acceptors). Some examples are given in Table 7 [51]. The decomposition temperature is taken as a measure of the rate of the intermolecular proton shift.

Table 7. Temperatures at which alkylidenetriphenylphosphoranes $R^1-CH_2-CR^2=P(C_6H_5)_3$ *(92)* decompose into olefins and triphenylphosphine.

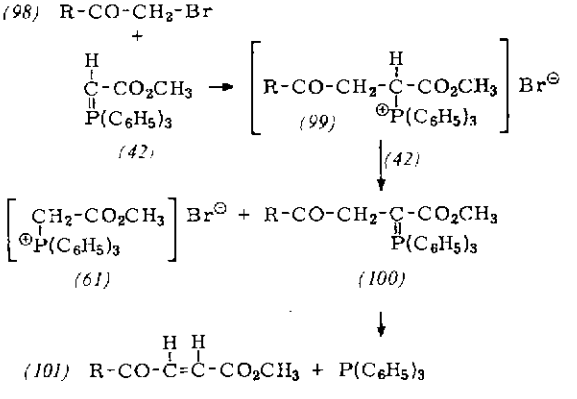
Ylide	R^1	R^2	Temperature of decomposition [°C]	Olefin
(95)	C_6H_5	CO_2CH_3	Stable to 200 °C	—
(96)	CH_3O_2C	CO_2CH_3	170	Dimethyl fumarate
(97)	CH_3O_2C	C_6H_5	50	Methyl cinnamate

Compound *(95)* is more stable than *(96)*, since the (−I)-effect of the residue R^1 is greater for the methoxycarbonyl group than for the phenyl group. For the same reason, *(97)* decomposes more readily than *(96)*.

The Hofmann degradation of quaternary phosphonium salts is of interest for reactions taking place by transylidation. If a phosphonium salt *(91)* with activated hydrogen atoms β to the phosphorus atom is formed by the reaction of a halogen compound with an alkylidenephosphorane, the ylide *(92)* formed primarily by transylidation is expected to decompose into an olefin and triphenylphosphine, as described above. This sequence of reactions can also be employed in syntheses, as will be shown below.

2. Synthesis of Esters of β-Acylacrylic Acids [47]

α-Bromoketones *(98)* react with methoxycarbonylmethylidenetriphenylphosphorane *(42)* to form a phosphonium salt *(99)*, which gives the ylide *(100)* and the salt *(61)* by transylidation with a second molecule of *(42)* [51].



(98) *(42)* *(99)* *(61)* *(100)*

(101)

In the ylide *(100)*, the H atoms β to the P atom are activated by the adjacent carbonyl group. The ylide *(100)* therefore decomposes to form an ester of a β-

Table 8. Methyl β-acylacrylates, R—CO—CH=CH—CO_2CH_3 *(101)* obtained from methoxycarbonylmethylidenetriphenylphosphorane *(42)* and α-bromoketones R—CO—CH_2—Br *(98)*.

	R	M.p. [°C]	Yield [%]
(101a)	C_6H_5	32 [a]	67
(101b)	β-Naphthyl	110 [b]	58
(101c)	CH_3	60.5 [c]	69
(101d)	C_5H_{11}	48–49 [c]	71
(101e)	C_6H_{13}	48 [c]	85
(101f)	Cyclohexyl	57 [c]	74
(101g)	$C_6H_5-(CH_2)_2$	47–48 [c]	75

[a] Yellow needles, b.p. 70–80 °C/10^{-3} mm, from cold methanol.
[b] Yellow-brown crystals from cold methanol.
[c] Colorless needles from cold methanol.

[47] *H. J. Bestmann* and *H. Schulz*, Chem. Ber. *95*, 292 (1962); *H. J. Bestmann*, *F. Seng*, and *H. Schulz*, ibid. *96*, 465 (1963).

[48] Cf. the reviews: *A. C. Cope* and *E. R. Trumbull*, Org. Reactions *11*, 317 (1960); *J. F. Bunnett*, Angew. Chem. *74*, 731 (1962); Angew. Chem. internat. Edit. *1*, 225 (1962); *G. Köbrich*, Angew. Chem. *74*, 453 (1962); Angew. Chem. internat. Edit. *1*, 382 (1962).

[49] *A. C. Cope*, *N. A. LeBel*, *P. T. Moore*, and *W. R. Moore*, J. Amer. chem. Soc. *83*, 3861 (1961); *E. M. Hodnett* and *J. J. Flynn*, ibid. *79*, 2300 (1957); *S. J. Cristol* and *D. I. Davies*, J. org. Chemistry *27*, 293 (1962).

[50] *W. v. E. Doering* and *A. K. Hoffmann*, J. Amer. chem. Soc. *77*, 521 (1955).

[51] *H. J. Bestmann*, *H. Häberlein*, and *I. Pils*, Tetrahedron *20*, 2079 (1964).

acylacrylic acid *(101)* and triphenylphosphine [47]. A number of examples is given in Table 8.

The new method for the preparation of β-acylacrylates is inferior in a number of cases to the reaction of maleic anhydride with aromatic compounds [52]; however, the esters of β-acylacrylic acid with aliphatic and cycloaliphatic residues R, which had previously been difficult to prepare, can now be readily obtained in high yields by a "single pot process".

Esters of α-branched β-acylacrylic acids can be obtained from alkoxycarbonylalkylidenetriphenylphosphoranes *(49)* and α-bromoketones [24] (cf. Sections B 2b and B 3a).

Since α-bromoketones can be easily prepared from carboxylic acids *via* the diazoketones *(102)* [53], we now have a new method of synthesizing the ester *(101)* of an acid containing three more C atoms in its chain than the original carboxylic acid.

$$R\text{-}CO_2H \rightarrow \underset{(102)}{R\text{-}CO\text{-}CHN_2} \rightarrow \underset{(101)}{R\text{-}CO\text{-}CH{=}CH\text{-}CO_2CH_3}$$

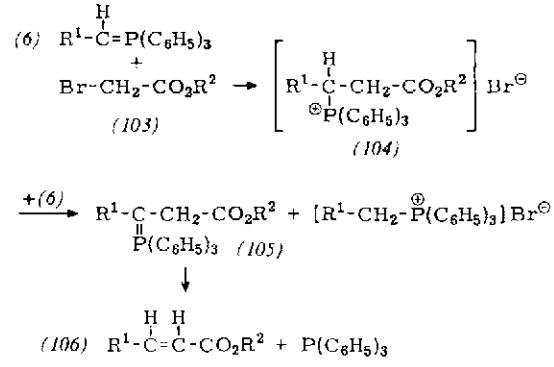
Procedure:

Methyl β-Acylacrylates

To a boiling solution of 20 mmole of methoxycarbonylmethylidenetriphenylphosphorane *(42)* in 100 ml of anhydrous benzene, 10 mmole of the bromoketone *(98)* is added, and the mixture is refluxed for 2 h. The triphenylmethoxycarbonylmethylphosphonium bromide *(61)* which precipitates is filtered off (yield 90–100%), and the solution is mixed with 10 mmole of methyl bromoacetate (possibly in slight excess) and boiled for a further 2 h. The phosphonium salt *(61)* formed from triphenylphosphine and methyl bromoacetate precipitates and is filtered off (yield 70–80%). The benzene is evaporated from the filtrate under reduced pressure. The residue is recrystallized from methanol, cooling to between −60 and −40 °C being preferable in many cases. If the acrylate cannot be recrystallized from methanol, the residue left when the benzene has evaporated is distilled in a rotating bulb tube at about 0.1–1 mm Hg. The yields of the methyl β-acylacrylates are given in Table 8.

3. Synthesis of Esters of α,β-Unsaturated Carboxylic Acids

Alkylidenetriphenylphosphoranes *(6)* react readily with esters of bromoacetic acid *(103)*. Transylidation of the initially formed salt *(104)* with *(6)* leads to the ylide *(105)* and a phosphonium salt. The H atoms β to the P atom in *(105)* are activated by the ester group. The compounds therefore decompose more or less readily, depending on the inductive effect of R^1, into esters of α,β-unsaturated acids *(106)* and triphenylphospbine [54].



This process is particularly suitable for reactions with ylides *(6)* in which the basicity is weakened as a result of a (−I)-effect of R^1 (*e.g.* aromatic compounds and CO_2R). As the basicity of *(6)* increases, side reactions become pronounced; these are being investigated [54].

Procedure:

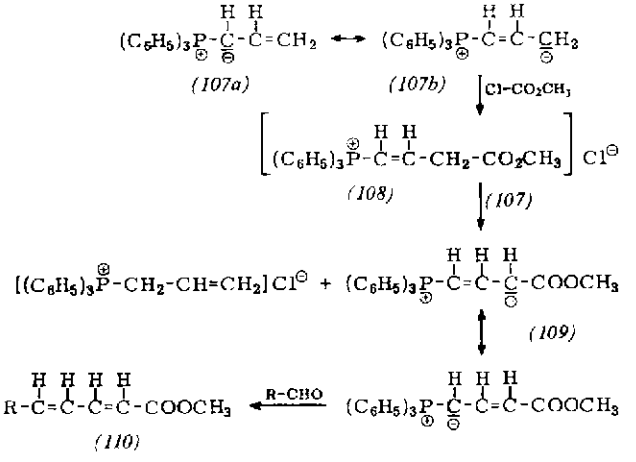
Cinnamic Acid

A salt-free ylide solution is prepared (see Part I, Section D 2) from 16 g of triphenylbenzylphosphonium chloride. Methyl bromoacetate *(103)* (3.05 g) is added to this solution, and the mixture is refluxed for 1 h. The phosphonium salt formed is filtered off, and the solvent distilled off over a small column. The residue is hydrolysed by refluxing for 2 h with 2.4 g of KOH in 100 ml of aqueous methanol. The methanol is distilled off, and the remaining solution is diluted with 200 ml of water. The triphenylphosphine oxide is filtered off, the filtrate is acidified, and the cinnamic acid is extracted with ether, which is then removed; m.p. 135 °C, yield 2.2 g (75%).

D. Reactions Involving γ-Elimination

1. Reaction of Allylidenetriphenylphosphoranes with Esters of Chloroformic Acid. Preparation of Esters of Polyenecarboxylic Acids

The reactions described so far show that transylidation can occur during the reaction of phosphonium salts with alkylidenephosphoranes by α-elimination. If the β position with respect to the P atom is activated, the α-elimination is often followed by a reciprocal β-elimination with simultaneous loss of triphenylphosphine.



[52] *H. G. Oddy*, J. Amer. chem. Soc. *45*, 2156 (1923).

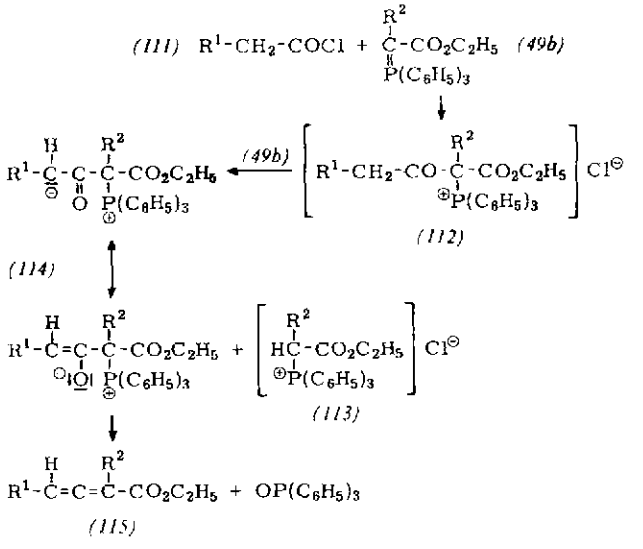
[53] Cf. *B. Eistert* in *W. Foerst*: Neuere Methoden der präparativen Organischen Chemie. Verlag Chemie, Weinheim/Bergstr. 1944, Vol. I, p. 359; *F. Weygand* and *H. J. Bestmann*, Angew. Chem. *72*, 535 (1960).

[54] *H. J. Bestmann* and *K. Rostock*, unpublished work.

We have now also observed γ-eliminations. Allylidenetriphenylphosphorane *(107)* reacts from the resonance form *(107b)* with methyl chloroformate to form the salt *(108)* [24], from which another molecule of the ylide *(107)*, acting as a base, extracts a proton from the γ position with respect to the P atom. The result is the ylide *(109)*, which has previously been prepared by another method [55], and which undergoes Wittig reactions to yield esters of polyenecarboxylic acids *(110)*.

2. Synthesis of Esters of Allenecarboxylic Acid

Another reaction which proceeds by γ-elimination is the formation of esters of allenecarboxylic acid [56].



Acyl chlorides *(111)* and 1-ethoxycarbonylalkylidenetriphenylphosphoranes *(49b)* react to form phosphonium salts *(112)*. A second molecule of ylide *(49b)* removes a proton from the γ position with respect to the P atom in *(112)*, with formation of a phosphonium salt *(113)* and a betaine *(114)*. The latter spontaneously loses triphenylphosphine oxide, providing a simple route to the esters of allenecarboxylic acids *(115)*, which were formerly very difficult to prepare, and which can be smoothly hydrolysed to form the crystalline allenecarboxylic acids. Some examples of the esters *(115)* are given in Table 9.

Table 9. Esters of allenecarboxylic acids $R^1HC=C=C(CH_3)CO_2C_2H_5$ *(115)* obtained from acyl chlorides R^1-CH_2-COCl *(111)* and 1-ethoxycarbonylethylidenetriphenylphosphorane $(C_6H_5)_3P=C(CH_3)-CO_2C_2H_5$.

	R^1	B.p. [°C/mm Hg]	Yield [%]
(115a)	H	52/11	59
(115b)	C_2H_5	70/11	55
(115c)	C_4H_9	97/11	66
(115d)	C_5H_{11}	109/11	80
(115e)	$C_6H_5-CH_2$	114/1	51

The infrared spectra of the esters *(115a)–(115e)* show a pronounced allene band at 1950 cm^{-1}.

The reaction is best carried out in tetrahydrofuran. The phosphonium salt *(113)* precipitates in this solvent, and can be used for regeneration of the ylide *(49b)*. The solution retains the ester of the allenecarboxylic acid, which can be distilled off from the triphenylphosphine oxide after removal of the solvent. The ylides *(49b)* can be synthesized from alkylidenephosphoranes and esters of chloroformic acid (cf. Section B 2).

Procedure:

Esters of Allenecarboxylic Acids (115)

1-Alkylethoxycarbonylmethylidenetriphenylphosphorane (60 mmole) is dissolved in 70 ml of anhydrous tetrahydrofuran by heating in the absence of moisture. This solution is cooled to about 40 °C, and 30 mmole of the acyl chloride, dissolved in 5–10 ml of tetrahydrofuran, is added. After a short time, the phosphonium salt precipitates. The mixture is refluxed for 3–4 h, and the phosphonium salt is filtered off and washed with 20 ml of ether. The solvent is distilled from the filtrate over a small column. The residue is mixed with 30–40 ml of petroleum ether, whereupon the greater part of the triphenylphosphine oxide crystallizes. The solution is filtered, the petroleum ether evaporated off, and the allenecarboxylate is distilled in vacuum.

E. Reactions of Alkylidenephosphoranes with Halogen Compounds at a Molar Ratio of 1:1

1. Synthesis of Esters of α-Branched β-Oxocarboxylic Acids

In the above reactions of alkylidene phosphoranes with halogen compounds, the initially formed phosphonium salt reacts with a second molecule of ylide. This step can be suppressed in some cases, *e.g.* by the use of low temperatures, and the salts so obtained can be used for further reactions. In this way, compounds *(118)* difficult to obtain by other methods can be synthesized.

Acyl chlorides *(116)* react with methoxycarbonylmethylidenetriphenylphosphoranes *(49)* at 0–20 °C to

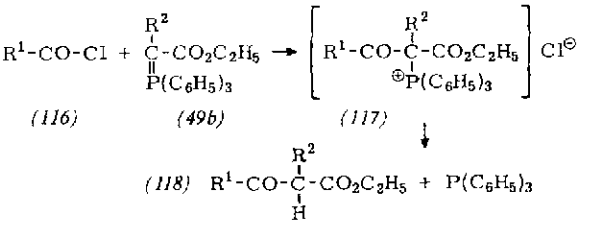


Table 10. Esters of α-branched β-oxocarboxylic acids $R^1-CO-CHR^2-CO_2C_2H_5$ *(118)* obtained from acyl chlorides R^1-COCl and ylides $(C_6H_5)_3P=CR^2-CO_2C_2H_5$ by electrolysis of the phosphonium salt *(117)*.

Ester	R^1	R^2	B.p. [°C/mm Hg]	Yield [%]
(118a)	CH_3	CH_3	70–71/13	77
(118b)	C_3H_7	CH_3	93/10	64
(118c)	C_5H_{11}	CH_3	115/10	78
(118d)	$(CH_2)_2-CO_2CH_3$	CH_3	95/2	68
(118e)	C_6H_5	CH_3	100/0.4	70
(118f)	$C_6H_5-CH=CH-$	CH_3	117/0.3	73
(118g)	$C_6H_5-CH_2-CH_2$	CH_3	115/0.2	73
(118h)	C_5H_{11}	C_3H_7	75/0.3	50
(118i)	C_6H_5	C_3H_7	95/0.3	45

[55] *E. Buchta* and *F. Andree*, Chem. Ber. *92*, 3111 (1959).

[56] *H. J. Bestmann* and *H. Hartung*, Angew. Chem. *75*, 297 (1963); Angew. Chem. internat. Edit. *2*, 214 (1963).

[57] *H. J. Bestmann, G. Graf*, and *H. Hartung*, unpublished work.

form the acylated salts *(117)*. Electrolysis of these compounds at a mercury cathode yields triphenylphosphine, together with esters of α-branched β-oxocarboxylic acids *(118)* [57]. Some examples are shown in Table 10.

Procedure:

Esters of α-Branched β-Oxocarboxylic Acids

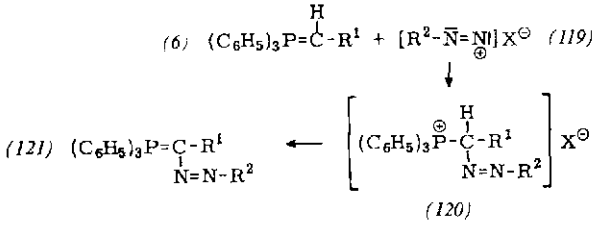
Acyl chloride (0.11 mole) is added to a solution of 0.1 mole of the α-alkyl- or α-arylalkoxycarbonylmethylidenetriphenylphosphorane in anhydrous benzene (0–20 °C). The mixture is allowed to stand for 24 h in a refrigerator, and the benzene is then decanted from the oily phosphonium salt. The latter is freed from solvent in vacuum at 30 °C and dissolved in a little water. The solution is extracted with ether, and the aqueous phase electrolysed.

The electrolysis is carried out in a three-necked flask with a cooling jacket. The middle neck carries a diaphragm with a carbon anode. A pool of mercury on the bottom of the flask is used as the cathode, to which connection is made by a fused-in molybdenum wire. The electrolysis is carried out at a temperature of under 35 °C with a current of 1–2 amp at 24 volts.

During the electrolysis, the triphenylphosphine and the keto-ester separate at the surface as an oil. As soon as the current ceases to flow, the mixture is extracted with ether. The ether phase is dried over anhydrous $MgSO_4$, and the solvent is evaporated. The residue is distilled at 15 mm Hg, using a rotating bulb tube. The ester distils, leaving the triphenylphosphine behind. The latter is recrystallized from methanol; the ester is purified by vacuum distillation.

2. Reactions with Diazonium, Nitrilium, and Oxonium Salts

Alkylidenephosphoranes *(6)* react with diazonium salts *(119)* to form diazotized phosphonium salts *(120)* which can be isolated, and which react with bases to yield the azoylides *(121)* [58].

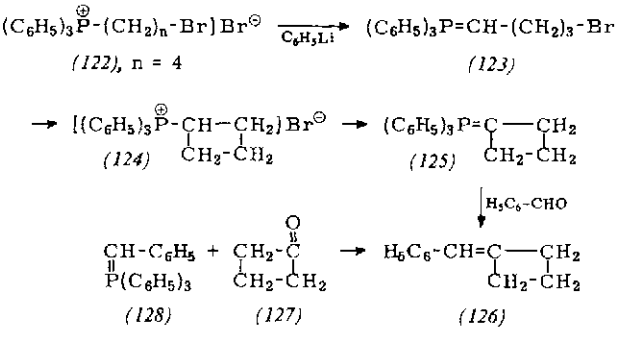


The salt *(120)* can evidently be isolated only when weakly basic ylides *(6)* (*e.g.* $R^1 = C_6H_5$, CO_2R^3) are used. In reactions involving more strongly basic alkylidenephosphoranes, a transylidation again appears to take place [58]. Similar reactions occur with nitrilium salts and trialkyloxonium fluoroborates [37].

F. Intramolecular Ring Closure

1. Monocyclic Compounds

Intramolecular reactions between alkylidenephosphoranes and halogen compounds are also possible, and offer new methods for the synthesis of cyclic compounds. *Mondon* [59] presumed that, in the reaction of the salt *(122)* with phenyl-lithium, the initially formed ylide *(123)* cyclizes to give the salt *(124)*. This assumption was subsequently confirmed by conversion of *(124)* into cyclobutylidenetriphenylphosphorane *(125)* and the reaction of the latter with benzaldehyde to form benzylidenecyclobutane *(126)* [60], which was synthesized from cyclobutanone *(127)* and benzylidenetriphenylphosphorane *(128)*.



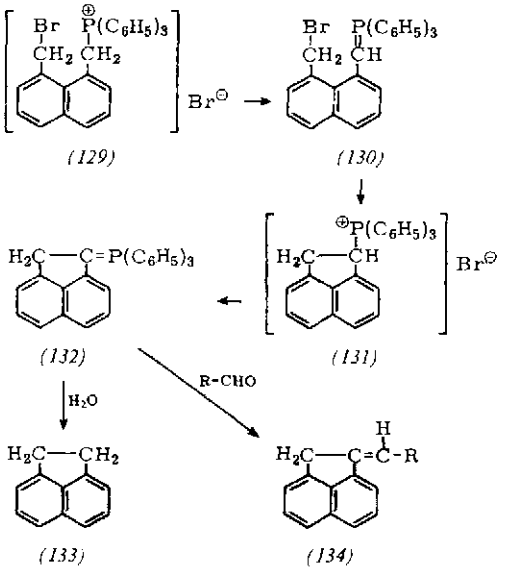
These reactions are generally given by phosphonium salts such as *(122)* containing more than 3 methylene groups [60, 61].

The reaction of ω,ω'-bishalogen compounds with 1 mole of triphenylphosphine [62] for the preparation of the phosphonium salts *(122)* is almost useless at $n \geq 5$, since as the chain length is increased, the reaction yields mixtures of the mono- and bis-phosphonium salts, or the latter alone [60].

2. Polycyclic Compounds

a) Acenaphthene and Indene Derivatives

Ring closure by intramolecular C-alkylation of alkylidenephosphoranes provides a particularly suitable method for the synthesis of polycyclic compounds



[58] *G. Märkl*, Tetrahedron Letters *1961*, 807.

[59] *A. Mondon*, Liebigs Ann. Chem. *603*, 115 (1957).

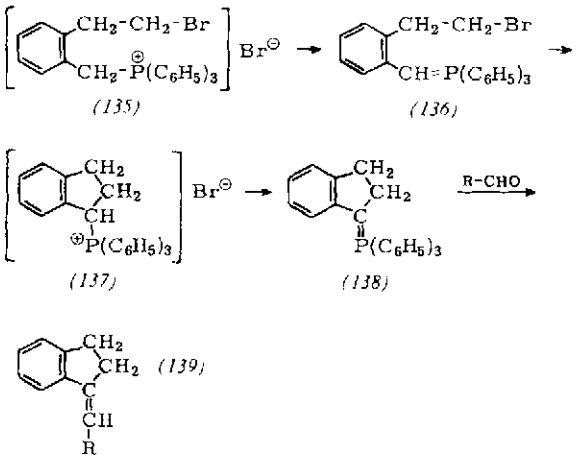
[60] *H. J. Bestmann* and *H. Häberlein*, unpublished work.

[61] *H. J. Bestmann* and *H. Häberlein*, Z. Naturforsch. *17b*, 787 (1962).

[62] *K. Friedrich* and *H. G. Henning*, Chem. Ber. *92*, 2756 (1959).

[60, 61]. The phosphonium salt *(129)* reacts with one mole of sodium alkoxide to form the ylide, which very readily undergoes ring closure with formation of the salt *(131)*. Compound *(131)* reacts with a second mole of alkoxide to form the cyclic alkylidenephosphorane *(132)*, which yields acenaphthene on hydrolysis, and which undergoes a Wittig reaction with aldehydes to give olefins *(134)* [61].

Similarly, the reaction of the phosphonium salt *(135)* with 2 moles of sodium alkoxide leads *via* compounds *(136)* and *(137)* to the ylide *(138)*, which reacts with aldehydes to form the hydrindene derivatives *(139)* [60].



Procedure:

1-(8-Bromomethyl-1-methylnaphthalene)-triphenylphosphonium Bromide (129)

A solution of 20 mmole of 1,8-bis(bromomethyl)naphthalene and 20 mmole of triphenylphosphine in 30 ml of benzene is heated for 15 to 20 h on an oil bath at 120 °C. The mono-quaternary phosphonium salt *(129)* which crystallizes out is extracted twice with boiling benzene and dried in a high vacuum at 100 °C over P_2O_5; m.p. 203 °C, yield 10.5 g (91 %).

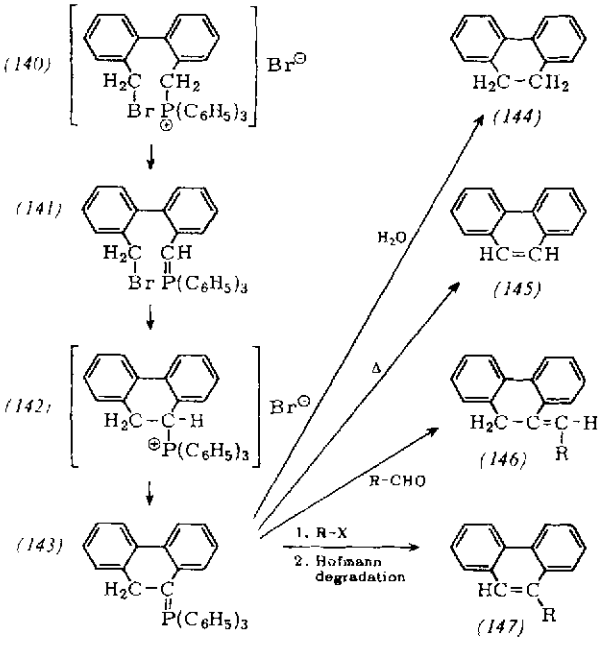
Acenaphthene

The phosphonium salt *(129)* (5 mmole) is dissolved in 30 ml of ethanol. 10 mmole of sodium ethoxide in ethanol is added dropwise to the colorless solution, with stirring, in an atmosphere of nitrogen. The solution turns red-orange and is boiled with 20 ml of water until no further lightening of the color occurs. The N_2 atmosphere can now be dispensed with. Acenaphthene *(133)* crystallizes on cooling (if no crystallization occurs, more water may be added). The crystals are filtered off, washed with dilute alcohol, and allowed to dry in air. A further crop of hydrocarbon can be obtained by steam distillation of the strongly concentrated filtrate. The melting point of the unrecrystallized product agrees with the value given in the literature (96 °C); yield 62 %.

b) Synthesis of Phenanthrene Derivatives [60, 61]

The great variety of syntheses made possible by intramolecular C-alkylation is illustrated by a new synthesis of phenanthrene derivatives.

On reaction with sodium alkoxide, the phosphonium salt *(140)* loses a proton to form the ylide *(141)*, which immediately undergoes ring closure to yield the salt *(142)*. Compound *(142)* reacts with a second mole of sodium alkoxide or with sodamide to form the deep red ylide *(143)*. The reaction of *(143)* with water yields 8,9-dihydrophenanthrene *(144)*, whilst heating, preferably in alcohol, results in Hofmann degradation to phenanthrene *(145)*. The formerly unknown compounds of the type *(146)* can now be obtained by reaction of *(143)* with aldehydes. The ylide *(143)* reacts with



halogen compounds in a molar ratio of 2:1 with simultaneous Hofmann degradation to the compounds *(147)*. It is possible in this way to introduce alkyl groups and ester groups into the 9,10 position of phenanthrene. 4,5-Dimethylphenanthrene and 2,7-dinitrophenanthrene have also been synthesized by this method [60]. The same sequence of reactions can also be used for the specific labeling of phenanthrene with tritium in the 9,10 position [51].

Procedures:

2'-Bromomethylbiphenyl-2-ylmethyl-triphenylphosphonium Bromide (140)

A solution of 100 mmole of 2,2'-bis(bromomethyl)biphenyl and 100 mmole of triphenylphosphine in 100 ml of benzene is refluxed for 5 hours. The crystals which separate are extracted twice with boiling benzene and dried in a high vacuum at 120 °C over P_2O_5; yield 57.2 g (95 %), m.p. 239–240 °C.

9,10-Dihydrophenanthryl-9-triphenylphosphonium Bromide (142)

The phosphonium salt *(140)* (20 mmole) is dissolved in 50 ml of anhydrous methanol under nitrogen, and 20 mmole of sodium methoxide in 50 ml of anhydrous methanol is added dropwise, the solution being agitated with a magnetic stirrer. The mixture turns yellow, and simultaneously the cyclic phosphonium salt *(142)* crystallizes out. The stirring is continued

for some time at room temperature, the N_2 atmosphere is removed and the salt is filtered off. It is extracted with boiling benzene until the extract gives no reaction for triphenylphosphine [24], and is finally dried in a high vacuum at 100 °C over P_2O_5. The phosphonium salt *(142)* obtained is very sparingly soluble in water, alcohol, or chloroform; m.p. 223–224 °C, yield 87%.

9,10-Dihydrophenanthrene (144)

Five millimoles of the phosphonium salt *(140)* is dissolved in 1000 ml of hot water, 50 mmole of NaOH is added, and the mixture is heated to boiling. Two substances separate out, one being crystalline, and the other an oil which solidifies on cooling. The solids are filtered off and washed with water, and the crystals are dried in air. The hydrocarbon *(144)* is sublimed from the crystal mixture on the water bath at 90–100 °C/1 mm Hg, and recrystallized from methanol, yield 89%. The sublimation residue is pure triphenylphosphine oxide (m.p. 153 °C).

9-Benzylidene-9,10-dihydrophenanthrene

The phosphonium salt *(140)* (10 mmole) is converted under nitrogen by the sodamide method (see Part I, Section D 2) to a suspension of the ylide in anhydrous benzene. The ylide is only sparingly soluble; for this reason, the sodium bromide formed is not filtered off. To the red suspension of the ylide 10 mmole of freshly distilled benzaldehyde is added, and the reaction mixture is stirred magnetically at room temperature until it becomes colorless (about 10 h). The N_2 atmosphere can now be dispensed with. The sodium bromide is filtered off, and the filtrate is evaporated to dryness. The residue is extracted twice with 25 ml portions of boiling methanol to remove the triphenylphosphine oxide. The benzylidene compound, which is practically insoluble in methanol, has m.p. 152 to 156 °C in the crude form, and can be purified by recrystallization from n-hexane (m.p. 158 °C, yield 72%).

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Modern Theoretical Views on the Chemical Bond

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Starting from classical concepts, semi-empirical approaches to an understanding of the chemical bond are critically discussed, particularly with respect to their limitations. Rules such as the additivity of the bond constants and the octet rule are reviewed in relation to new chemical compounds. It is shown that these rules are not sufficient to explain chemical bonding; this is also true of the simple concept of hybridization, the basis of which is discussed. Some generally valid statements regarding the chemical bond can be propounded on the basis of wave-mechanical considerations. It is shown that the hybridization concept and a number of other rules are too primitive to provide generally valid information or a basis for predictions about the chemical bond, and even that they are partly based on false premises. A better foundation for an understanding of the chemical bond can only be laid with the aid of wave mechanics.

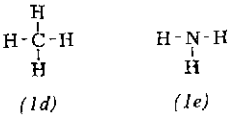
1. Introduction

When chemists speak about the chemical bond, they differentiate between the ionic bond, the covalent bond, or the semipolar bond. The first two are often termed polar and non-polar (homopolar) bonds.

In ionic bonding, it is assumed that electrons are transferred from one of the bonded atoms to the other, so that oppositely charged ions result which attract one another. This picture was first proposed by *Kossel* (1917). It explained certain properties of a limited number of ionic compounds, but was found to be inadequate in many cases, since the formation of ionic molecules does not necessarily proceed by initial ionization of the atoms being linked, and since many ionic compounds do not dissociate to form ions. In this picture, the number of bonds drawn in a structural formula is identified with the number of electrons transferred to the other atom. For example, if we assume that CaO, HF, and CO contain the ions Ca^{2+}, O^{2-}, F^-, C^{2+}, and the proton, we obtain

Ca=O *(1a)*, F–H *(1b)*, or C=O *(1c)*.

It could even be assumed that CH_4 and NH_3 contained the ions C^{4-} and N^{3-}. This would lead to the formulae *(1d)* and *(1e)*, which are generally drawn in two dimensions, although experience has shown that they are



(1d) *(1e)*

tetrahedral and pyramidal, respectively (see Fig. 1).

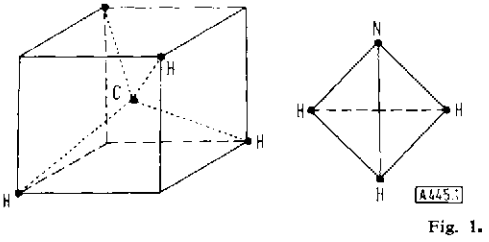


Fig. 1.

According to this view, all the atoms of a compound have the "rare gas configuration", which was formerly

thought to be particularly stable, and hence chemically inert. In the above examples, we have the following correspondences:

$Ca^{2+} \triangleq Ar$, $C^{2+} \triangleq Be$,
$O^{2-} \triangleq Ne$, $C^{4-} \triangleq Ne$,
$F^{-} \triangleq Ne$, $N^{3-} \triangleq Ne$.

This concept has been extended somewhat in putting C^{2+} in correspondence to Be. Although the electronic configuration of Be does not correspond to that of any of the rare gases (He, Ne, Ar, Kr, Xe, Rn), it can be regarded as being similar to that of the rare gases.

Almost simultaneously with the rise of the electrostatic theory, *Lewis* developed his "octet rule". It was essentially intended to apply to molecules consisting of atoms from the first and second periods. According to this rule, the atoms do not become ionized; instead, the bonding electrons are shared by the atoms in such a way that each atom "fills up" its electron shell to "rare gas configuration" [two or ten (8+2) electrons]. It is usual to represent the electrons by dots, so obtaining, for example, Figures 2 and 3.

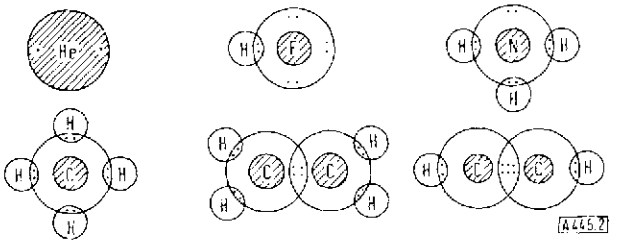


Fig. 2.

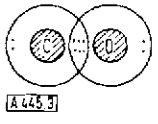


Fig. 3.

In these illustrations, the shaded circle represents the configuration of a closed shell containing two electrons, as found in helium. The Lewis model is also applicable to bonds between similar atoms (see *e.g.* Fig. 4). In Cl_2,

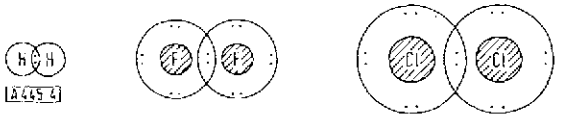


Fig. 4.

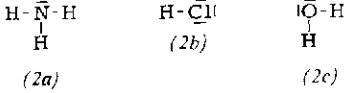
the inner circles represent the shells containing two (He) and eight electrons (Ne).

The Lewis rule presupposes some knowledge of the electronic configurations of the atoms involved, and can be extended to elements with nuclear charges of up to $Z = 36$ by assuming the formation of a krypton shell. The remaining elements can be included in a similar manner. In every case, the configurations assumed to be stable have "magic" numbers of electrons, *e.g.* 2 or 10, which are correlated with the inert gas configurations. Every pair of electrons between atoms corresponds to a bond, and is represented by a line; all bonds are thus two-electron bonds.

Thus the valence bond has different meanings in the Kossel picture and in the Lewis picture, although both concepts often give the same valence-bond diagram, as is shown by *(1b)*, *(1d)*, *(1e)* and Figures 2 and 4. Even when the valence-bond representations are identical, however, they are generally not chemically equivalent (cf. the C–C bond in CH_3–CHO and CCl_3–CHO).

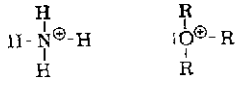
From the valence-bond representation it would be assumed that the same bond in different molecules has the same properties. The chemical nature of a molecule would then be determined by the sum of the properties of the bonds in the molecule. Such additivity actually does exist to a close approximation in many classes of compounds. There are other compounds, however, in which the molecular properties cannot be even roughly described in this way. There is always some interaction between bonds, often leading to completely new properties in a molecule. Thus the valence-bond representation gives only a rough indication. It shows the atoms between which the most important interaction, leading to chemical bonding, exists.

In pursuance of *Lewis'* ideas, the outer-shell electron pairs in an atom which are not involved in a bond are referred to as "lone" pairs of electrons, which appear to be outwardly saturated, so to speak, by an "internal bond". In such a case, a line is often drawn beside the atom in question, as shown in *(2a)* and *(2b)*. This



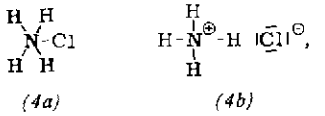
(2a) *(2b)* *(2c)*

concept also leads to the structures *(3a)* and *(3b)*, since the octet rule can be applied to ions, too. By the same



(3a) *(3b)*

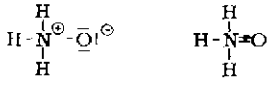
token, we have not *(4a)*, but *(4b)*, a representation which agrees with experience. Thus there is an ionic



(4a) *(4b)*

bond between the $[NH_4]^{\oplus}$ and the chloride ion, whereas the four $N^{\oplus}$–H bonds are covalent.

In the Kossel scheme, the bond between $[NH_4]^{\oplus}$ and $Cl^{\ominus}$ would also be denoted by a line. However, it has become common practice to use the line for a two-electron bond only, and to indicate an ionic bond by the signs of the charges, as shown in *(4b)*. Thus amine oxide should be written as *(5a)*. This compound contains a "semipolar"



(5a) *(5b)*

bond and is therefore frequently represented by *(5b)*, the arrow indicating that negative charge has been transferred from the nitrogen to the oxygen.

These methods of bringing order to the maze of chemical experience have not lost their value. In many cases, chemical bonds are formed by sharing electrons, but an increasing number of new chemical compounds fit into this scheme only with great difficulty, or not at all. This group includes the simplest molecule $H_2^{\oplus}$, or *e.g.* the molecule NO, which is stabilized by an odd number of electrons. New structural representations must be found for free radicals, in order to take into account the unsaturated electron. The van der Waals molecules or molecules containing ion-dipole bonds also fail to fit into this scheme. The group further includes the boron hydrides and their derivatives, as well as the "sandwich" complexes. Compounds of the inert gases should be incapable of existence, since it is the inert gas configuration which is considered to be the most stable one.

Although schemes of this type bring a certain order into experimental observations, this order is formal, and offers no possibility of quantitative calculation. This is also true for most symmetry considerations, unless they exclude certain atomic constellations.

Using the general valence-bond representation (including atomic charges and lone pairs of electrons), it is possible to write several "structures" for many compounds. This ambiguity, which arises from the definition of the valence-bond structure, has often been erroneously correlated with energy principles, by assuming that the stability of a compound increases with the number of valence-bond structures which can be used to represent it. In reality, this is an incorrect application of a wave-mechanical approximation method, as we shall show (Section 4, Eq. 44).

2. Semi-empirical Approaches

The ability of atoms to form molecules can be explained by the electronic structure of the atoms. Two important properties of the electron systems are the first ionization energy I_Z and the electron affinity A_Z of the atom Z. If energy supplied to a system is regarded as positive, the energy which must be expended to transfer an electron from the atom Z to the atom Y is

$$I_Z - A_Y \qquad (a)$$

Similarly, if the electron is transferred from Y to Z, the energy is

$$I_Y - A_Z \qquad (b)$$

If the two atoms approach each other, the behavior of the electrons will depend on which of these two energies is greater, unless they are equal, as is the case when $Z = Y$.

$$I_Z - A_Y \gtrless I_Y - A_Z \qquad (c)$$

Rearrangement of (c) gives

$$I_Z + A_Z \gtrless I_Y + A_Y \qquad (d)$$

The atomic parameter

$$\chi = I + A \ \text{[kcal/mole]} \qquad (e)$$

is known as the electronegativity, and has been used by *Pauling* and by *Mulliken* in the discussion of chemical bonds. Using this parameter, *Pauling* introduced some order into the diversity of bonds. The important quantity here is the difference in the electronegativities of the two atoms A and B:

$$X = \chi_A - \chi_B \qquad (f)$$

It was found that the dissociation energies D(A–B) of single bonds approximately satisfy the relationship

$$D(A-B) \approx \alpha + \beta X^2 \qquad (g)$$

where α and β are constants. When $X = 0$, Equation (g) becomes

$$D(A-B) \approx \alpha \qquad (h)$$

Since α is independent of X, it represents the dissociation energy of a bond between two identical atoms when $A \equiv B$. Therefore, Equations (i) and (k) can be written, both of which satisfy Equation (g) reasonably well.

$$\alpha = \frac{1}{2}\left\{D(A-A) + D(B-B)\right\} \qquad (i)$$

$$\alpha = \sqrt{D(A-A)D(B-B)} \qquad (k)$$

This ambiguity shows that Equation (g) is a somewhat arbitrary formulation using the quantity X; if (g) is expressed in the form (l) it is seen that in some cases the

$$D(A-B) - \frac{1}{2}\left\{D(A-A) + D(B-B)\right\} = \beta X^2 \qquad (l)$$

left-hand side of Equation (l) becomes negative, which is meaningless, since β is always positive. The question therefore arises of to what extent bond relationships can be described by the simple parameters χ. The expression (c) can have meaning only for single bonds. Second ionization energies (and second electron affinities) are not considered at all.

Thus we have a greatly simplified picture of the bond, although originally this represented a considerable advance. The main value of expression (c) is that, in contrast to the octet rule and the valence-bond scheme, it points to a continous transition between ionic and covalent bonding. The line representing a bond is correlated with the ionization energy and electron affinity, both of which can be calculated only with the aid of wave mechanics.

According to the octet rule, the xenon atom (like all inert gas atoms) has a full shell of electrons (octet), *i.e.* it cannot be expected to combine with another atom in order to share further electrons. With the concept of electronegativity, however, we must ask whether the transfer of an electron to another atom might not be energetically favored. Thus the inert gases are distin-

guished by their first ionization energies. A possible bonding partner must have an electron affinity which is comparable with these ionization energies, since only then can an electron be transferred from the inert gas atom. However, it cannot be decided on the basis of these semi-empirical rules whether this process in fact takes place, since it remains unknown whether or not the four pairs of electrons in an octet are equivalent. Moreover, the behavior of the inner electrons (and other effects) are not taken into account. The semi-empirical rules must therefore be regarded as a primitive stage of theory. In fact, examples show that Equation (g) is only of limited applicability. Thus, with $\beta = 0.00137$, expression (m)

$$\left[\frac{1}{\beta}\left\{D(A-B)-\frac{1}{2}D(A-A)+D(B-B)\right\}\right]^{1/2} \qquad (m)$$

yields the following values for P–H, C–S, H–Br, and O–F, respectively:

36.4 66.3 96.2 80.6 kcal/mole. (n)

According to Equation (l), these values should be equal to $|X|$. Equations (e) and (f) give the values

85.4 2.0 30.8 126.5 kcal/mole. (o)

The electronegativity χ as given by Equation (e) is usually divided by 130 to facilitate comparison with *Pauling's* scale of electronegativities (cf. below). Thus

$$\chi' = (I + A)/130 \qquad (e')$$

This leads to the values (n') and (o'), since β in Equation (m) must now be replaced by the constant $\beta' = 23.11$.

0.28 0.51 0.74 0.62 (n')
0.66 0.02 0.23 1.02 (o')

There is no agreement between the sets of values (n') and (o'). It should be remembered, however, that α in Equation (g) is large in comparison with the "correction" βX^2, which for the above examples is

1.8 6.7 12.5 9.1 kcal/mole.

These values are small in comparison with D(A–B), so that the expression (g) does not appear to be unjustified. It is obvious that corrections must be applied to the electronegativity values introduced in Equation (e). *Pauling* therefore calculated another scale of χ'' values, using Equation (p).

$$D(A-B)-\frac{1}{2}\left\{D(A-A)+D(B-B)\right\}=\beta' X''^2 \qquad (p)$$

$$X'' = \chi''_A - \chi''_B \qquad (q)$$

From this and with an arbitrary reference value, *e.g.* $\chi''_F = 4.0$, we obtain:

$\chi''_H = 2.1$ $\chi''_C = 2.5$ $\chi''_O = 3.5$
$\chi''_F = 4.0$ $\chi''_P = 2.1$ $\chi''_S = 2.5$ $\chi''_{Br} = 2.8$ (r)

These values of χ'' were calculated by averaging the values of X'' obtained for the same bond in various compounds. The value of β' was also found in this way, so that the χ'' values can be compared with the electronegativities χ' [see Equation (e')] introduced by *Mulliken*:

$\chi'_H = 2.53$ $\chi'_C = 2.23$ $\chi'_O = 3.08$
$\chi'_F = 4.06$ $\chi'_P = 1.87$ $\chi'_S = 2.21$ $\chi'_{Br} = 2.76$ (s)

It is thus possible to construct different electronegativity scales, one based on Equation (e) or (e') and the other on Equation (p). Comparison of the two sets of values, (r) and (s), shows that the results correspond to within certain limits. A similar agreement is found in other examples:

$\chi''_{Cl} = 3.0$ $\chi''_I = 2.5$ $\chi''_{Li} = 1.0$ $\chi''_{Rb} = 0.8$ (r')
$\chi'_{Cl} = 3.01$ $\chi'_I = 2.43$ $\chi'_{Li} = 0.95$ $\chi'_{Rb} = 0.74$ (s')

It should be noted that the accuracy of the approximation (g) is greatly affected by the differences between χ'' and χ'. We shall prefer the definition of electronegativity given by Equation (c) or (e'), which is unambiguous and consistent. Equation (g) might be improved by taking χ'^4 into account, as in Equation (g'),

$$D(A-B) = \alpha + \beta X^2 + \gamma X^4 \qquad (g')$$

and fixing the coefficients α, β, and γ. The choice of α in Equation (g), using Equation (i), gives negative values for the left-hand side of Equation (l) for some bonds. Thus the values found for As–H, C–I, and Se–H are −12.0, −1.8, and −7.5 kcal/mole, respectively.

Clearly, the electronegativity is of some importance, but it has not yet been possible to find completely satisfactory relationships between electronegativity and other measurable quantities. Thus X is an important, but insufficient quantity for the description of the bonding processes, so that all semi-empirical relationships involving X must be incomplete to some extent.

This is particularly true of the ionic character λ_{AB} of a bond, which is defined in terms of X [see Equation (u)]. This property is applicable only in the case of the hydrogen halides, for which it was first derived. The assumption that Δ in Eq. (t) should be a measure of the polarity of a bond,

$$\Delta = D(A-B)-\frac{1}{2}\left\{D(A-A)+D(B-B)\right\} \qquad (t)$$

because $\Delta = 0$ when $X = 0$, appears to have little justification if, for example, the expression Δ' is compared with Δ (see Table 1). As expected, there is no relation between Δ and Δ'.

$$\Delta' = D(A-B)-\left\{D(A-A)D(B-B)\right\}^{1/2} \qquad (t')$$

Table 1. Dissociation energies and energy values Δ and Δ' for a number of hydrogen compounds AH.

AH	HF	HCl	HBr	HI	LiH	NaH
D(A–H)	147.5	102.7	87.3	71.4	57.7	52.3
Δ	64.0	22.1	12.5	1.6	−7.6	8.7
Δ	66.5	25.4	18.3	10.2	4.7	8.7

For this reason, equations such as (u), which relate X to the ionic character [1] should be viewed with suspicion. It can

$$\lambda_{AB} = 0.16\,|X| + 0.035\,|X|^2 \qquad (u)$$

[1] *L. Pauling*: The Nature of the Chemical Bond. 3rd Edit., Cornell University Press, Ithaca (N.Y.) 1960.

be shown with the aid of wave mechanics that the polarity of a bond need not be directly related to the dipole moment. Consequently the so-called effective charges introduced in this connection suffer greatly from their arbitrary nature. The definition

$$\mu_{AB}/eR^{\circ}_{AB} = \lambda_{AB} \qquad (v)$$

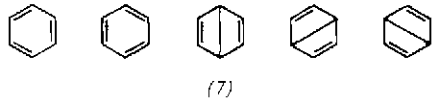
in which μ_{AB} is the dipole moment of the single bond and R°_{AB} is the bond length (e = electronic charge), is therefore applicable only in the case of a pure single bond, *i.e.* where bonding is effected by one pair of electrons, so that each of the atomic residues carries a positive charge; this condition is adequately fulfilled in only a few cases. It is desirable not to identify λ_{AB} in Equation (v) with that in Equation (u), since $|X|$ can only be a measure of the approximate charge separation in a bond, if no other effects are involved. Polarization effects are also disregarded.

Let us repeat, then, that although a large $|X|$ may indicate the existence of charge displacement in the single bond, *e.g.* as in H(+)Cl(−) or Li(+)H(−), any quantitative data derived from the semi-empirical rules should be regarded with caution, and the value of such data is at best orientative.

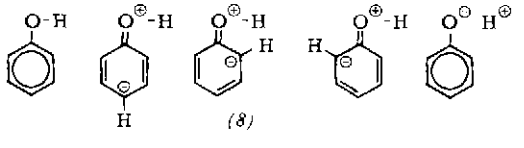
However, the symbols (+) and (−) go further than + and − or $^{\oplus}$ and $^{\ominus}$, since partial charge transfers can now be included. Thus ionic bonding and covalent bonding (as well as semipolar bonding) become limiting cases of the same bonding mechanism. This view, which is very close to the wave-mechanical picture, has unfortunately been over-simplified in the semi-empirical representation. Here a superposition of ionic and non-polar structures, *e.g. (6a)*, *(6b)* and *(6)*, is assumed. The same is true of

$A^{\ominus}B^{\ominus}$ *(6a)* $A^{\ominus}B^{\oplus}$ *(6b)* A–B *(6)*

the resonance picture, which is based on the fact that one molecule can be represented by several structural formulae. The best-known example is that of benzene *(7)*. If ionic structures are also admitted, the number of formulae can be greatly increased as, for example, in the case of phenol *(8)*. Here it is assumed that the bonding



(7)



(8)

behavior of the atom ions is essentially the same as that of neutral atoms containing the same number of electrons, *i.e.*

$C^{+} \triangleq B(III)$, $C^{-} \triangleq O^{+} \triangleq N(III)$,
$B^{-} \triangleq N^{+} \triangleq C(IV)$, $N^{-} \triangleq O(II)$, $O^{-} \triangleq F(I)$.

In this picture, the valence is a purely empirical quantity, and the properties of the atoms are characterized only by the number of electrons. With the introduction of the concept of electronegativity it becomes possible to distinguish, at least in one property, the most weakly bound electron and the eletron which can be taken up. In some cases lone pairs of electrons occur.

It is widely believed that the structures which make the greatest contributions to a molecule are those in which the most electronegative atoms are negative with respect to their neighbors; however, the situation is not always quite so simple. The stability of a compound cannot be determined by the number of possible structures, since on the basis of the electronegativity concept, certain statistical weights must be assigned to the various structures, although these weights cannot be given quantitatively, particularly to excited states. In other words, the resonance treatment cannot lead to a quantitative theory, since it is incapable of yielding information regarding the actual contribution of a given structure. It is therefore very misleading to suppose that certain structures are responsible for given aspects of the behavior of the molecule. For this reason, an interpretation of this type is generally given *after* a reaction has been found to occur.

An important point which is almost always overlooked in the resonance picture is the interatomic distance. Taking this into account, it is even less plausible to attribute resonance energy to a structure whose significance must remain unknown.

In writing structures, care is taken to ensure that all the valences are saturated, *i.e.* the only structures written are those in which the number of bonds leaving an atom corresponds to its valence; this is also borne in mind in the case of ionic structures. Structures in which valences remain unsaturated represent free radicals.

It might be asked, however, whether free-radical structures should also be considered for molecules in which each atom is using all its valences. It is generally believed that such structures have only small statistical weights, the doubtful (and sometimes false) argument being that these "molecular states" are energetically "unfavorable". This question will be examined in connection with the wave-mechanical arguments.

Thus structural formulae are made to satisfy the octet rule as far as possible. The principle of saturation of valence is taken to mean that the most stable compound is obtained when all valences are saturated, and when no further atoms will be bound, *i.e.* when the approach of other atoms does not lead to a further decrease in the energy of the system.

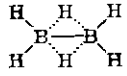
According to this principle, the H_2 molecule cannot bind a further H atom, and the sum of the energies of He and H is smaller the energy of HeH. The energy of $NH_3 + H$ should also be smaller than the energy of NH_4, and the approach of a hydrogen atom to an HF molecule should lead to repulsion. Recent wave-mechanical calculations have shown, however, that the energy of NH_4 is lower by about 5 kcal/mole than that of $NH_3 + H$, and that the four H atoms are situated about 1.0 Å from the nitrogen, and form the corners of a regular tetrahedron [2]. This is an infringement of the octet rule, although NH_4 probably cannot exist as a stable molecule, and almost certainly decomposes rapidly [Reaction (w)].

$$NH_4 + NH_4 \rightarrow 2\,NH_3 + H_2 \qquad (w)$$

[2] *D. M. Biskop*, J. chem. Physics *40*, 432 (1964).

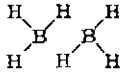
Who can guarantee that there are no stable molecules which should, according to the octet rule, be unstable or metastable. How is the NH_4 radical stabilized, *i.e.* why does NH_4 contain less energy than $NH_3 + H$?

One may adopt the view that the octet rule is only applicable to molecules, and not to molecular complexes. How then are we to explain *e.g.* the simplest of the boron hydrides, namely diborane *(9)*, or the sandwich compounds derived from cyclopentadiene (*e.g.* ferrocene)?

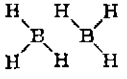


(9)

In order to satisfy the "valence rule", B_2H_6 must be assumed to contain the structures *(9a)* and *(9b)*; these representations seem very artificial, since what are we to

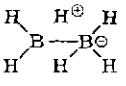


(9a)

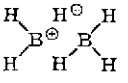


(9b)

understand by σ-bonds which oscillate back and forth? The difficulty is not resolved by assuming that the structures *(9a)* and *(9b)* are present in diborane, since there are in fact two BH_3 units simultaneously exchanging two H atoms. Since the electronegativities of B and H are essentially the same, ionic structures such as *(9c)* and *(9d)* can be ruled out.

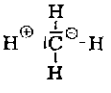


(9c)

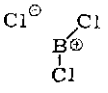


(9d)

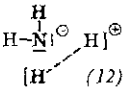
On the other hand, formulae such as *(10)* and *(11)* are often written. So why should we not represent NH_4 by



(10)

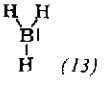


(11)



(12)

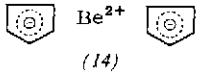
formula *(12)* (there are six possible structures)? Thus an H_2^+ unit would be indicated in NH_4 as BH_3 is in diborane by formula *(9a)*. It can be seen that the octet rule is satisfied in formula *(12)*. In *(9a)* or *(9b)* it would be necessary to include "inner" electrons in order to obtain formula *(13)*. In *(11)*, on the other hand, only Cl^-



(13)

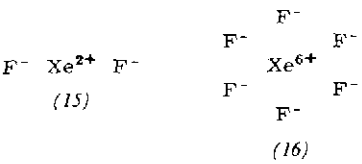
has a closed shell, whereas two electrons of B^+ participate in bonding, and the K shell forms the atomic residue.

If it is still impossible to satisfy the octet rule using considerations of this kind, it is usual to turn to completely ionic formulae, as in the case of $Be(C_5H_5)_2$ *(14)*, or



(14)

XeF_2 *(15)*. Is it then permissible to write the structure *(16)*? Here things become doubtful, particularly since Be in $Be(C_5H_5)_2$ is not centrally positioned between the rings as is postulated in structure *(14)* [3].



(15) *(16)*

We can see from all this that such an "interpretation" of bonding relationships is unsatisfactory. On the one hand, more and more knowledge of the electronic structures of the atoms involved is required, and on the other, we encounter ambiguities, so that it is no longer possible to speak of a true understanding. Here it is felt that the relative importance of the individual structures of the real molecule is not known. What does it mean to say a certain structure of a molecule is more important than the others? Can this conclusion be drawn with certainty from the physical and chemical properties of the compound? Should it not be possible to predict, and possibly understand, the behavior of the molecule from theoretical considerations?

Clearly, many compounds can be decribed by the octet rule and the usual structural formulae. Although these descriptions are not accurate, they can at least be used by the chemist as a temporary measure, without which all practical experience would remain unrelated. However, many of the compounds discovered in recent years can be reconciled with these rules only with difficulty, or fall entirely outside the scope of previous chemical views. It is clear, moreover, that false information may be obtained for these new compounds if the old scheme is used indiscriminately.

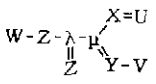
Normally a rule is applicable only to certain classes of compounds. For example, the additivity of the mean dissociation energies is valid only in the case of localized bonds, *i.e.* for molecules which can be essentially described by a single valence structure. The bond constants remain additive as long as the interactions between the various bonds are of the same type. However, it is difficult to determine the range of validity, particularly since the significance of the individual valence structures can only be discussed on the basis of wave mechanics. All molecules for which the mean dissociation energies are approximately additive are compounds for which the octet rule is approximately valid.

The rule of the additivity of dissociation energies gives only a rough representation of the situation; this can be seen in the case of the ideal disosciation energies $\tilde{D}_T$ introduced by *Szabo* [4], for which there is no additivity rule. Assuming, however, that the perturbations on a given bond are due only to the adjacent atoms and bonds, it is possible to determine the true dissociation energies D_T such that a useful rule is obtained. The di-

[3] *A. Almenningen, O. Bastiansen,* and *A. Haaland,* J. chem. Physics *40*, 3434 (1964).

[4] *Z. G. Szabo,* Z. Elektrochem., Ber. Bunsenges. physik. Chem. *61*, 1183 (1957). – $\tilde{D}_T$ refers to a bond which is unperturbed by neighboring atoms and bonds.

sturbances due to the neighbors are given by a quantitivity d, which should be constant for a given atom and a given bond, irrespective of the nature of the molecule. Thus in



(17)

the case of a compound of the type *(17)*, the expression for the bond λ–μ is:

$$D_T(\lambda-\mu) \approx \widetilde{D}_T(\lambda-\mu) + d(-X) + d(=Y) + d(-Z) + d(=Z) \qquad (x)$$

This rule can be extended to cover unsaturated and aromatic systems and is important for the estimation of activation energies. The form of this rule comes close to the theoretical views of the valence bond and group function methods. It fails when there is a change in the bonding relationships.

3. Hybridization

No concept is so frequently used in valence theory and none is so controversial as that of hybridization.

The problem of directed valence, *i.e.* the spatial structure of a molecule, was essentially explained by *Slater* and *Pauling* [5] in 1931. However, the usual elementary picture involves more theory than is supposed, and has therefore not been free from serious objections [6].

The logical application of the hybridization concept requires the use of wave-mechanical concepts such as that of the atomic state (O) and the atomic functions (φ_s, φ_p), as well as the introduction of electron spin (↑, ↓). This is generally illustrated graphically, *e.g.* for the atoms Be, C, N, and O, as shown in Figure 5. In this illustration, C* denotes an excited state.

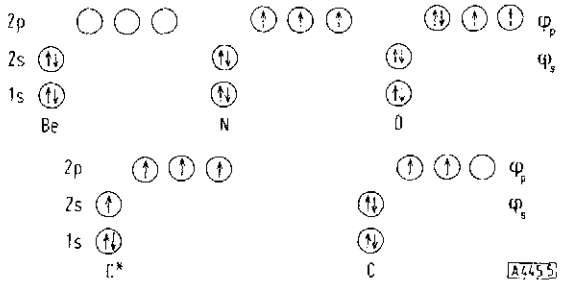


Fig. 5.

According to this concept, the directed valence is determined by the electronic structure of the central atom; this assumption is by no means satisfactorily fulfilled in every case, as we shall see.

The elementary picture of hybridization is based on two postulates:

(1) the wave functions ψ_1, ψ_2 ... ψ_M of the valence electrons of the central atom are mutually orthogonal, and

(2) the surrounding atoms arrange in those directions in which the wave functions ψ_1, ψ_2 ... have their maxima.

The ψ_j functions are linear combinations of the atomic functions φ_s and φ_p, as shown in Equation (y), where λ

$$\psi_j = \frac{\varphi_s + \lambda\varphi_{p_j}}{\sqrt{1+\lambda^2}} \qquad (j = 1, 2, 3 \ldots M) \qquad (y)$$

is the hybridization parameter. The form of Equation (y) is so chosen that ψ_j is normalized:

$$\int \psi_j^* \psi_j \, d\tau = 1 \qquad (y')$$

The p functions in Equation (y) at first lie in any direction in space; the number of ψ_j functions involved depends on the number of valence electrons, which are defined here as the electrons of the singly occupied energy levels of the free atoms. The direction of the p_j functions and the value of λ are given by assumptions 1 and 2. When d and f functions are involved, Equation (y) expands to give (z). However, the most important points can be studied with the aid of Equation (y). According to Figure 5, four ψ_j functions must be formed in the excited state C* of carbon. According to assumption 1, Equation (a*) must be satisfied. This together

$$\psi_j = \frac{\varphi_s + \lambda\varphi_{p_j} + \mu\varphi_{d_j} + \nu\varphi_{f_j}}{\sqrt{1+\lambda^2+\mu^2+\nu^2}} \qquad (z)$$

$$\int \psi_i^* \psi_j \, d\tau = 0; \; (i \neq j) \qquad (a^*)$$

with Equation (y) leads to Equation (b*), where Θ_{ij} is

$$\cos\Theta_{ij} = -1/\lambda^2; \; (i, j = 1 \cdots M; \; i \neq j) \qquad (b^*)$$

the angle between the two functions φ_{pi} and φ_{pj}. In order to satisfy postulate (2) we introduce the bond strength, as defined in Equation (c*), which represents the angular dependence of a ψ_j function in the direction of maximum

$$B(\lambda) = \frac{1+\lambda\sqrt{3}}{\sqrt{1+\lambda^2}} \qquad (c^*)$$

$$\frac{dB}{d\lambda} = 0 \qquad (d^*)$$

extension [*]. Thus, with (d*), Equation (c*) leads to (e*):

$$\lambda = \sqrt{3} \qquad (e^*)$$

This value of λ leads to Equation (f*), which shows that the four bonds of C* are directed towards the corners of

$$\cos\Theta_{ij} = -1/3, \; i.e. \; \Theta_{ij} = 109.5^\circ \qquad (f^*)$$

a tetrahedron, according to postulate (2). It should be remembered here that the four atoms bound by a carbon atom are assumed to combine with the carbon in

[5] *J. C. Slater*, Physic. Rev. *37*, 481 (1930); *38*, 1109 (1930); *L. Pauling*, J. Amer. chem. Soc. *53*, 1367 (1930); Physic. Rev. *37*, 1185 (1930); The Nature of the Chemical Bond [1].

[6] *K. Artmann*, Z. Naturforsch. *1*, 426 (1946); Z. Physik *137*, 137 (1954); *141*, 445 (1955); *142*, 518 (1955); *D. v. Loessl*, Doctorate Dissertation, Universität Hamburg, 1952.

[*] The factor $\sqrt{3}$ in Eq. (c*) is contributed by the p-function.

these directions, in which the ψ_j functions have maximum values. This assumption is not, as often asserted, self-evident since there are systems in which carbon has five neighbors. This brings us back to the NH_4 radical or compounds in which phosphorus could be assumed to be tetravalent. According to Figure 5, N (like P) has three valence electrons in p states, and no s functions. Thus λ in Equation (y) must be infinitely large, and there is no hybridization [$\Theta = 90°$ according to Equation (b*)]. Pentavalent phosphorus might be thought to contain states such as those shown in Figure 6. However, which

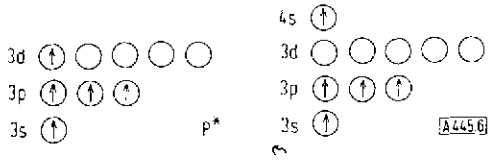


Fig. 6.

valence state is closest to the true situation evidently depends on energetic factors and on the number of different states (*e.g.* five in the case of d states), which must be found from wave-mechanical considerations. Can nitrogen also exist in a pentavalent state, as has sometimes been assumed, *e.g.* for the azide ion *(18)*? Would it not also be possible to write *(18a)*?

(18) *(18a)*

Whereas *(18)* should involve hybridization with 3d or 3s functions, the electron shell of the central nitrogen atom-ion in *(18a)* is the same as that of carbon, so that we can again use Equation (y). This does not enable us to decide whether *(18)* or *(18a)* is closer to reality, since the energy required for the participation of d states in *(18)* is offset by the need to form charges in *(18a)*.

If we consider the molecules BeX_2 and BX_3 (Figure 7), the result obtained using Equations (d*) and (b*),

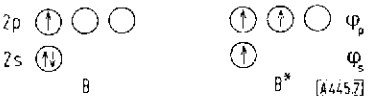


Fig. 7.

which led to $\lambda = \sqrt{3}$, is in conflict with observation, since BeX_2 is linear, whereas BX_3 is planar, with bond angles of 120°. It is usual in these cases to assume $\lambda = 1$ and $\lambda = \sqrt{2}$, respectively; Equation (b*) then gives $\Theta = 180°$ and $\Theta = 120°$. This is contrary to postulate (2), which gave such good agreement with experiment in the case of carbon. These examples (and many others) show that postulates 1 and 2 are not sufficient to lead to directed valence. It is the empirical assumption that $\lambda = 1$ and $\lambda = \sqrt{2}$ which ensures that the desired result will be obtained. *Artmann* [6] was probably the first to point out this discrepancy; he gave a better interpretation which did not make use of hybrization, and which we shall discuss in Section 4.

The lower values of λ are often explained by assuming that the production of the sp (or sp^2) configuration from the ground state of the central atom requires an excitation energy ($\varepsilon_p - \varepsilon_s$), with the result that the p-component in Equation (y) is smaller than predicted by Equation (d*); the transitition to the sp^3 state also requires an excitation energy. This gives rise to an energy principle which opposes postulate (2). At the same time, some uncertainty is introduced into the determination of the valence angle, since it is necessary to know the relationship between λ and the excitation energy. Estimates made in theoretical studies show [7] that this relationship can be represented by Equation (g*), where ε_D is

$$\lambda \approx (\varepsilon_p - \varepsilon_s)/\varepsilon_D \qquad (g^*)$$

the energy of dissociation of a bond partner from the central atom. Equation (g*) is obviously not connected with Equation (b*). The criterion of maximum overlap, which is involved in Equation (d*), is therefore not sufficient for a calculation of valence angles, as has already been pointed out by *Van Vleck* [8]. In agreement with the above considerations, it was found that both postulates (1) and (2) cannot be satisfied simultaneously even for CH_4, when small deviations of the H atoms from their equilibrium positions are considered.

The above discussion shows that, in addition to its ambiguity, the usual elementary form of the hybridization concept cannot be satisfactorily substantiated, and leads to contradictions. The value of this concept in chemical bonding is therefore doubtful. It is generally called upon only as an aid to the interpretation of experimental findings.

4. Wave-Mechanical Aspects

The determining factor here is the wave function Ψ, which depends on all the electronic coordinates (including the two possible electron spin directions, which are described by spin co-ordinates), and the square of which, $\Psi^*\Psi$, is proportional to the probability W of finding the electrons at the positions given by the chosen values of the electronic coordinates:

$$W \propto \Psi^*\Psi \qquad (h^*)$$

Each electron distribution ${\Psi_k}^*\Psi_k$ is associated with a certain energy ε_k ($k = 0, 1, \ldots$) of the system as a whole, which is a function of the positions of the atoms in space. In fact

$$\varepsilon_k = E_k + \Lambda, \qquad (k = 0, 1, 2\ldots) \qquad (k^*)$$

where E_k is the electronic energy and Λ is the repulsive energy of the positive atomic nuclei (charge $Z_\lambda e$;

$$\Lambda = \sum_{\lambda=1}^{N-1} \sum_{\mu=\lambda+1}^{N} \frac{e^2 Z_\lambda Z_\mu}{R_{\lambda\mu}} \qquad (l^*)$$

$\lambda = 1 \ldots N$), which is of the form (l*) for N atoms, where $R_{\lambda\mu}$ is the distance between the nuclei of atoms λ and μ. Ψ_k and the associated energy ε_k (or E_k) can in principle be determined as accurately as desired from the Schrödinger equation. Generally, however, it is sufficient to know the approximate values $\tilde{\Psi}_k$ and $\tilde{\varepsilon}_k$ for

[7] *K. Artmann*, Z. Physik *138*, 640 (1954).

[8] *J. H. van Vleck*, J. chem. Physics *1*, 209 (1933).

a discussion of bonding. Every conceivable fact about an atom or molecule can theoretically be found from Ψ^* and ε.

According to Equation (k*), a molecule generally has an infinite number of energy states ε_k, which should be regarded as a function of the bond length R (see Figure 8a). The electron energies E_k (Figure 8b) are described

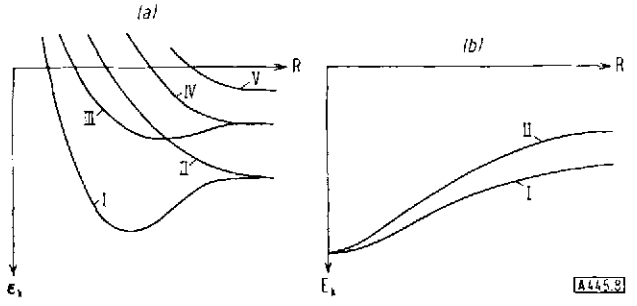


Fig. 8. Total energy ε_k and electronic energy E_k of a diatomic molecule, as functions of the interatomic distance R. Curves I, II, III, IV and V correspond to different values of k.

for $R \rightarrow 0$ as the energy $E_{UA}^{(k)}$ of a united atom, and for $R \rightarrow \infty$ as the energy $E_{SA}^{(k)}$ of the separated atoms. For example, as far as the electronic energy is concerned, the united atom of the H_2 molecule is the He atom. CH_4 corresponds to Ne when all the C–H distances tend to zero; if only one C–H distance tends to zero, the result corresponds to the NH_3 system.

It can be seen from Figure 8 that the repulsion of two atoms at short interatomic distances is not due to interpenetration of the "electron clouds" and the resulting mutual repulsion of the electrons. The repulsion is due only to the Λ term in Equation (k*), since E_{UA} is always smaller than E_{SA}.

The kinetic energy K of the electrons is found [9] with the aid of the virial theorem to be

$$K = -\varepsilon - R\frac{d\varepsilon}{dR'} \qquad (m^*)$$

Since in the case of bond formation there is an equilibrium distance $R = R_0$ such that, for $0 < R < \infty$,

$$\varepsilon(R_0) \leqslant \varepsilon(R) \qquad (n^*)$$

and

$$(d\varepsilon/dR)_{R=R_0} = 0, \qquad (o^*)$$

(cf. Figure 8, Curve I), we find from (m*):

$$K(R_0) = -\varepsilon(R_0) \qquad (p^*)$$

When $R \rightarrow \infty$, on the other hand, the second term in (m*) disappears to give:

$$K_{R\rightarrow\infty} = -\varepsilon_{R\rightarrow\infty} = -E_{SA} \qquad (q^*)$$

Because of the relationship (n*), a comparison of Equations (p*) and (q*) gives

$$K(R_0) > K_{R\rightarrow\infty} \qquad (r^*)$$

[9] *E.g. P. O. Löwdin*, Molecular Spectroscopy *3*, 46 (1959).

which is valid for all bonds, and which states that the kinetic energy of the electrons is higher in a bond. The total energy ε is equal to the sum of the kinetic energy K and the potential energy P of the total system, as expressed in Equation (s*). In general, therefore, the

$$\varepsilon = K + P \qquad (s^*)$$

potential energy of the entire system is so greatly reduced in any bond, that it more than compensates for the increase in the kinetic energy of the electrons.

An important factor in chemical bonding is the change in the energies ε as a function of the internuclear distances. Energy curves such as those shown in Figure 8a can intersect. It can now be shown that the overlapping of certain energy states is forbidden [10]. In this case, we may obtain Figure 9a, where the energy ε_1 corresponds to an excited state, since when $R \rightarrow \infty$, ε_1 is greater

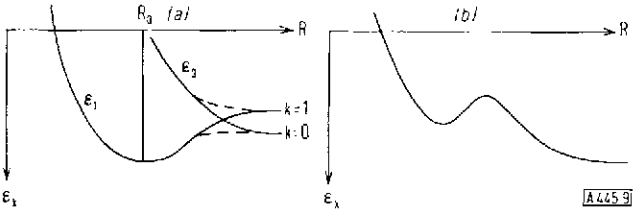


Fig. 9. (a): Change in the total energy for a bonding and a non-bonding state; overlapping forbidden.
(b): Energy curve for metastable systems (*e.g.* XeF).

than the energy of the ground state ε_0. At the "intersection", the curves follow the broken lines. Thus if we were to examine only the ground state, disregarding ε_1, there would be no bonding, since $\varepsilon_0 = f(R)$ does not have a minimum.

A similar situation is found *e.g.* in CH_4, when R is the C–H distance (all the C–H distances being regarded as equal). When $R \rightarrow \infty$, ε_1 corresponds to the energy of the system $C^* + 4\,H$, whereas ε_0 is the energy of the system $C + 4\,H$. Similar bonding relationships probably also prevail in the xenon fluorides: ε_1 corresponds to $Xe^{\oplus}$–$F^{\ominus}$, and ε_0 to Xe–F. If the ε_1 curve is higher, while still intersecting ε_0, metastable states can be formed, giving a lowest energy curve as shown in Figure 9b. This is the case in $He_2^{\oplus}$ or in the metastable systems formed by the rare gases Ne and Ar with fluorine or oxygen.

Knowing the potential energy curves (or the potential energy surfaces when more than two atoms are under consideration), we can calculate the vibrational and rotational states of the systems with the aid of wave mechanics. Reactions can also be examined, since these can be regarded as movements of a system on the energy surfaces. Thus the theories of reaction kinetics and spectroscopy are based on a knowledge of ε as a function of the distances between the atomic nuclei. The difference between a stable and a transient molecule can also be seen from the energy curves.

[10] *E.g. H. Hellmann*: Einführung in die Quantenchemie. Deuticke, Wien 1937, pp. 285–290.

For the molecule $M(C_5H_5)_2$, it would be feasible as an approximation to express the energy as the sum of the curves of the potential energy between the metal and each ring.

$$\varepsilon(H_5C_5\text{-}M\text{-}C_5H_5) \approx \varepsilon(H_5C_5\text{-}M) + \varepsilon(M\text{-}C_5H_5) \qquad (t^*)$$

The ε values on the right-hand side of Equation (t*) change as shown in Figure 8a, whereas the left-hand side is of the form shown in Figure 10 if the

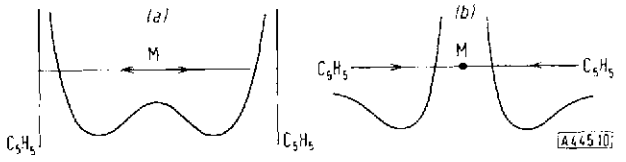


Fig. 10. Change in the course of the energy curve for a dicyclopentadienylmetal $M(C_5H_5)_2$, according to the masses of the partners.
(a) $m_M < m_{C_5H_5}$ (b) $m_M > m_{C_5H_5}$.

metal can move. We find that, under certain circumstances, the asymmetric position of the metal becomes understandable if the "potential peak" in the middle (Figure 10a) is sufficiently high and the vibrations of the molecule consist preferentially in the vibration of the metal. This can be the case only if the mass of the metal is small in comparison with that of the five-membered rings [*e.g.* in *(14)*]. If the metal atom is heavy, on the other hand, the vibrations will be essentially those of the rings, thus leading to the potential curve of Figure 10b; in this case the molecule should not be asymmetric, even if the two rings are identical in structure.

The chemical significance of potential energy surfaces has gained increasing recognition in recent years. Liquefaction and solidification are also connected with molecular interaction energies, the temperatures at which these processes occur being determined by the position and depth of the minima. The slight minimum in the potential energy curve of He...He, for example, causes the formation of condensation nuclei at very low temperatures.

There is no place for the hybridization concept in considerations involving the use of energy surfaces, unless several energy curves corresponding to different states of the central atom are being studied. More can be said about hybridization if we introduce the Ψ functions. In theoretical work, the approximation $\tilde{\Psi}$ is generally used instead of Ψ, constructed by a linear combination [Equation (u*)] of the Φ_j functions; the sum can repre-

$$\tilde{\Psi} = \sum_{j=i}^{M} C_j \Phi_j \qquad (u^*)$$

sent the accurate Ψ function when the number of Φ_j functions becomes very large ($M \to \infty$). The coefficients C_j are given by the requirement that $\tilde{\Psi}$ (for a fixed M) should be as close as possible to Ψ. (This requirement can be used, although Ψ itself is unknown). In this case, $\tilde{\varepsilon}$ is also an approximation to ε.

The functions Φ_j are generally expressed as determinants, which depend on one-electron functions χ_i

$$\Phi = \left| \chi_1(1)\begin{Bmatrix}\alpha\\\beta\end{Bmatrix}, \chi_2(2)\begin{Bmatrix}\alpha\\\beta\end{Bmatrix}, \ldots, \chi_n(n)\begin{Bmatrix}\alpha\\\beta\end{Bmatrix} \right| \qquad (v^*)$$

($i = 1, 2 \ldots$). It has been assumed in the expression (v*) that the system in question contains n electrons. α and β represent the spin functions for the two possible spin directions, which we shall indicate by $\uparrow$ (α) and $\downarrow$ (β). Equation (v*) satisfies one requirement imposed on Ψ, *i.e.* that only the sings of the wave functions should change when the coordinates of two electrons are interchanged (Pauli's principle).

It is demanded of the chosen χ functions that they should represent a complete system of functions, and that the integrals formed from them be defined.

Let us again consider BeX_2 as an example. This molecule may be regarded as a four-electron system, since for each bond there are two electrons situated inside the field of the remaining electrons. According to Figure 5, the two valence electrons of the Be occupy a 2s and a 2p state (φ_s, φ_p), so that two functions ψ_1 and ψ_2 must be formed according to Equation (y). The electrons of the two atoms X should occupy the orbitals φ_x and $\varphi_{x'}$. As an approximation to the wave function of BeX_2, we find:

$$\tilde{\Psi} = |\psi_1\alpha, \psi_2\alpha, \varphi_x\beta, \varphi_{x'}\beta| + |\psi_1\beta, \psi_2\beta, \varphi_x\alpha, \varphi_{x'}\alpha| - |\psi_1\beta, \psi_2\alpha, \varphi_x\alpha, \varphi_{x'}\beta| - |\psi_1\alpha, \psi_2\beta, \varphi_x\beta, \varphi_{x'}\alpha| \qquad (w^*)$$

(the derivation cannot be discussed in the present paper). According to Equation (y), λ has not yet been fixed, and is determined so that $\tilde{\Psi}$ is the best possible approximation to Ψ. Similarly the directions of φ_{p1} and φ_{p2} are still undecided, but the molecule is assumed in the first place to be linear, in order to simplify the calculations. One obtains $\lambda = 0.61$, and it is found, in accordance with Equation (x*), that ψ_1 and ψ_2 are not mutually orthogonal, as assumed in the hybridization theory [postulate (1) and Equation (a*)].

$$\int \psi_1^* \psi_2 d\tau = 0.40 \qquad (x^*)$$

Equation (x*) means that postulates (1) and (2) cannot be imposed if all the bonding electrons are taken into consideration. The same has been found for BX_3 and CH_4. More generally, we can say that the orthogonality requirement (1) is almost always a violation of the wave-mechanical treatment of the molecule. There are therefore no reasons for imposing condition (a*) on the functions (y). A wave-mechanical discussion of the valence angle shows that, *e.g.* in the case of BeX_2, an angular molecule is obtained if we admit only the λ values which agree with Equation (a*) [6, 7].

If, as a simplification, we assume the interatomic distances to be increased, so that to a close approximation only the central atom need be considered in relation to the valence angle, this atom is only slightly influenced by the outer atoms (separated atom model). For example, if we consider the C* atom of Figure 5, we can write

$$\tilde{\Psi} = |\varphi_s\alpha, \varphi_{p_x}\alpha, \varphi_{p_y}\alpha, \varphi_{p_z}\alpha| \qquad (y^*)$$

where p_x, p_y, and p_z denote the p functions in the x, y, and z directions.

If we now examine the probability W [cf. Equation (h*)] of finding electrons on a spherical surface surrounding the C atom, we obtain the remarkable result that the maximum probabilities for the four electrons occur at the corners of a tetrahedron, so that the outer atoms can best be accommodated in these directions [6, 7].

This result follows from the simple assumption that the four valence electrons are present in the sp^3 configuration, and is not restricted to the C atom. This procedure also gives the correct angles for the sp^2 and sp configurations. The maximum probabilities for the four electrons in the case of the sp^2d configuration occur at the corners of a square; this agrees with experimental results, *e.g.* for $[PdCl_4]^{2-}$.

It must be emphasized that the notation of Equation (y*) follows purely from Pauli's principle, and that no electrostatic effects among the electrons are involved; moreover, the concept of hybridization has not been used. The wave-mechanical procedure is therefore already superior to the elementary hybridization theory, particularly since it permits an unambiguous determination of the bond directions. If there are several configurations to be discussed, the potential energy curve for each configuration should be derived from these calculations, paying attention to forbidden overlapping. One reason why the usual concept of hybridization is unsatisfactory is that partial wave functions are used.

The procedure indicated in Equation (v*) may be carried further, in order to obtain a better approximation to Ψ. For example, the Ψ function of He is known with very great accuracy. The most probable distribution of the electrons on the surface of a sphere surrounding the helium atom, as shown in Figure 11, is that of case (a).

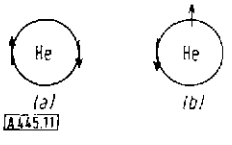


Fig. 11.

In the case of the Xe atom, the most probable distribution is that of Figure 12, if we consider the p^6 configuration of the ground state. On the approach of another atom whose electron affinity is comparable with the ionization energy of Xe (*e.g.* F or O), this new atom can

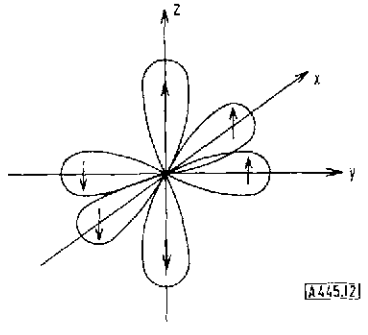


Fig. 12. Most probable distribution of electrons in the xenon atom (p^6 state).

attract a p-electron to itself, so that a bond is formed. The bonding in XeF_2, XeF_4, and XeF_6, which are reported to have linear, square, and octahedral structures respectively, could be of this type.

These greatly simplified considerations on the xenon fluorides show that the electronegativity as defined in Equation (e) can be used for a rough treatment. However, the detailed situation can only be correctly represented by the wave-mechanical calculations involving Ψ and ε. A number of wave-mechanical points have already been taken into account in Figures 11 and 12.

As was pointed out above, we must seek a $\tilde{\Psi}$ which closely approaches Ψ. When M is small the expressions corresponding to Equation (u*) are somewhat arbitrary as regards the choice of the Φ_j functions. In the valence-bond method, the Φ_j functions are sometimes identified with particular structures. Such a procedure is dubious, however, since we do not always know the part played by the structures which have been omitted. It is only when a large number of Φ_j functions (all, if possible) are considered, that we can assign a certain significance to the C_j values obtained. It must be remembered that the Φ_j functions do not occur in the molecule, since they do not describe a stationary state of the system. In this interpretation, therefore, the Φ_j functions have an imaginary character; consequently, the resonance energies which are often calculated in this connection are also without absolute significance, since these depend on the Φ_j functions chosen. Since the only important point is $\tilde{\Psi}$, it is possible to use entirely different Φ_j systems, provided that they represent the exact Ψ functions when $M \to \infty$. In other words, a picture of chemical bonding is only admissible if it is based on adequate wave-mechanical foundations. An example of what we mean is the remark which is sometimes made, that antiparallel electron spins in different atoms lead to bonding. This is not, however, the reason for chemical bonding, but the fact that the spins are antiparallel is a characteristic of a special type of bond.

Finally, from $\tilde{\Psi}$ and the integral

$$\int \Psi^* \begin{Bmatrix} x_1 + x_2 + \cdots x_n \\ y_1 + y_2 + \cdots y_n \\ z_1 + z_2 + \cdots z_n \end{Bmatrix} \Psi d\tau \qquad (z^*)$$

for a system containing n electrons, the coordinates of the center of negative charge can be determined, which can provide information on dipole moments. It should be noted, however, that this center of charge must be correlated with that of the positive nuclear charges. Thus, the relationship between the dipole moment and Ψ is not mathematically simple. There is no relationship between the dipole moment and the difference in the electronegativities of the bonded atoms. An example is carbon monoxide, for which there is a strong tendency to attach considerable importance to the structure $C^{\ominus} \equiv O^{\oplus}$, particularly since CO is very similar to N_2; however, the dipole moment of CO is very small.

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Progress in the Chemistry and Molecular Biology of Flavins and Flavocoenzymes [1]

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An attempt is made to create a basis for the understanding of flavin- (Vitamin B_2-) dependent oxidations in terms of molecular structure. The main points of this survey can be summarized as follows: a) The flavins must be differentiated according to their redox states (quinone state, radical state, hydroquinone state), since configuration, energy content of the tautomeric forms, metal affinity etc., alter drastically during reduction. – b) The methyl group on C–8 of the flavoquinone is reactive. – c) The electron transfer properties of the flavin system frequently depend on the coupling of secondary redox systems to the apoprotein. This interaction thermodynamically stabilizes the half-reduced state of the flavin. – d) Numerous novel flavin types, among them stabilized free radicals, have become available through syntheses at the dihydro stage. – e) Reaction of the flavin radical with O_2 is slow as long as no disproportionation occurs, i.e. the fast flavin autoxidation proceeds via the dihydro state. – f) The flavin nucleus gains affinity for heavy metal ions only by the acceptance of one, and only one, electron. – g) Redox activity and contact with the flavin coenzyme have been confirmed for Fe and Mo, which occur in flavoproteins. The properties of the metal coordination sphere are determined primarily by sulfur-containing groups of the apoprotein.

I. Introduction

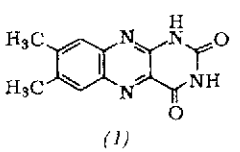
1. Definition and Nomenclature of the Flavins

Flavin is the trivial name of the chromophoric, redox-active prosthetic group of a class of respiratory enzymes occurring widely in animals and plants, *i.e.* the flavoproteins. The flavin group forms part of the flavocoenzyme, a non-protein, low molecular-weight sub-unit, which is linked with the apoprotein (cf. Section VI,1). The two known flavocoenzymes are called flavin nucleotides (FMN = flavin mononucleotide, FAD = flavin adenine dinucleotide, Scheme 1), although this term is inapt, since the flavin is not held by a glycosidic linkage in the flavocoenzymes.

Acid hydrolysis therefore leaves the polyhydroxy substituent on the flavin nucleus intact, and leads to riboflavin. This compound is the oldest known flavin derivative (*Warburg* and *Christian* 1932) [3] and was initially termed lactoflavin (vitamin B_2).

Unlike FAD, riboflavin and FMN are light-sensitive in dilute solution (cf. Section II,2). Flavin is a redox system which on absorption of light dehydrogenates its own hydroxylic side chain. This irreversible process ("photolysis") can be prevented by addition of exogenic electron donors, *e.g.* tertiary amines, which are more easily attacked (dehydrogenated) by the light-activated flavin (triplet state) so that merely a "photoreduction" (reversible with O_2) takes place.

Photolysis under acidic or neutral conditions is a special case of the N–10 dealkylation which is characteristic of all flavins (cf. Section II,2). The product of this reaction, lumichrome *(1)*, has no flavin properties. Under alkaline conditions photolysis does not lead to dealkylation; rather the side chain is degraded until only a methyl group is left. The simplest flavin compound, lumiflavin *(2)*, obtained in this way resembles the native coenzyme in its spectral, acid-base, and redox properties. Lumiflavin was the first flavin to be synthesized (*Kuhn* and *Weygand*, 1934) [4].



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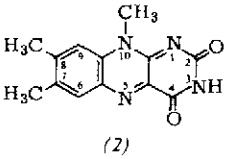


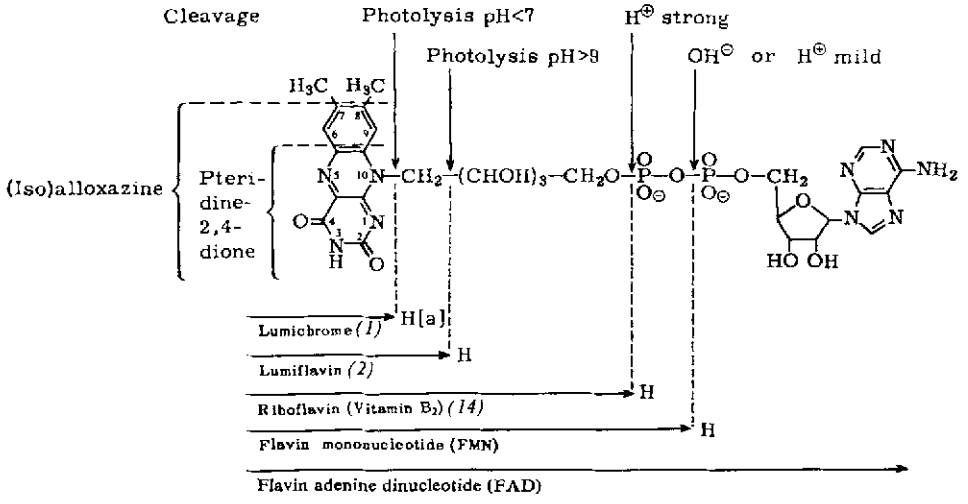
(2)

[1] Only selected references can be given here. For complete coverage, the reader is referred to more extensive reviews, such as *P. D. Boyer, H. Lardy*, and *K. Myrbäck*: The Enzymes. Academic Press, New York-London, Vol. II, 1960, p. 360, Vol. VII, 1963; *v. Massey* and *C. Veeger*, Annual Rev. Biochem. *32*, 553 (1963); see also [2].

[2] *P. Hemmerich* in: Mechanismen enzymatischer Reaktionen. 14. Mosbacher Colloquium der Ges. f. Physiologische Chemie, Springer-Verlag, Heidelberg 1964, p. 183; *C. Veeger*, ibid. p. 157.

[3] *O. Warburg* and *W. Christian*, Naturwissenschaften *20*, 688 (1932).

[4] *R. Kuhn* and *F. Weygand*, Ber. dtsch. chem. Ges. *67*, 1409 (1934).



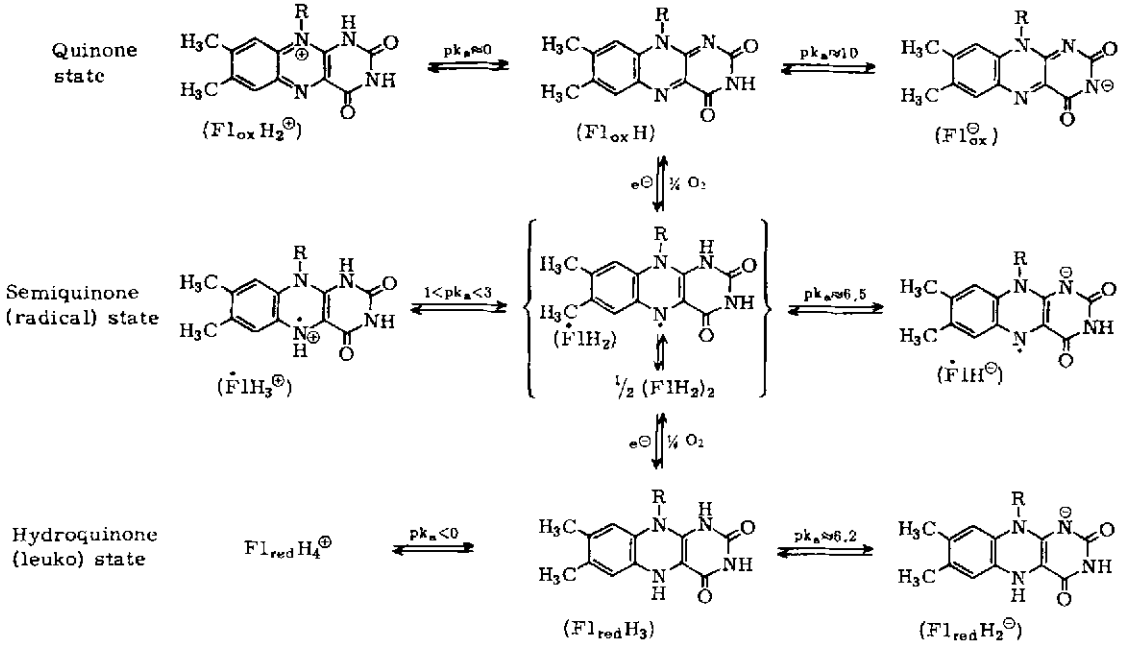
Scheme 1. Flavin nomenclature. — [a] The hydrogen is on N-1.

This synthesis started from alloxane and therefore the name "isoalloxazines" was assigned to the flavins [5]. We prefer the name benzopteridines. This nomenclature is justified by the biosynthesis of these compounds (cf. Section III,2) which proceeds *via* pteridine; at the same time it shows the relationship among flavins, folic acid, and the purines. In the following, the designation "flavins" is taken to mean 10-alkylated 2,4-diones with a benzopteridine skeleton, *e.g.* lumiflavin *(2)*.

Lumichrome *(1)*, the product of the N–10 dealkylation of flavin, is the prototype of a separate class of compounds, *i.e.* the alloxazines. The reverse reaction, *i.e.* the formation of flavins from lumichrome by alkylation, is not feasible. The 10-alkylation of alloxazines found by *Stern* and *Holiday* [6] can be conducted only at temperatures at which the opposite reaction ensues. Methylation therefore proceeds to an equilibrium in which a few percent of lumiflavin is present in addition to lumichrome.

The oxidoreduction of the flavins is thermodynamically reversible, irrespective of whether one or two electrons per flavin molecule are being transferred. Thus flavin fulfils the criteria of a "quinoid" redox system. The chemical properties of the flavin species which is stable under aerobic conditions are frequently taken to be representative of the entire system. However, the chemistry of the reduced, autoxidizable flavin species is entirely different. For this reason, a differentiation of the flavin oxidation states is required (Scheme 2 and Table 1).

In addition, each of the three redox states of flavin is amphoteric, although the "isoelectric intervals" extend over wide pH ranges. A total of at least nine monomolecular flavin species can be distinguished, *i.e.* one cation, one neutral species, and one anion in each redox state. We shall use the abbreviations shown in Scheme 2, *i.e.* in particular "flavoquinone" for the air-stable form, "flavosemiquinone" for the radical form, and "flavo-



Scheme 2. The flavin redox system. Occurrence of the flavin species as a function of pH and redox state.

[5] *R. Kuhn* and *H. Cook*, Ber. dtsch. chem. Ges. *70*, 761 (1937), were the first to criticize the isoalloxazine nomenclature. Although "flavin" may be confused with "flavone" or "flavan", the compounds named by these terms are so different that serious misunderstandings are unlikely.

[6] *K. G. Stern* and *E. R. Holiday*, Ber. dtsch. chem. Ges. *67*, 1442 (1934).

Table 1. Absorption data of the flavin species in Scheme 2.

Compound	λ_{max} [mμ]
$Fl_{ox}H_2^{\oplus}$	390, 264, 222 [a]
$Fl_{ox}H$	446, 370, 270, 230 [b]
$Fl_{ox}^{\ominus}$	444, 350, 270, 230 [c]
$\dot{F}lH_3^{\oplus}$	488, 358, 258 [a]
$\dot{F}lH_2$	622, 590 (sh) [d], 570 [b]
$\dot{F}lH^{\ominus}$	612? [g]
$Fl_{red}H_4^{\oplus}$	316, 250 [a]
$Fl_{red}H_3$	ca. 400 (sh), ca. 280 (sh), 250 [e]
$Fl_{red}H_2^{\ominus}$	ca. 350 (sh), 288, 256 [f]
$^1/_2\,(FlH_2)_2$	>800 [b]

[a] In 6 N HCl. [d] In $CHCl_3$.
[b] In phosphate buffer, pH 7.0. [e] In sulfate buffer, pH 2.0.
[c] In 2 N NaOH. [f] In borate buffer, pH 9.0.
[g] In $CHCl_3$ containing 2×10^{-2} M Triethylamine.
sh = shoulder.

hydroquinone" for the completely reduced form. The synonym "leucoflavin" is intentionally avoided, since flavohydroquinone is colorless only in very dilute solution; under certain conditions it may be even more intensely colored than flavoquinone (cf. Section IV,5). In concentrated aqueous solutions flavin molecular complexes occur (cf. Section IV,8); here "flavoquinhydrone" $(FlH_2)_2$ is the prototype. "Intermediate valences" can occur in these complexes but there is no evidence that such "sandwich" structures are biochemically important.

2. Function of Flavin in Flavoproteins

Two main groups of flavoproteins can be distinguished. One contains iron (and sometimes also molybdenum) as an essential cofactor, while the other is independent of metals.

The "teleological" question as to the function of the iron cannot yet be answered with certainty. In no instance has it been possible to separate the metal (or the flavin) from iron flavoproteins without irreversible deactivation. Further, it is certain that flavin and iron belong to the same active center and are in direct contact with one another (cf. Section VI,5). For this reason the problem of the flavin-metal interaction is of fundamental importance.

Flavoproteins of both groups [7], like the free coenzymes [7a], are able to react with their substrates in a two-electron process, which is evidently independent of the metal. Since this reaction is not always accompanied by proton exchange with the medium, one may talk formally of a "hydride transfer". The electrons accepted by the flavin can then be transferred further, either simultaneously, as a "hydride equivalent", or successively, in the form of two radical electrons and a proton.

[7] *Ph. Strittmatter*, J. biol. Chemistry *237*, 3250 (1962); *O. Gawron, A. J. Glaid, J. Francisco*, and *T. P. Fondy*, Nature (London) *197*, 1270 (1963): Hydrogen transferred to flavoprotein is inactive. This is surprising in view of the fact that it must be bound to N–5 of the flavin. Model compounds are being prepared in order to determine whether the inactivity of the hydrogen atom at N–5 is caused by the enzyme protein or can be found in the free coenzyme as well.

[7a] *C. H. Suelter* and *D. E. Metzler*, Biochem. biophysica Acta *44*, 23 (1960).

The latter reaction requires stabilization of the half-reduced state of the flavin, for example by complex formation with a heavy metal (cf. Section V,2), by coupling with a secondary redox system of suitable potential (*e.g.* 2 RSH $\rightleftharpoons$ $(RS)_2$; cf. Section IV,4), or by coupling with a second flavin molecule.

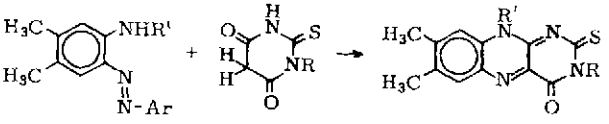
A survey of the substrates [dihydropyridine nucleotides, succinate, dihydrolipoamide, acyl-CoA, aldehyde (glucose), azomethines (purines), and amino acids] reveals that in contrast to the pyridine nucleotide dependent enzymes, the flavoproteins can attack only activated X–H bonds. It is further significant that flavohydroquinone reacts extremely rapidly with O_2 to form H_2O_2. Very probably, this reaction does not involve a radical intermediate but proceeds directly to H_2O_2 in a two-electron step (cf. Section IV,6).

Flavoproteins thus occupy a key position in the metabolism of all respiratory organisms. The manifold nature of the phenomena in the biochemistry of flavoproteins has made it difficult to describe these reactions in terms of molecular mechanisms. It is the aim of this article to provide a bridge between the chemistry and biology of the flavin group.

II. Synthesis and Breakdown of the Flavin Nucleus

1. Advances in Flavin Synthesis

The classical flavin synthesis [4] from aromatic *o*-diamines and alloxane by *Kuhn* and *Weygand*'s method is of very limited applicability, since even the simplest functional derivatives of alloxane are hardly accessible. In addition, alloxane derivatives behave as oxidizing agents towards phenylenediamines, so that the yields are rarely satisfactory. The process of *Tishler et al.* [8], in which an azo group is split by a carbanion, is similarly limited; 2-thiobarbituric acid *(3)* is the only functional derivative of barbituric acid which can be used to give an acceptable yield [9]. The *S*-methyl derivative of *(3)* does not react.



(3) R = H, CH_3

For this reason, despite many experiments [10] no flavins with altered functions at C-2 or C-4 were known up to 1956, although it was established by that time that the natural purines are flavin precursors [11]. If natural flavin is regarded as a xanthine analogue, then syntheses and properties of "(iso)-guanine-analogous flavins" *[(4)*; X,Y = O, NH] and of flavins with strictly monovalent substituents at C-4 [*e.g. (4a)*] are of interest.

In the two flavin syntheses mentioned above, N–5 and N–10 of the flavin nucleus are introduced by the homoaromatic component. The reverse path, which is the

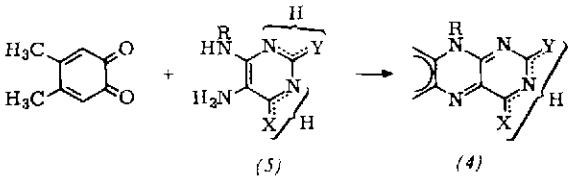
[8] *M. Tishler, K. Pfister, R. D. Babson, K. Ladenburg*, and *A. J. Fleming*, J. Amer. chem. Soc. *69*, 1487 (1947).

[9] *P. Hemmerich, S. Fallab*, and *H. Erlenmeyer*, Helv. chim. Acta *39*, 1242 (1956).

[10] *G. H. Hitchings*: Chemistry and Biology of Pteridines (Ciba-Foundation Symposium). Churchill. London 1954, p. 121.

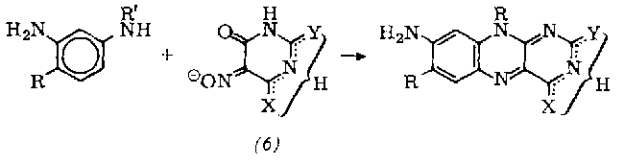
[11] *W. S. McNutt*, J. Amer. chem. Soc. *83*, 2303 (1961).

natural one (cf. Section III), was followed by *Creswell et al.* [12], who for the first time prepared 4-alkylamino-5-amino-pyrimidines *(5)* and treated them with *o*-xyloquinone.



(5) *(4)*

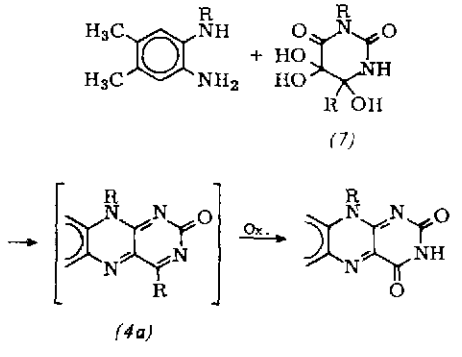
This synthesis suffers from the sensitivity of both starting components and their tendency to autocondensation, and from the equivalence of the carbonyl functions, which in the case of asymmetrically substituted quinones leads to the formation of isomer mixtures. These difficulties are avoided by the condensation of 5-nitrosopyrimidones *(6)* with aromatic *m*-diamines [13].



(6)

The second donor function in the benzene nucleus, which unfortunately is a prerequisite for the synthesis, must be subsequently removed. In the analogous reaction of 4-alkylamino-5-nitrosopyrimidines with phenols, a second donor function would not be absolutely necessary since the *o*-position of a phenoxide is sufficiently activated for attack by the nitroso group. To the best of our knowledge, no such reaction has so far been studied.

Replacement of alloxane in *Kuhn* and *Weygand*'s synthesis by "isodialuric acids" *(7)* should lead to "desoxo"-flavins *(4a)* with H or alkyl on C-4. However, only 2,4-dioxo products, *i.e.* "normal" flavins, could be obtained [14].



(7) *(4a)*

This was the first indication of the instability of strictly monovalent groups at C-2 and C-4 of the flavin nucleus. The *de novo* synthesis of such flavins was not followed further, since they had meanwhile become accessible by other routes (cf. Section IV).

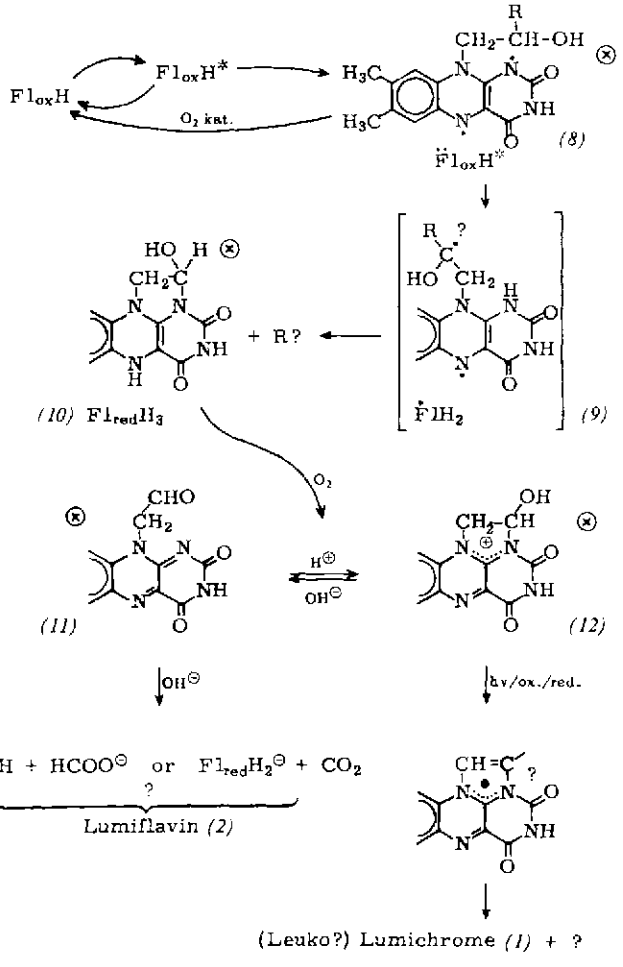
[12] *R. M. Cresswell, Th. Neilson,* and *H. C. S. Wood,* J. chem. Soc. (London) *1961*, 476.

[13] *P. Hemmerich, B. Prijs,* and *H. Erlenmeyer,* Helv. chim. Acta *42*, 1604 (1959).

[14] *P. Bamberg, P. Hemmerich,* and *H. Erlenmeyer,* Helv. chim. Acta *43*, 395 (1960).

2. The Breakdown of Flavin

As already mentioned, it is appropriate to distinguish between flavin photolysis and flavin dealkylation. The course of riboflavin photolysis, unresolved for decades, has recently been essentially clarified [15–17] (Scheme 3).



Scheme 3. Flavin breakdown. The abbreviations denote the redox state of the flavin nucleus but not that of the side chain. The stages marked with ⊗ have been confirmed.

Photolysis occurs only in those flavins which contain a >CHOH group in the 2′-position. The C–H bond of this group is split by the flavoquinone triplet state *(8)* [17], with one electron passing to the flavin nucleus along with the proton (confirmed by the deuterium effect, cf. [15]). The resulting flavosemiquinone *(9)* has been identified (flash photolysis, cf. [18]). How the second unpaired electron is primarily stabilized in the side chain remains to be investigated. In the absence of O_2, the next product [*] is a flavohydroquinone *(10)* which is irreversibly [15] oxidized to formyl-lumiflavin *(11)* (identical with the product of periodate degradation of riboflavin, cf. [16]). The irreversibility of this oxidation is explained by the equilibrium *(11)* ⇌ *(12)*, which is displaced to the right in the reduced state. Similar 1-alkylflavins have been obtained as flavoquinonium perchlorates (cf. Section IV).

[15] *W. M. Moore, J. T. Spence, F. A. Reymond,* and *S. D. Colson,* J. Amer. chem. Soc. *85*, 3367 (1963).

[16] *E. C. Smith* and *D. E. Metzler,* J. Amer. chem. Soc. *85*, 3285 (1963).

[17] Review: *B. Holmström,* Ark. Kemi *22*, 329 (1964).

[*] The second flavin occurring upon photolysis was termed "deuteroflavin". Use of this name should be avoided, however, because of its similarity to "deuterioflavin".

[18] *B. Holmström,* Bull. Soc. chim. belges *71*, 869 (1962).

With $OH^{\ominus}$, *(11)* reacts to form lumiflavin *(2)*. Whether this reaction is purely hydrolytic (haloform reaction), *i.e.* whether it proceeds with quantitative liberation of formate, is not yet known. Because of its aldehyde group, *(11)* is even more photolabile than riboflavin in neutral solution. The formylmethyl side chain is completely eliminated by air, and more rapidly by peracetic acid. Flavin-10-acetic acid could not be obtained as an intermediate [19]. The aldehyde *(11)* can also be dealkylated reductively, *e.g.* with zinc and acid, provided that sufficient O_2 is present to maintain the flavosemiquinone state [19]. In general, each substituent at N-10 of flavosemiquinone, $\dot{F}lH_2$, can be eliminated under weakly acidic or neutral conditions [20]. While photolysis represents a disproportionation of the flavoquinone triplet state *(8)* (the side chain is dehydrogenated, the nucleus reduced), dealkylation represents a (thermal) decomposition of the flavosemiquinone, which presumably proceeds according to a fragmentation mechanism [21]. The nature of the fragments formed from the substituent at N-10 will have to be elucidated using model compounds.

The photoreduction, *i.e.* the reversible photocatalysed "substrate" dehydrogenation by flavin is entirely independent of the nature of the side chain [17], but may be strongly influenced by agents which bring about a change in the energy content or life-time of the flavoquinone triplet state, *e.g.* by paramagnetic co-solutes (O_2, heavy metal ions) or by agents forming charge transfer complexes (cf. Section IV, 8).

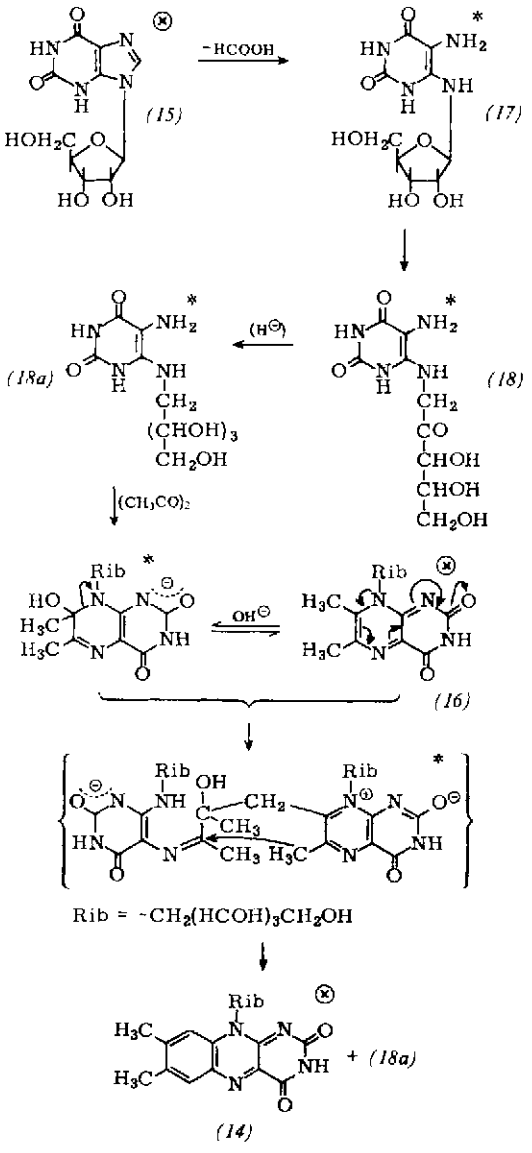
III. Flavin Biosynthesis

1. Synthesis of Riboflavin from Pteridine Precursors

The essential steps of flavin biosynthesis have been elucidated during the past few years, particularly by the studies of *McNutt* [11,22], *Masuda* [23], and *Plaut* [24]. In this article, the biosynthesis will be discussed only insofar as it contributes to the understanding of flavin chemistry (Scheme 4).

The nitrogen atoms of natural riboflavin *(14)* are derived from purine nucleotides *(15)* [25–27], while the dimethylbenzene part is built up from C_2-fragments (diacetyl or acetoin) originating from pyruvate. An important advance was the isolation from *Eremothecium ashbyii* [28,29] of an intermediate which proved to be 6,7-dimethyl-8-D-ribityllumazine *(16)*.

Surprisingly, the enzymatic transformation of this pteridine *(16)* into riboflavin requires no further carbon source. Hence compound *(16)* acts as both donor and acceptor of a C_4-fragment.



Scheme 4. Biosynthesis of riboflavin *(14)*. ⊗: confirmed stages; *: intermediates proposed from model reactions.

Experiments with model compounds [30] showed that "quinoid" 8-alkylpteridones [31], for example *(16)*, readily take up $OH^{\ominus}$ at C-7 under the influence of chelating metal ions even at neutral pH (cf. Section V, 1), so that the pyrazine ring closure is reversible in such pteridines. On the other hand, hyperconjugated CH_3 groups of strongly electron-deficient heteroaromatic compounds readily undergo aldol-like condensations, so that the route from *(16)* to riboflavin requires little additional activation. Thus, *Rowan* and *Wood* [32] obtained riboflavin *(14)* by non-enzymatic reaction of *(16)* in an aqueous phosphate buffer at pH 7.3, in 56 % yield.

2. Biosynthesis of the Precursor Pteridine *(16)*

Studies of the biosynthesis of pteridines indicate that the following reactions contribute to the transformation of the ribosyl group of the precursor purine into the ribityl group of flavin:

[19] *F. Müller* and *P. Hemmerich*, unpublished work; *D. E. Metzler*, personal communication.

[20] *P. Hemmerich, B. Prijs*, and *H. Erlenmeyer*, Helv. chim. Acta *43*, 372 (1960).

[21] Cf., for example, *C. A. Grob*, Experientia *13*, 126 (1957).

[22] *W. S. McNutt*, J. biol. Chemistry *210*, 511 (1954); *219*, 365 (1956).

[23] *T. Masuda*, Chem. pharmac. Bull. (Tokyo), *4*, 71, 375 (1956); *5*, 28 (1957).

[24] Review: *G. W. E. Plaut*, Annual Rev. Biochem. *30*, 409 (1961).

[25] *A.J. Birch* and *C.J. Moye*, J. chem. Soc. (London) *1957*, 412.

[26] *G. W. E. Plaut*, J. biol. Chemistry *211*, 111 (1954).

[27] *T. W. Goodwin* and *D. H. Treble*, Biochem. J. *70*, 14P (1958).

[28] *T. Masuda, T. Kishi, M. Asai*, and *S. Kuwada*, Chem. pharmac. Bull (Tokyo) *7*, 361 (1959).

[29] *G. F. Maley* and *G. W. E. Plaut*, J. biol. Chemistry *234*, 641 (1959).

[30] *T. Rowan, H. C. S. Wood*, and *P. Hemmerich*, Proc. chem. Soc. (London) *1961*, 260.

[31] *W. Pfleiderer* and *G. Nübel*, Chem. Ber. *93*, 1406 (1960).

[32] *T. Rowan* and *H. C. S. Wood*, Proc. chem. Soc. (London) *1963*, 21.

(a) Opening of the imidazole ring in adenosine *(15)*.

(b) Amadori rearrangement of the 5-amino-4-ribosylaminopyrimidine *(17)*.

(c) Reduction of the keto sugar *(18)*.

As regards (a), it is known that purines can be hydrolysed at C-8 by weak alkali after blocking the electron pair at N–7 by alkylation [33, 34] or (for enzymatic reactions) by coordination of metal ions or hydrogen bonding to N–7. With regard to (b), a mechanism like the one postulated by *Micheel* and *Dijong* [35] for the Amadori rearrangement of simple glycosylamines (intermediate formation of a 1,1-diamine) can be assumed. For (c), *Neilson* and *Wood* [36] were able to show that the reduction of a pyrimidylaminopentulose of type *(18)* proceeds stereospecifically even *in vitro*, which is ascribed to a specific conformation of the pyrimidyl residue and the side chain.

3. Substrate Specificity in the Biosynthesis of Flavocoenzymes

The search for flavin antimetabolites has so far met only with little succes. Biological effects achieved with riboflavin analogues were traced back to an inhibition of the flavocoenzyme synthesis but not of the flavocoenzyme function [38–40]. The correct ribityl side chain is required for both flavin synthetase [37], which catalyses the reaction *(16)* → *(14)*, and flavokinase [38], which transforms riboflavin into its 5'-phosphate by means of ATP. Surprisingly, even the slightest modification of the heteroaromatic nuclei abolishes the substrate function for flavin synthetase and even for flavokinase, although the kinase reaction seems not to concern the heteroaromatic system. This leads to the conclusion that, contrary to expectation, the flavin nucleus does participate in the kinase reaction. In any case, it follows that the inhibition of the flavin-dependent respiration by FMN analogues can only be tested if these have previously been phosphorylated. A flavin enzyme which can be reversibly split into FMN and apoprotein [39], *i.e.* the NADPH-cytochrome-c-oxidoreductase from yeast, has already been investigated.

The biosynthesis of FAD from FMN is not very substrate-specific [40], *i.e.* other flavin purine dinucleotides can also be prepared enzymatically. Further studies in this direction should help to elucidate the role of the adenosine moiety in FAD.

[33] *J. A. Haines, C. B. Reese,* and *Lord Todd,* J. chem. Soc. (London) *1962*, 5281.

[34] *L. B. Townsend* and *R. K. Robins,* J. Amer. chem. Soc. *85*, 242 (1963).

[35] *F. Micheel* and *J. Dijong,* Liebigs Ann. Chem. *658*, 120 (1962).

[36] *T. Neilson* and *H. C. S. Wood,* J. chem. Soc. (London) *1962*, 44.

[37] *C. H. Winestock, T. Aogaichi,* and *G. W. E. Plaut,* J. biol. Chemistry *238*, 2866 (1963).

[38] *D. B. McCormick, C. Arsenis,* and *P. Hemmerich,* J. biol. Chemistry *238*, 3095 (1963).

[39] *C. Arsenis* and *D. E. McCormick,* Biochim. biophysica Acta *92*, 440 (1964).

[40] *D. B. McCormick, B. M. Chassy,* and *J. M. C. Tsibris,* Biochim. biophysica Acta *89*, 447 (1964).

IV. Structural Chemistry of the Flavin Nucleus

1. Nucleophilic Substitution

Nucleophilic attack at a flavoquinone does not lead to substitution. Reactions at the carbonyl groups under solvolytic conditions lead to opening of the strongly electron-deficient pyrimidine ring. Solvolysis is always accompanied by a reaction at the C–8 methyl group (cf. Section IV,2). Under non-solvolytic conditions this last reaction is the predominant one. Therefore, reactions with phosphorus halides in tertiary amines are not possible with flavoquinone.

The introduction of sulfur with P_4S_{10} is an exception, but here a reduction initially takes place [41]. Flavoquinone is quite generally reduced by sulfides (thiolates), although only slowly [42]. The flavohydroquinone formed can then react with P_4S_{10}, the sulfur entering selectively at C–4 (cf. Scheme 5); a similar reaction occurs in the purine and pteridine series [43].

Nucleophilic substitutions are possible with flavoquinones in which the 2- (or 4-) positions has been activated. Two methods are available: (a) the (indirect) alkylation of the carbonyl oxygen with intermediate formation of the "active" flaviniminol esters (Section IV,3) and (b) nucleophilic replacement of the "active" sulfur in 2-thioflavins *(28)* (cf. Section II,1) and 4-thioflavins *(30)* [44] (see above). The thioflavins have a thioquinone rather than thioamide character, and hence react even at room temperature with carbonyl reagents to form oximes, hydrazones, or azines of flavoquinone [*(26)*, *(31)*, X = OH, NH_2, or N = CHAr]. These deep-violet to blue derivatives can generally be isolated only in the form of their orange-yellow to brownish-red salts. The free bases gradually disproportionate in solution, particularly under the influence of light, with dehydrogenation of =NOH or $=NNH_2$ and reduction of the flavin nucleus. In the presence of oxygen the reaction ultimately leads back to unsubstituted flavoquinone. The thioflavins *(28)* and *(30)* are similarly sensitive and are slowly desulfurized by autoxidation even at room temperature.

S-Methylation of the thioflavins *(28)* and *(30)* is possible under very mild conditions (cf. Section IV,3). The resulting "flaviminol thioesters" *(25)* and *(27)* react also with weakly nucleophilic reagents such as primary and secondary amines [cf. Scheme 5, *(19)*, *(24)*], but not easily with ammonia [*(33)*]. The NH_2 group can, however, be introduced *via* hydrazones [*(26)*, *(31)*; X= NH_2] and reduction with $SnCl_2$.

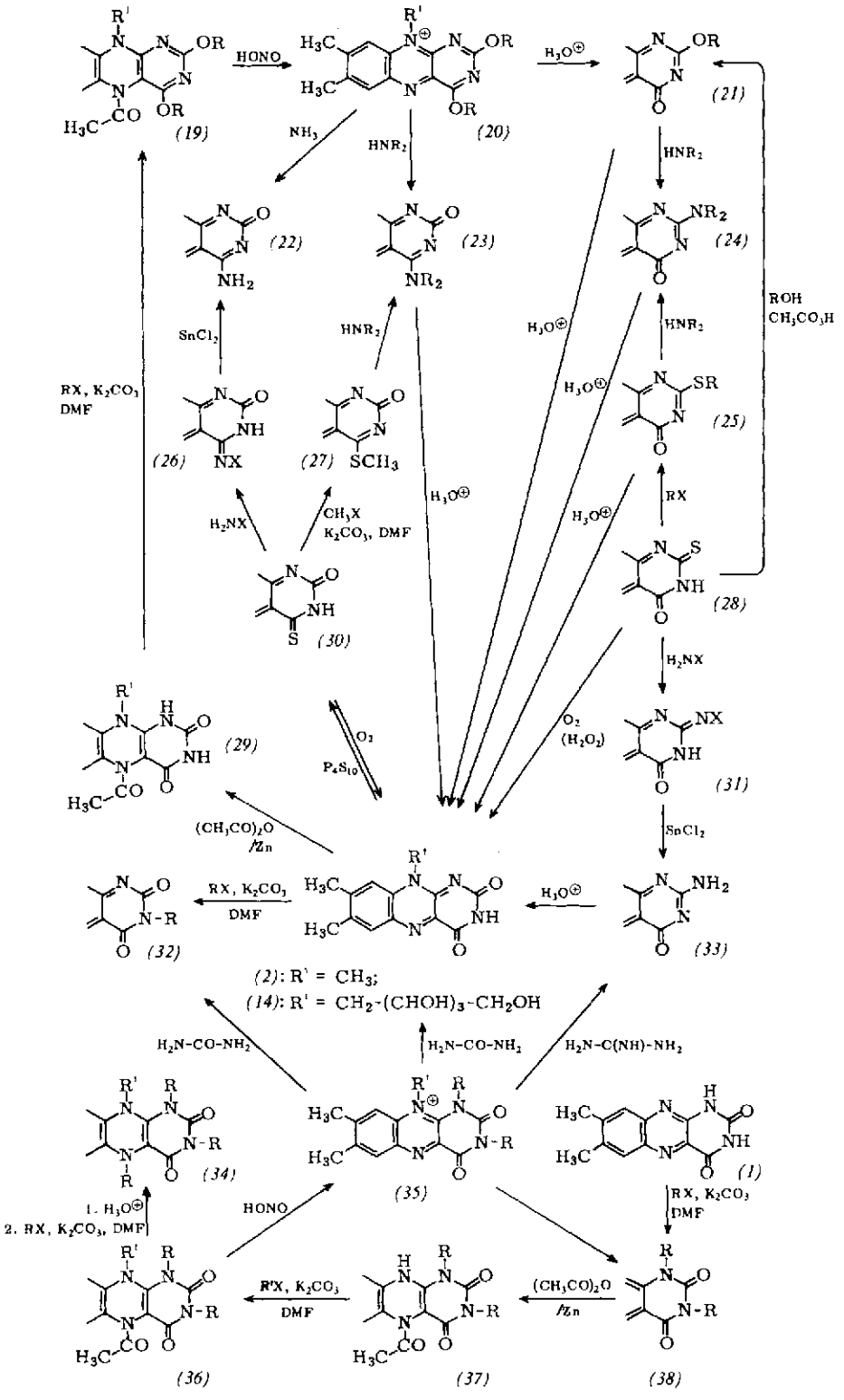
Monovalent substituents at C–2 or C–4 of flavoquinone, which cannot be oxidized, can be readily removed by hydrolysis, some even in neutral aqueous solution (cf. Section IV,3), *e.g.* in *(27)* and *(20)*.

[41] *P. Hemmerich* and *H. Erlenmeyer,* Helv. Chim. Acta *40*, 187 (1957).

[42] *Ph. Ellinger* and *W. Koschara,* Ber. dtsch. chem. Ges. *66*, 1411 (1933).

[43] *A. G. Beaman,* J. chem. Soc. *76*, 5633 (1954).

[44] *F. Müller, P. Hemmerich,* and *H. Erlenmeyer,* Experientia *18*, (1962); *P. Hemmerich* and *F. Müller,* unpublished work.



Scheme 5. Substitution reactions at the flavin nucleus.

2. Reactions of the C-8 Methyl Group

Similarly to vitamin K and ubiquinone [45], flavoquinone has a methyl group whose reactivity has received little recognition in the past. There are, however, flavoquinones, *i.e.* salts of type *(20)*, which irreversibly dimerize to form the diradicals *(40)* even at pH 7 and room temperature, even before the very sensitive iminol ester functions have had time to undergo hydrolysis [46]. An irreversible disproportionation is involved, in which the substituent is oxidized while the nucleus is reduced (as in photolysis).

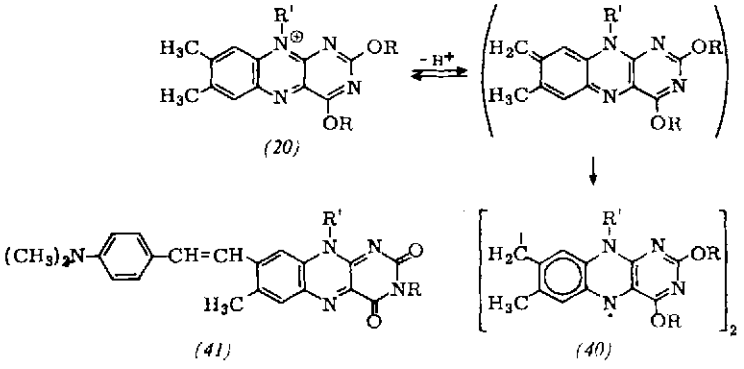
The diradicals *(40)* react with excess flavoquinone or O_2 to form "diflavoquinones". The same reaction occurs in the case of unsubstituted flavoquinones, *e.g.* riboflavin, under strongly basic, non-solvolytic conditions [$HCON(CH_3)_2/(CH_3)_3COK$ or CH_3OH/BaO] or with weak bases (K_2CO_3) on heating [47]. Analogously, the C-8 methyl group of a flavoquinone can

[45] *E. Lederer*, Experientia *20*, 473 (1964).

[46] *K. Dudley*, *P. Hemmerich*, and *F. Müller*, unpublished work.

[47] *P. Hemmerich*, *B. Prijs*, and *H. Erlenmeyer*, Helv. chim. Acta *42*, 2164 (1959).

react with aldehydes to form Fl_{ox}–CH=CH–R [48], *e.g.* *(41)*. The C-8 methyl group appears to be at least as reactive as the methyl group in nitrotoluenes, and for this reason can be classified as a functional group of the flavoquinones.



(20)

(41)

(40)

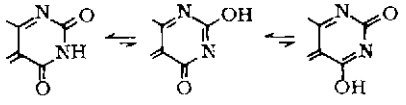
3. Electrophilic Substitution, Flaviniminol Esters

The base-catalysed alkylation of flavoquinone is possible only under non-solvolytic conditions and with bases that are weak enough to avoid irreversible dimerization (cf. Section IV,2), for example with potassium carbonate in dimethylformamide at room temperature [49]. Substitution occurs exclusively at N–3 *(32)*. With flavohydroquinone, N–5 of which has been protected by acetylation *(29)*, the same reaction does not lead to the expected *N*–1,*N*–3-dialkyl derivative *(36)*, but to an easily separable mixture of the *N*–3,*O*- and the *O*,*O*-dialkyl derivatives *(19)* [20]. Thus, N–1 is not alkylated, and this is probably due to hindrance by the alkyl group on N–10; on the other hand, sterically hindered *N*–1-alkylflavohydroquinones such as *(36)* are accessible *via* lumichrome *(1)* [20], which in the oxidized form is dialkylated at N–1 and N–3 to form *(38)*. The N–10-alkyl group can be subsequently introduced into the *N*–5-acetyldihydro derivative *(37)*. The lack of reactivity at N–1 of the flavohydroquinone *(29)* is thus reinforced by the higher electron density in the 2,4-dioxo groups. In confirmation, the flaviniminol esters in the hydroquinone state *(19)* are difficult to hydrolyse; the acetyl group on N–5 can be selectively eliminated [50]. If an oxidizing radical scavenger, *e.g.* HONO, is added, then the dialkylflavoquinonium salts *(35)* and *(20)* are obtained directly from *(19)*, and partial hydrolysis of these leads to the formation of the flavoquinone-2-iminol esters *(21)* [46, 51]. These are still very reactive, as are the analogous thioesters *(25)* (cf. Section IV,1). For example, CH_3SH is quantitatively eliminated in 30 minutes from the thioester *(27)* at pH 2–3 and 20 °C. Such esters do not differ markedly in their spectra from normal flavoquinone, but differ in their basicity [51].

The formation and hydrolysis of the esters *(21)* indicate that the energy content of the iminol forms increases sharply during oxidation of flavohydroquinone to flavoquinone (cf. Section IV,4).

4. Carboximide-Iminol Tautomerism

The positions of the tautomer equilibria in the different flavin redox states have been investigated by comparison of the visible, ultraviolet, and infrared spectra, and also of the pK_a values of *O*- and *N*-alkylated derivatives [51]. In accord with the high energy content of the flavoquinoneiminol esters *(21)* (cf. Section IV,3), flavin is present almost entirely in the carboximide form *(39)* in the oxidized state.



(39)

The reduced flavin likewise exists predominantly in the carboximide form; however, the properties of the flavohydroquinoneiminol esters *(19)* indicate a marked participation of the iminol form in the equilibrium.

Thioflavins such as *(30)* and *(28)* likewise occur in the C(S)NH form; only the "flavimines" *(22)* and *(33)* do not have the mobile proton at N–3 and therefore must be designated as aminobenzopteridones. In the semiquinone state, *N*–1-alkylflavins exhibit a behavior strongly deviating from that of the *O*-alkyl isomers and the unsubstituted parent substances, in regard to both stability and spectrum [51–53]. While the visible and ESR spectra of the neutral flavosemiquinones O,O-$\dot{F}lR_2$ and O,N–3–$\dot{F}lR_2$ are in good agreement with those of N-3-$\dot{F}lHR$ and $\dot{F}lH_2$, no evidence of an N–1,N–3-$\dot{F}lR_2$ has yet been obtained, although the protonated forms, $\dot{F}lHR_2^{\oplus}$ (*Kuhn*'s "Rhodoflavins" [54]), behave normally in every case irrespective of the location of the alkyl group.

O,O- and O,N–3–$\dot{F}lR_2$ are obtained by alkylation of chloroform-soluble $Fl_{ox}H$ or N–3–$Fl_{ox}R$, *e.g.* tetraacetylriboflavin or 3-alkyl-lumiflavin (in chloroform/triethylamine plus supernatant aqueous $Na_2S_2O_4$), and partial reoxidation with I_2 [55]. They form deep green, strongly paramagnetic solutions, which on replacement of the chloroform by a mixture of methanol and water change color towards blue, and on addition of acid turn red. Deep red N–1,N–3–$\dot{F}lHR_2^{\oplus}$ [46] is formed on mild acid hydrolysis of *(36)*. The green chloroform solution obtained on neutralization does not show a magnetic susceptibility proportional to the optical extinction [51, 52]. In the aqueous phase the neutralization is accompanied by irreversible secondary reactions, which lead to *N*-10-dealkylated products, among others [46].

[48] *P. Hemmerich*, Helv. chim. Acta *43*, 1942 (1960).

[49] *P. Hemmerich*, Helv. chim. Acta *47*, 464 (1964).

[49a] *Y. Ogura, S. Nakamura*, and *T. Nakamura*, Acta chem. scand. *17*, p. 184 (1963).

[50] *N*–1, *N*–10-dialkyl derivatives of flavohydroquinones, *e.g.* *(42)*, are obtained as deep-yellow crystals which are relatively stable towards air, cf. [51].

[51] *K. H. Dudley, A. Ehrenberg, P. Hemmerich*, and *F. Müller*, Helv. chim. Acta *47*, 1354 (1964).

[52] *A. Ehrenberg, G. Erikson*, and *P. Hemmerich* in *T. E. King, H. S. Mason*, and *M. Morrison*: Oxidases and Related Redox Systems. Wiley, New York, in the press.

[53] *P. Hemmerich, F. Müller*, and *A. Ehrenberg* in *T. E. King, H. S. Mason*, and *M. Morrison*: Oxidases and Related Redox Systems. Wiley, New York, in the press.

[54] *R. Kuhn* and *R. Ströbele*, Ber. dtsch. chem. Ges. *70*, 753 (1937).

[55] *P. Hemmerich*, unpublished work.

As a result, a mixture of the monoiminol forms *(21a)* and *(21b)* can be regarded as the most probable structure of the flavosemiquinone. Further studies are required to confirm this point.

(21a) ⇌ *(21b)*

Accordingly, the semiquinone would be more closely related to the hydroquinone than to the quinone, *i.e.* on abstraction of an electron from the radical a flavoquinoneiminol is the primary product, which is a very energy-rich form of the flavin (the term energy-rich here always refers to hydrolytic or prototropic processes). This may be of significance for the conservation of energy during biological oxidations.

It is frequently assumed that the distribution of the localized electrons in aromatic or heteroaromatic systems does not alter on addition or abstraction of delocalized electrons. Almost all quantum-chemical studies of the flavin system are based on this assumption. However, as shown above, the σ-bond system of the flavins is altered by the addition of an electron and a proton, because of a displacement, possibly even a reversal, of the energy content of the protopropic forms. So far only *Grabe* [56] has allowed for this phenomenon in MO calculations.

5. Stereochemistry

On the addition of a further electron, *i.e.* on transition from the semiquinone to the hydroquinone, the flavin molecule folds in the N–5,N–10 axis (Fig. 1). This

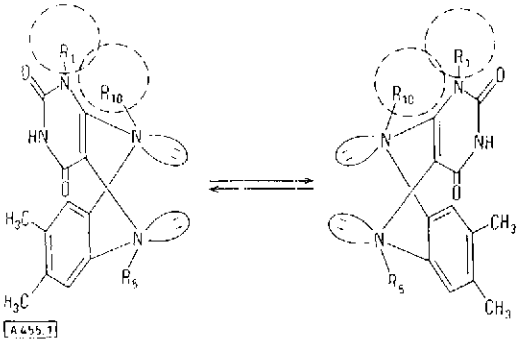


Fig. 1. Stereochemistry of flavohydroquinone; "Butterfly conformations".

means that the planar form can be described as an excited vibrational state. The change corresponds to the "buckling" of a planar CH_3 radical on transformation into a CH_3 carbanion. In the case of flavohydroquinone this buckling is indicated by the following observations [51]:

(1) The flavohydroquinone spectrum has a shoulder at 400 mμ, which disappears on protonation and deprotonation as well as on acylation (Fig. 2). Protonation and acylation occur at the most basic nitrogen atom, *i.e.* at N-5, which thereby assumes sp^3 configuration. The long-wavelength end absorption is therefore a measure of the delocalization (p-character) of the formally non-bonding electrons at N-5, which is highest in the planar state. The shoulder at 400 mμ has an extinction of ca. 2000 (mole·cm)$^{-1}$, which is too strong

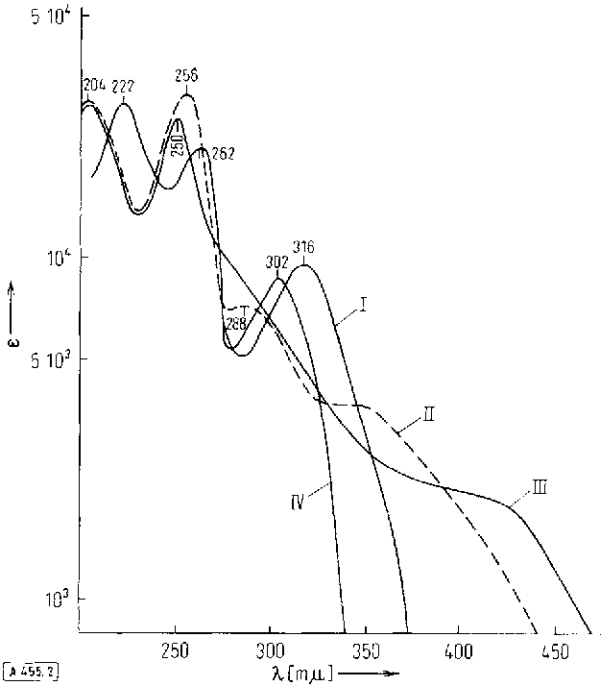


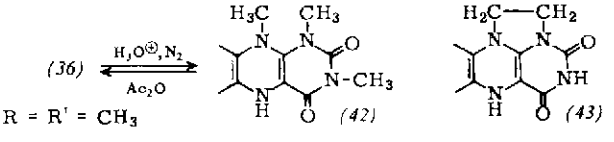
Fig. 2. Electronic spectra of the flavohydroquinone species (in H_2O unless otherwise stated), taken from [51].
I: $Fl_{red}\,H_4^{\oplus}$, pH < 0
II: $Fl_{red}\,H_2^{\ominus}$, pH ≈ 9
III: $Fl_{red}\,H_3$, pH ≈ 5
IV: *(29)*, R' = CH_3, in CH_3OH (cf. Scheme 2).

for an (n,π*)-transition but is relatively weak for a (π,π*)-transition, *i.e.* the orbital configuration on N-5 is neither strictly planar nor strictly tetrahedral.

(2) If alkyl substituents are introduced at N-1, as in *(42)*, a strongly hypsochromic shift occurs, although the direct electronic effect exerted by the conversion >NH → >N-alkyl in an N-heteroaromatic system should produce a bathochromic shift, if any.

Accordingly, alkyl substitution must have a steric effect which favors the buckled non-coplanar state. This corresponds to the steric hindrance which is to be expected of N–1 and N–10 substitution.

The effect disappears [51] if the two methyl groups at N–1 and N–10 in *(42)* are replaced by a $-CH_2-CH_2-$ bridge *(43)*.



A flattening of the flavohydroquinone system can also result from the formation of sandwich complexes (*e.g.* in $FADH_2$, cf. Section IV,8).

6. Acid-Base and Disproportionation Equilibria

Following the fundamental potentiometric studies of *Michaelis et al.* [57], *Beinert* [58] was the first to attack the problem of spectral classification of the individual

[56] *B. Grabe*, Doctorate Dissertation, University of Uppsala (Sweden) 1960.

[57] *L. Michaelis* and *G. Schwarzenbach*, J. biol. Chemistry *123*, 538 (1938).

[58] *H. Beinert*, J. Amer. chem. Soc. *78*, 5323 (1956).

flavin species. He assigned to the free monomeric radical $\dot{F}lH_2$ the band in the 600 mμ region and to the dimeric flavoquinhydrone $(\dot{F}lH_2)_2$ the diffuse absorption in the near infrared (Figs. 3a and 3b). This assignment was checked using model compounds [50] and extended (cf. Table 1). The problem is complicated by the unfavorable position of the disproportionation equilibrium

$$2\ \dot{F}lH_2 \rightleftharpoons Fl_{ox}H + Fl_{red}H_3,$$

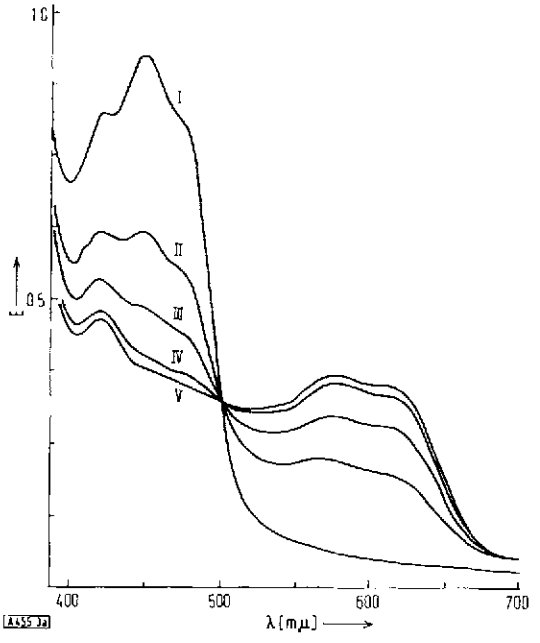


Fig. 3a. Change in absorption with time during reduction of metal-free flavoprotein [60] from *Azotobacter vinelandii* with $S_2O_4^{2-}$ at pH 7.0 in phosphate buffer. The kinetically stable blue semiquinone is not reduced further by excess $S_2O_4^{2-}$ under these conditions. About 30 minutes have elapsed between curve V (full reduction) and curve I. The ESR absorption likewise reaches a stable maximum during this period. Thanks are due to Prof. *H. Beinert*, Madison, for permission to publish these results.

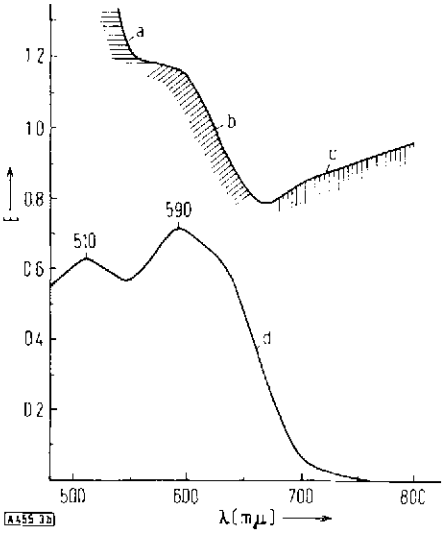


Fig. 3b. Spectrum of half-reduced FMN [Mixture of FMN, $(FMNH)_2$ and $\dot{F}MNH$] (upper curve) and a non-dimerizing model *(44)* of type $\dot{F}lR_2$ (lower curve) in aqueous solution, pH ≈ 5; taken from [51].

a = FMN- (flavoquinone-) part of the spectrum

b = $\dot{F}$MNH- (flavosemiquinone-) part of the spectrum

c = $(FMNH)_2$- (flavoquinhydrone-) part of the spectrum

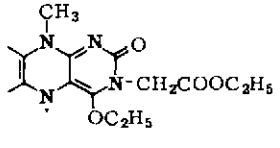
d = *(44)*.

which permits only very small radical concentrations in the protein-free half-reduced system. The pH-dependence of this equilibrium is extremely complex [49]. In strongly acidic solution the system is entirely comproportionated [49a] (*i.e.* the equilibrium is shifted to the left) and the radical cations $\dot{F}lH_3^{\oplus}$ (Scheme 2) can be readily observed. Since $\dot{F}lH_2$ is by far the most strongly basic of all uncharged flavin species, almost complete disproportionation occurs on neutralization, provided the dissociation $Fl_{ox}H_2^{\oplus} \rightarrow Fl_{ox}H$ is not blocked [*e.g.* by alkylation as in $Fl_{ox}R_2^{\oplus}$ *(20)*]. At physiological pH, five of the nine flavin species reproduced in Scheme 2 must be considered, *i.e.* $Fl_{ox}H$, $\dot{F}lH_2$, $\dot{F}lH^{\ominus}$, $Fl_{red}H_3$, and $Fl_{red}H_2^{\ominus}$, since the acid dissociation of both reduced states falls inside this pH range [57]. The pH-dependence of the disproportionation at physiological pH follows Equation (a) [49]

$$K(H) = \frac{[\dot{F}l_{total}]^2}{[Fl_{ox,\,total}]\,[Fl_{red,\,total}]} = Const. \cdot \frac{(1 + \dot{k}/[H])^2}{(1 + k_{red}/[H])} \qquad (a)$$

where H is the hydrogen-ion activity and $\dot{k}$ and k_{red} are the acid dissociation constants of $\dot{F}lH_2$ and $Fl_{red}H_3$, respectively. Since $Fl_{red}H_3$ is somewhat more acidic than $\dot{F}lH_2$, it follows that K(H) passes through a minimum (corresponding to a minimum in the radical concentration) precisely in the physiological pH range. Hence $\dot{F}lH_2$ is thermodynamically unstable and the same is true kinetically, since the disproportionation proceeds extremely fast as is common in the case of molecular charge transfer. The minimum of radical concentration was confirmed by *Ehrenberg* [59] from ESR measurements. The bonding of the flavin to the protein may be accompanied by an appreciable kinetic stabilization of the radical, provided the "active center" of the protein does not contain a second redox function in addition to that of the flavin, which is often the case (cf. Section VI).

A kinetically stabilized flavosemiquinone of this type has recently been found in a flavoprotein from *Azotobacter vinelandii* [60]. Figure 3a shows the spectral changes occurring when this flavoprotein is reduced with $S_2O_4^{2-}$. At pH 7 this reduction leads to a deep-blue radical. In Figure 3b the spectrum of this radical is compared with that of a likewise deep-blue model radical O,N-3-$\dot{F}lR_2$ *(44)* (cf. Section IV,3) [51].



(44)

Both radicals, *i.e.* the natural product and the model, exhibit proportionality between ESR intensity and optical extinction. Neither is able to dimerize to the quinhydrone, the natural product for kinetic reasons, the synthetic model for thermodynamic ones (cf. Section IV,8). This behavior confirms the spectral assignment

[59] *A. Ehrenberg*, Ark. Kemi *19*, 97 (1962).

[60] *Y. I. Shethna, H. Beinert*, and *P. Hemmerich*, unpublished work.

made by *Beinert* [58]. Both radicals react only slowly with O_2 and $S_2O_4^{2-}$, which shows that these reagents react faster by a two-electron transfer with the flavin species resulting from $\dot{F}lH_2$ by disproportionation. The autocatalysis of flavohydroquinone autoxidation [61] and the red intermediates observed during the reduction of certain flavoproteins [62] cannot, therefore, be ascribed to $\dot{F}lH_2$, nor to any other radical, *i.e.* paramagnetic species, unless there is proportionality between visible and ESR absorption.

As a rule, thermodynamic stabilization of a formally half-reduced flavin, *e.g.* by metal complex formation (cf. Section V,2), must also be considered.

7. Spin Density in Flavosemiquinones

Conclusions regarding the delocalization of the unpaired electron in the flavin radical species have been drawn from the ESR hyperfine structure. By the introduction of ^{15}N into positions 1, 3, and 5, and of deuterium at C–6, C–9, and C–10α, *Ehrenberg et al.* [52, 63] were able to show that in all radical species ($\dot{F}lH_3^{\oplus}$, $\dot{F}lH_2$, and $\dot{F}lH^{\ominus}$) the unpaired electron (or the electron hole) is predominantly found in the phenylenediamine part and not in the pyrimidone part of the tricyclic system. Thus, radical reactions in the flavin plane will occur only at positions 5, 8α, and 10α.

This is of significance for the understanding of flavin-catalysed one-electron transfer reactions (cf. Sections V,VI). In addition the question arises as to under what conditions electrons can be transferred vertically to the flavin plane (cf. Section IV,8).

8. Sandwich Complexes

Weber [64] has shown that flavin fluorescence occurs when the adenine frequency in FAD is excited. From this observation he deduced a sandwich arrangement of the two heteroaromatic components in FAD. Further studies by *Harbury* [65] and *Szent-Györgyi* [66] have shown a similar arrangement for the "charge-transfer interaction" between flavin and apoprotein. It is important that the stability of such a complex does not primarily depend on the energy which is gained by the charge transfer. Instead the formation of a stable complex in dilute solution is governed by a sterically favorable fixation of a donor-acceptor pair, and this is secured by the tertiary structure of the active center in the protein or by the covalent linkage between the flavin and adenine moieties in FAD. Alternatively, a stable complex arises only in concentrated solutions.

Charge-transfer effects are all the stronger if the donor and acceptor skeletons have a similar structure (self-charge-transfer in quinhydrones). The relatively most stable association is therefore that between neutral or dissimilarly charged flavin species at different redox states, as was shown by *Kuhn* and *Ströbele* [54] for solids and later by *Massey et al.* for concentrated solutions [67]. Such a complex can dissociate in two ways according to Equation (b) and thus could be interpreted as a radical

$$Fl_{ox} + Fl_{red}H_3 \rightleftharpoons \left\{ \begin{matrix} [FlH\text{-}FlH_3] \\ \Updownarrow ? \\ [FlH_2\text{-}FlH_2] \end{matrix} \right\} \rightleftharpoons 2\,\dot{F}lH_2 \qquad (b)$$

dimer or as a charge-transfer complex. Since the whole unit is diamagnetic, both forms must be tautomers. However, as has been discussed (Section IV,4), $\dot{F}lR_2$ forms no stable "dimer" $[FlR_2\text{–}FlR_2]$ so that $(FlH_2)_2 \equiv [FlH\text{–}FlH_3]$, *i.e.* a true charge-transfer complex is present. The comparison of $\dot{F}lH_2$ with $\dot{F}lR_2$ is permissible, since hydrogen bonds do not contribute to the stability of such complexes [67a].

V. The Metal Coordination Chemistry of the Flavin System

1. Metal Chelates of Flavoquinone (Charge-Transfer Chelates)

Considering the structural analogy between flavoquinone *(50)*, *(53)*, and 8-hydroxyquinoline ("oxine") *(45)*, one would expect that flavoquinone is a good chelating agent. Stabilities of flavoquinone chelates measured by *Albert* [68] and *Freiser et al.* [69] cannot, however, be assigned to oxinate-like structures *(52)* [70]. In contrast to pteridine-4-one *(46a)*, which forms chelates of structure *(46)* (cf. Scheme 6), the metal affinity of riboflavin is insufficient to suppress hydrolysis of metal ions. Also participation of the ribityl side-chain in complex formation cannot be excluded [70].

The absence of an interaction between flavoquinone and divalent d-metal ions in dilute solution has been confirmed by *Metzler* and *Baarda* [71] as well as by *Radda* and *Calvin* [72]. Similarly, the distribution of lumiflavin between water and chloroform is independent of the d-metal ion concentration at constant ionic strength [55].

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[61] *Q. H. Gibson* and *J. W. Hastings*, Biochem. J. *83*, 368 (1962).

[62] See, *e.g.*, *K. Yagi* and *T. Ozawa*, Proc. VIth Internat. Congr. Biochem. New York 1964, IV-200.

[63] *L. F. G. Eriksson* and *A. Ehrenberg*, Acta chem. scand. *18*, 1437 (1964).

[64] *G. Weber*, Biochem. J. *47*, 114 (1950).

[65] *H. A. Harbury*, *K. F. LaNoue*, *P. A. Loache*, and *R. M. Amick*, Proc. nat. Acad. Sci. U.S.A. *45*, 1708 (1959); *H. A. Harbury* and *K. A. Foley*, ibid. *44*, 662 (1958).

[66] *J. Isenberg* and *A. Szent-Györgyi*, Proc. nat. Acad. Sci. U.S.A. *45*, 519 (1959).

[67] *V. Massey* and *G. Palmer*, J. biol. Chemistry *237*, 2347 (1962); *Q. H. Gibson*, *V. Massey*, and *N. M. Atherton*, Biochem. J. *85*, 369 (1962).

[67a] Cf., for example, *H. A. Staab*: Einführung in die theoretische organische Chemie. Verlag Chemie, Weinheim 1959, p. 696.

[68] *A. Albert*, Biochem. J. *47*, XXVII (1950).

[69] *T. R. Harkins* and *H. Freiser*, J. physic. Chem. *63*, 309 (1959).

[70] *P. Hemmerich* and *S. Fallab*, Helv. chim. Acta *41*, 499 (1958).

[71] *D. E. Metzler* and *J. F. Baarda*, Biochim. biophysica Acta *50*, 463 (1961).

[72] *G. K. Radda* and *M. Calvin*, Biochemistry *3*, 384 (1964).

In order to exclude any possible hindrance of metal coordination at N-5 by the CH group in position 6 of the flavin nucleus, comparison was made with the "pteroquinone" *(47)* whose structure is analogous to that of flavoquinone [73]. Upon addition of d-metal ions, this molecule, too, does not react like oxine, *i.e.* with liberation of $H^{\oplus}$, but accepts $OH^{\ominus}$ to form a "covalently hydrated" chelate *(48)*, R = H or CH_3, which cannot be dehydrated without decomposition.

In contrast, the affinity of Ag^+ toward flavoquinone is surprising [74]. Silver forms stable, oxinate-like chelates with flavoquinone. The spectra of these complexes AgFlR *(51)* and AgFl *(52)* correspond to that of the iso-π-electronic flavosemiquinone cation $\dot{F}lH_3^{\oplus}$. Copper(I) reacts similarly to silver [Equation (c) and Fig. 4].

$$CuFl \equiv [Fl_{ox}^{\ominus}Cu^{\oplus} \leftrightarrow \dot{F}l^{2\ominus}Cu^{2\oplus}] \qquad (c)$$

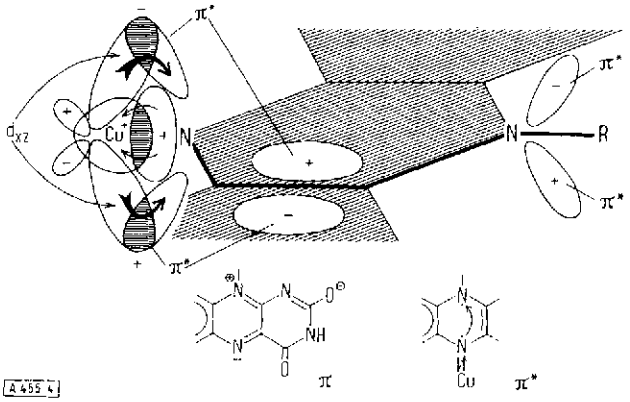
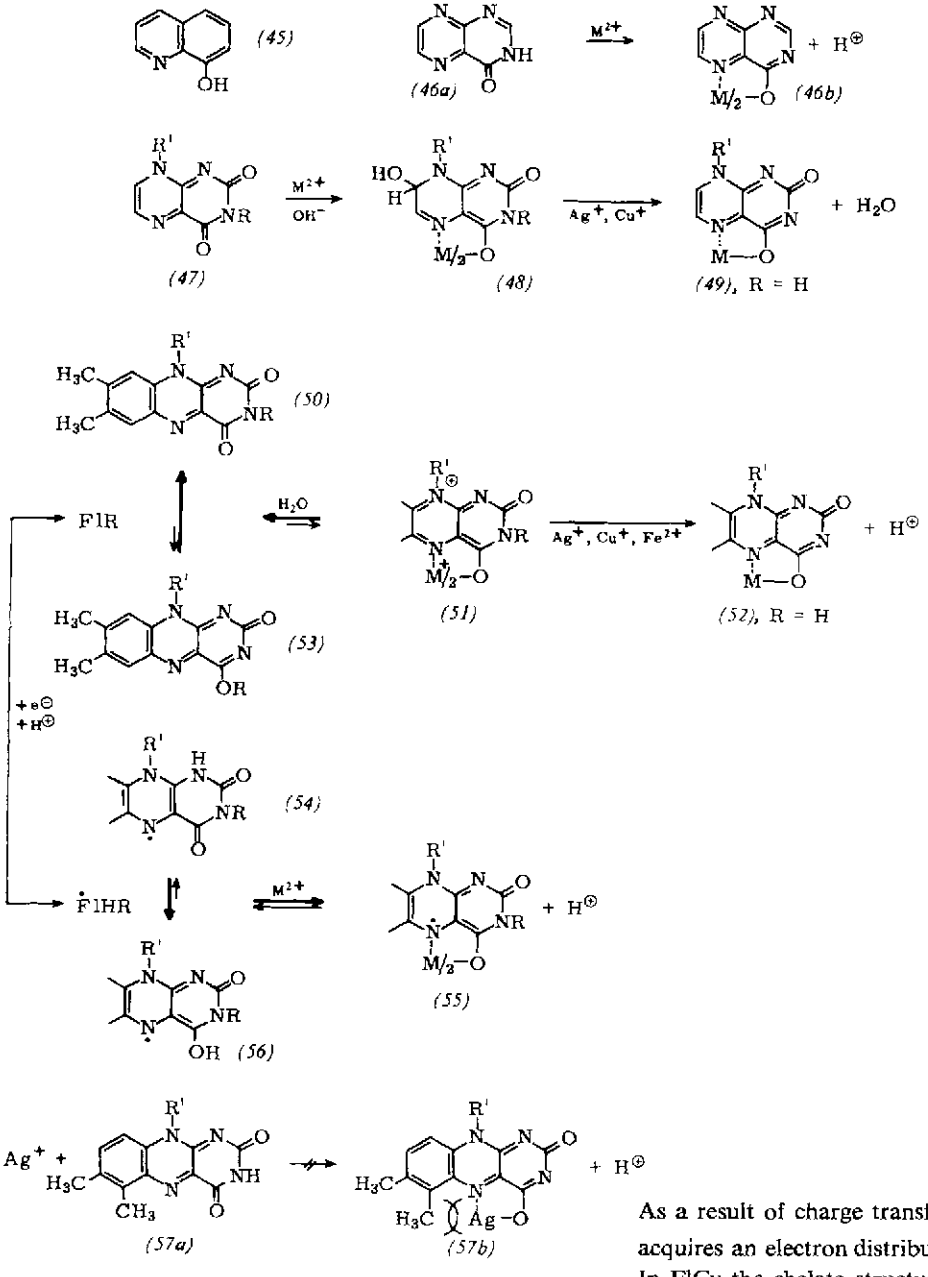


Fig. 4. Molecular orbital diagram of the metal-ligand charge transfer in flavoquinone-copper(I) chelate. Diagonal shading: plane of the flavin nucleus. Horizontal shading: overlap regions of metal and ligand orbitals on N-5 of the flavin; taken from [2].



Scheme 6. Metal chelate formation of flavin and related systems.

As a result of charge transfer, the flavoquinone ligand acquires an electron distribution similar to that of $\dot{F}lH_3^{\oplus}$. In FlCu the chelate structure, *i.e.* the bidentate nature of the ligand, was confirmed by Reaction (d) [75]:

$$Cu(CH_3CN)_2^{\oplus} + Fl_{ox}H \rightleftharpoons FlCu + 2\ CH_3CN + H^{\oplus} \qquad (d)$$

[73] *P. Hemmerich* in *W. Pfleiderer* and *E. C. Taylor*: Pteridin-Chemistry. Pergamon Press, Oxford 1964, p. 143.

[74] *P. Bamberg* and *P. Hemmerich*, Helv. chim. Acta *44*, 1001 (1961).

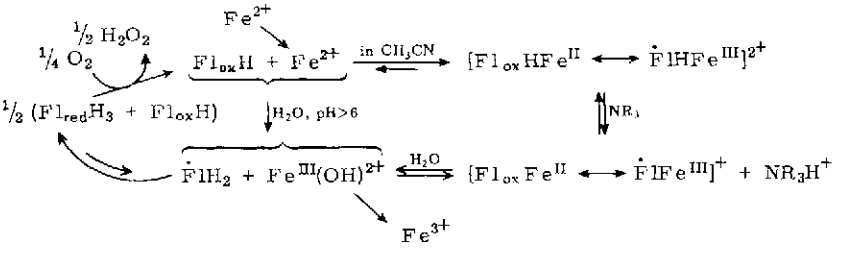
[75] *P. Hemmerich* and *C. Sigwart*, Experientia *19*, 488 (1963).

The observed dependence of FlCu-formation on the square of the CH_3CN concentration shows that FlH displaces two molecules of CH_3CN from the coordination sphere of Cu(I).

"Isoflavins" *(57a)* do not react with Ag^+ or Cu^+, because the coordination at N–5 is hindered by the CH_3 group at C–6 *(57b)* [74].

A more detailed study shows that all metal ions form chelates with flavoquinone under more drastic conditions, *i.e.* in anhydrous media. The extent of chelate formation depends on the ionization potential and on the hydration energy of the metal. Upon addition of a base, *e.g.* triethylamine, these chelates decompose. Thus, for example, the affinity of flavoquinone for Zn^{2+} is less than that of tertiary amines, *i.e.* $\log K^{Zn}_{FlZn} \approx 2.0$ [76, 77], whereas $\log K^{Ag}_{FlAg} = 8.0$ [74].

The interaction of Fe^{2+} and MoO^{3+} with flavoquinone is as strong as that of Ag^+ and Cu^+, *i.e.* on addition of triethylamine a proton is liberated from the complex $FlHM^{n\oplus}$ *[(51)* R = H]; however, in water the complex $[Fl_{ox}Fe]^{\oplus}$ from $Fl_{ox}H$ and Fe^{2+} dissociates into $\dot{F}lH^{\ominus}$ and $FeOH^{2+}$, whereas FlAg and FlCu are stable under similar conditions. In other words, flavoquinone is reduced by Fe^{2+} above pH 7. The $\dot{F}lH^{\ominus}$ liberated at once disproportionates to give $Fl_{ox}H + Fl_{red}H_2^{\ominus}$, and the latter is oxidized under aerobic conditions. The overall process represents a flavin-catalysed autoxidation of Fe^{2+} (Scheme 7).



Scheme 7. Flavin-catalysed autoxidation of Fe^{2+}.

2. Metal Chelates of Flavosemiquinone

As shown in Section V.1, flavin charge-transfer chelates can participate in two dissociation equilibria at different oxidation states. We assumed that the flavosemiquinone $\dot{F}lH_2$, unlike flavoquinone $Fl_{ox}H$, exhibits a general affinity for metal ions. As shown in Section IV.6, N–5 is more strongly basic in $\dot{F}lH_2$ than in $Fl_{ox}H$, and the C=O group in position 4 is more easily transformed into the hydroxy form required for chelate formation [cf. *(54)*, *(56)*]. During the pH titration of half-reduced flavin [49] it was found that the disproportionation maximum at pH 7–8, which is indicated by a color change from olive brown to light yellow, does not occur in the presence of arbitrary, non-oxidizing d-metal ions. Instead, the solution turns carmine red and an additional proton is liberated [Equation (e)].

$$Fl_{red}H_2^{\ominus} + Fl_{ox}H + 2\,M^{2\oplus} \rightleftharpoons 2\,[MFlH]^{\oplus} + H^{\oplus} \qquad (e)$$

(55), R=H

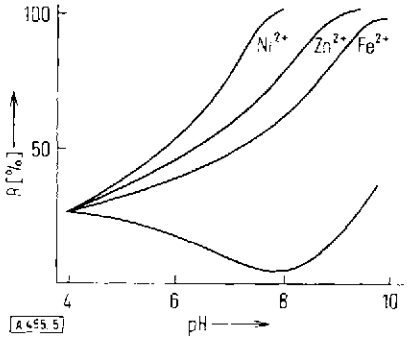
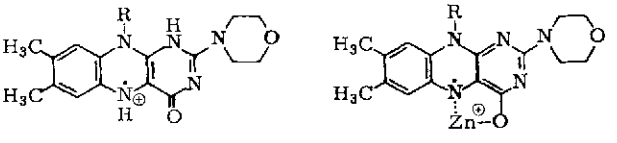


Fig. 5. pH-Dependence of flavosemiquinone disproportionation. R = radical. Bottom curve, disproportionation in the absence of metal ions. (Schematic representation).

Figure 5 shows the pH-dependence of the disproportionation in the presence and absence of d-metal ions. In Figure 6 the spectrum of a typical "radical chelate" *(57b)* with a diamagnetic central atom is compared with that of the iso-π-electronic radical cation $FlH_3^{\oplus}$ *(57a)*.

The position of the main band is practically the same, and that of the secondary band is more bathochromic for $[Zn\dot{F}lH]^{\oplus}$, since this compound exists entirely in the 4-iminol form. The visible spectrum of the chelates $[M\dot{F}lH]^{\oplus}$ is practically independent of the nature of the metal ion; the stability constants K^{M}_{FlHM} follow the normal sequence [78] $Mn^{2+} < Fe^{2+} < Co^{2+} < Ni^{2+}$



(57a) R = Tetraacetylribityl *(57b)*

$> Zn^{2+} > Cd^{2+}$ [49]. These radical chelates *(55)* and *(57b)* exhibit an additional weak characteristic absorption band in the near infrared [79]. In the region from 600 to above 1100 mμ the charge transfer band of the flavohydroquinone $(FlH_2)_2$ is diffuse ($\lambda_{max} \approx 1000$ mμ), but the radical chelate band is very sharp. The maximum occurs at 825 ⊥ 5 mμ for all the above-named divalent

[76] K^{B}_{AB} is the stability constant relating to the dissociation $AB \rightleftharpoons A+B$, cf. *J. Bjerrum, G. Schwarzenbach*, and *G. Sillén*: Stability Constants. Chem. Soc. Publ. No. 6, London 1957.

[77] *J. Bjerrum* and *S. Refn*, 6. Nordiska Kemistmöte, Lund, 1947, p. 227, quoted from [76], p. 51.

[78] *H. Irving* and *R. J. P. Williams*, Nature (London) *162*, 746 (1948); Review: *A. E. Martell* and *E. Calvin*: Die Chemie der Metallchelatverbindungen. Verlag Chemie, Weinheim 1958, p. 168ff.

[79] *A. Ehrenberg* and *P. Hemmerich*, Acta chem. scand. *18*, 1320 (1964).

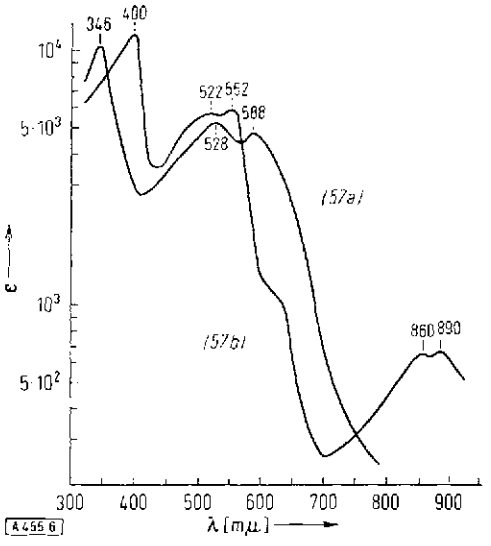


Fig. 6. Spectrum of a pure flavin radical chelate $\dot{F}lRZ_n^{\oplus}$ *(57b)* and of the isoelectronic $\dot{F}lRH_2^{\ominus}$ *(57a)* in $CHCl_3$; taken from [80]. To produce *(57a)*, $Fl_{ox}R$ in $CHCl_3$ is reduced to $Fl_{red}RH_2$ by shaking with aqueous $S_2O_4^{2-}$. Mixing with an identical volume of untreated solution in a Thunberg cell gives 50 % reduction. One drop of anhydrous formic acid or 1 equivalent of zinc acetate in CH_3CN plus 1 drop of triethylamine are then added. On exposure to air, $Fl_{ox}R$ is immediately and quantitatively reformed in both cases.

metal ions. This band is independent of the polarity of the medium and obeys Beer's law [80]. In contrast, the end absorption of the charge-transfer chelates in this region is more intense, but diffuse.

The hyperfine structure of the ESR spectrum of $ZnFlH^{\oplus}$ is entirely different from that observed for free $\dot{F}lH_2$. "Radical chelates" of paramagnetic ions exhibit no ESR signal (because of spin-spin coupling?). Further evidence for the reversal of the disproportionation of $\dot{F}lH_2$ by metal ions, first demonstrated potentiometrically (Fig. 5), is provided by the twentyfold increase of the ESR intensity on addition of diamagnetic Zn^{2+} or Cd^{2+} to a suitably buffered solution of the half-reduced flavin system [81].

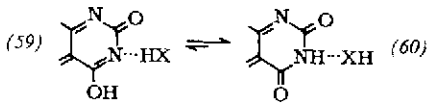
To sum up, flavosemiquinone is the redox state with the relatively highest metal affinity, while flavoquinone possesses absolute specificity for d-electron donating metal ions. Metal coordination provides a reasonable thermodynamic explanation for the stabilization of the radical state.

As expected, flavohydroquinone has no metal affinity [53], since the NH group in position 5 in $Fl_{red}H_3$ has no basic or acidic properties.

VI. Biochemical Aspects

1. Coenzyme Fixation in Flavoproteins

The flavoproteins contain coenzyme-apoenzyme bonds of widely different strength. The "old yellow enzyme" is the prototype of a flavoprotein which dissociates reversibly into coenzyme and apoprotein. On the basis of biochemical data, *Theorell et al.* [82] postulated a hydrogen bond at N–3 as the most likely mode of protein fixation. In view of the chemical evidence discussed above, position 3 is indeed the most plausible site of a directed, reversibly dissociable link between the apoprotein and the flavin nucleus, since it is the only position, the properties of which are almost independent of the redox state. The absorption maximum of the "old yellow enzyme" (λ_{max} = 464 mμ) is at a longer wavelength than that of the free coenzyme (FMN) (λ_{max} = 446 mμ). This shift is not due to H-bonding of the protein



(cf. Section VI,3). It seems impossible that a hydrogen bond at N–3 should favor the tautomeric iminol form of the flavoquinone; rather, the equilibrium *(59)* ⇌ *(60)* must be assumed to be completely displaced to the right, even in enzymatically bound flavin (cf. Section IV,4).

In succinic dehydrogenase [83] the flavocoenzyme is so tightly bound that it could so far not be dissociated from the apoprotein. *Wang et al.* [84], in substantial confirmation of the data found by *Kearney* [85], obtained an FAD-hexapeptide by enzymatic proteolysis of succinic dehydrogenase. From this the adenyl residue was removed by hydrolysis and the ribityl chain by photolysis without splitting off the peptide fragment. Further (alkaline) hydrolysis leads to opening of the pyrimidine ring of the flavin system with liberation of urea. Accordingly, the peptide fragment cannot be linked to the flavin nucleus in positions 1, 2, 3, or 10. The authors postulate a link in position 4. However, as shown in Section IV, substituents such as OR, NHR, SR, aryl, or alkyl can be eliminated from 4-substituted flavins by hydrolysis or mild oxidation. Thus position 4 can be excluded as the site linking the coenzyme with the apoprotein. Substitution in position 5 (*N*-quaternization) would bring about drastic changes in the spectrum. The homoaromatic part of the flavin nucleus is therefore left as the only possible bonding site. In this connection, the functional character of the 8-methyl group of flavoquinone seems relevant (cf. Section IV, 2).

2. FMN-FAD Interconversion in Flavoproteins

Firm evidence is available that both FMN and FAD are native. Nevertheless, *Massey* and *Swoboda* [86] have concluded that mitochondrial flavoproteins do not contain FMN, but that the latter is formed from FAD during preparation of the enzyme (as a result of pyrophosphatase present in the preparations?). *Cremona et al.*

[80] *F. Müller*, Doctorate Dissertation, Universität Basel 1964.

[81] *P. Hemmerich, D. V. Der Vartanian, C. Veeger*, and *J. D. W. Van Voorst*, Biochim. biophysica Acta *77*, 504 (1963).

[82] *Å. Åkeson, A. Ehrenberg*, and *H. Theorell* in *P. D. Boyer, H. Lardy*, and *K. Myrbäck*: The Enzymes. Academic Press, New York-London 1963, Vol. VII, p. 477.

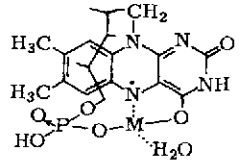
[83] *T. P. Singer* and *E. B. Kearney* in *P. D. Boyer, H. Lardy*, and *K. Myrbäck*: The Enzymes. Academic Press, New York-London 1963, Vol. VII, p. 384.

[84] *T. Y. Wang, C. L. Tsou*, and *J. L. Wang*, Sci. Sinica *5*, 73 (1956); *C. L. Tsou*, Vth Internat. Congr. Biochem. Pergamon Press, London 1963, Vol. 5, p. 235.

[85] *E. B. Kearney*, J. biol. Chemistry *235*, 865 (1960).

[86] *V. Massey* and *B. E. P. Swoboda*, Biochem. Z. *338*, 474 (1963).

[87] have doubted this conclusion and postulated a non-mitochondrial origin for the labile FAD found side by side with the FMN. However, since no labile FAD is found in the "electron transfer particles" (ETP) of *Crane et al.* [88], this postulate seems also doubtful. It is certain that labile FAD is found in mitochondrial NADH dehydrogenase [89]. Thus labile FAD can only be formed during fractionation of the electron transfer particles, so that a relationship between FMN–FAD interconversion and enzyme activity cannot be ruled out.



(61)

Since the phosphate groups may participate in metal coordination, *e.g. (61)*, autocatalysis of the FAD splitting by enzymatic iron seems at least possible [2], either in the native enzyme complex or "artificially" in the fractionated enzyme.

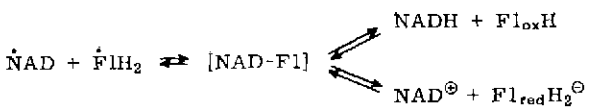
3. Red Intermediates in Flavoprotein Oxidoreduction

A shift of the main flavin absorption band towards the red has been observed with numerous flavoproteins, first of all by *Haas* [90] on reduction of the "old yellow enzyme" with dihydropyridine nucleotide. This shift must, however, not be taken to indicate the formation of "radical" intermediates unless a quantitative correlation of the visible and ESR spectra has been obtained.

As has been shown in Section IV, the only red radical species of metal-free flavin so far known is the cation $\dot{F}lH_3^{\oplus}$. In the free state, this cation is so strongly acidic that its stabilization at pH 7–8 by enzyme protein is highly improbable. Stabilization is effected in flavin metal chelates which are consequently red (cf. Section VI). However, they can be designated as "radicals" only when they contain diamagnetic metal ions (Zn^{2+}, Cd^{2+}) [81], as for example the Zn flavoproteins described by *Gregolin* and *Singer* [91].

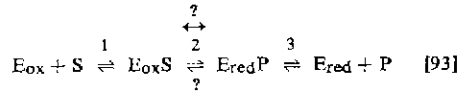
In many other cases the radical content of red intermediates is evidently due merely to a – possibly artificial – admixture of a small quantity of flavin radicals which do not contribute much to the visible spectrum. This is true mainly of crystalline preparations in which a thermodynamically unstable proportion of radicals may be "frozen in" [62].

As discussed in Section IV,8, a shift towards the red can occur quite generally in sandwich complexes, for example in the (NAD–Fl) of the "old yellow enzyme" [90,92]. These complexes are diamagnetic but can readily dissociate into radicals. A determination of the valence state of their components, if at all possible, has to rely upon physical means. Three dissociation paths are possible:



Neither the positions of these equilibria nor the kinetics of the dissociation permit an unambiguous interpretation of the structures of these complexes.

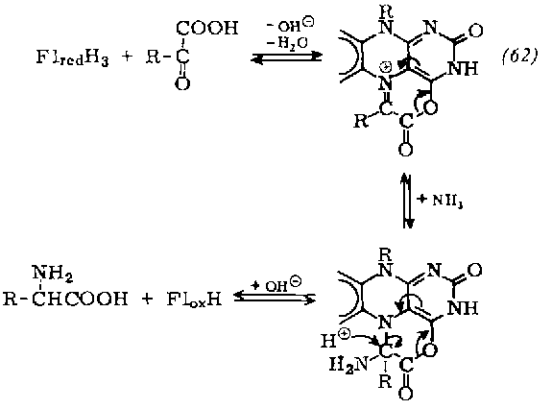
In the redox-catalysis exhibited by the flavoproteins it is debatable whether the second step of the sequence



[93]

represents a chemical reaction or merely a change in charge distribution (mesomerism). The latter seems to be the case with S = Fe^{2+} and P = Fe^{3+} (cf. Section V).

In addition to the sandwich complexes and metal chelates, red flavin intermediates with a purely covalent E_{ox}-substrate or E_{red}-product bonds appear possible. Thus a cyclic flavohydroquinone-azomethinium salt structure *(62)* might be tentatively assigned to the red (E_{red}-P)-complex arising from D-amino acid oxidase



(62)

(P = α-keto acid) [94]. According to the arguments advanced in Section IV,5, this compound represents a resonance-stabilized coplanar derivative of flavohydroquinone, for which a relatively intense absorption at about 500 mμ is to be expected; on decomposition it should give either E_{ox} + substrate or E_{red} + product, while radical dissociation is unlikely unless artificially (*e.g.* photochemically) induced [94]. – This purely hypothetical scheme is advanced merely in order to show that it is not absolutely necessary to look for "non-classical" types of bonds to explain such reactions.

The third possible explanation of the red intermediates is an indirect one. Reaction of a flavoenzyme with its substrate or an inhibitor can alter the tertiary structure of the active center to such an extent that the neighborhood of the flavin assumes a more lipophilic character. Such a change in polarity of the environment can bring about red shifts, *e.g.* in benzene-soluble derivatives of the free coenzyme with an unchanged flavoquinone chromophore [51,65].

Red intermediates are also encountered in flavoproteins which contain redox-active thiol groups (Section VI, 4) and in

[87] *T. Cremona* and *E. B. Kearney*, Nature (London) *200*, 542 (1963).

[88] *F.L.Crane, J.L.Glenn,* and *D.E.Green,* Biochim. biophysica Acta *22*, 475 (1956).

[89] *Z. Kaniuga,* Biochim. biophysica Acta *73*, 550 (1963); *Z. Kaniuga* and *C. Veeger,* ibid. *77*, 339 (1963).

[90] *E. Haas,* Biochem. Z. *290*, 291 (1937).

[91] *C. Gregolin* and *T. P. Singer,* Biochim. biophysica Acta *67*, 201 (1963).

[92] *A. Ehrenberg* and *G. D. Ludwig,* Science (Washington) *127*, 1177 (1958).

[93] S = Substrate, E = Enzyme, P = Product.

[94] *V. Massey* and *Q. H. Gibson,* Federat. Proc. *23*, 18 (1964).

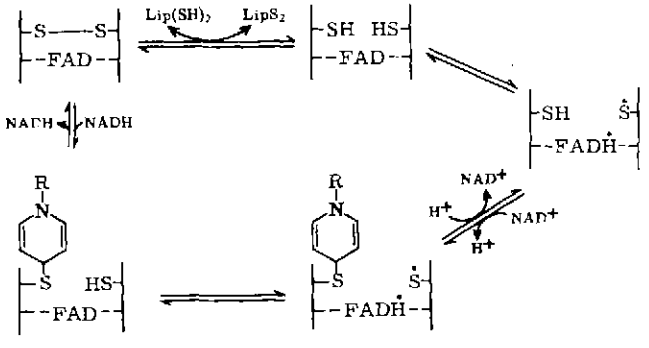
metal flavoproteins which exhibit red color in the aerobic resting state (cf. Section VI, 5).

It should be remembered that flavosemiquinone $\dot{F}lH_2$ is blue even in the protein-bound form (Section IV, 4), while the optical absorption of the radical anion $\dot{F}lH^{\ominus}$ remains to be established. Since the dissociation $\dot{F}lH_2 \rightleftharpoons \dot{F}lH^{\ominus} + H^{\ominus}$ occurs in position 1 or 4, a bathochromic effect is to be expected and accordingly $\dot{F}lH^{\ominus}$ should not be red.

4. Contact between Flavin and Sulfur in Flavoproteins

Massey and *Veeger* [95] were the first to show in the case of lipoamide dehydrogenase (≡ *Straub*'s diaphorase) that the system 2 RSH $\rightleftharpoons$ $(RS)_2 + 2\,H^+$ can participate as the corresponding redox system in the oxidoreduction of flavin, *i.e.* one cysteine group per flavin molecule participates in the active site of lipoamide dehydrogenase (and of other flavoproteins) [95–97].

On reduction with dihydrolipoamide or NADH, red, diamagnetic, stable intermediate forms of the enzyme are formed. Further reduction to flavohydroquinone is possible with NADH only if the product NAD^+ is removed from the equilibrium mixture. The enzyme is then no longer active. Dihydrolipoamide cannot, however, reduce



Scheme 8. Dihydrolipoamide dehydrogenase reaction, simplified scheme, taken from [95]. NAD = Nicotinamide adenine dinucleotide.

Prosthetic groups with a dot denote radicals or flavosemiquinone oxidation levels but not paramagnetic species; the overall spin is zero in each case.

the enzyme to the $Fl_{red}H_3$ stage. *Massey* and *Veeger* [95] interpret the reactions as shown in Scheme 8. The nature of the (Fl–S)-interaction remains unknown; certainly no well-defined oxidation states, in particular no radical character, can be assigned to the constituents of an (FlS) complex.

Evidently it is common to both metal-containing and metal-free flavoproteins that, under native conditions, complete reduction to the flavohydroquinone state need not take place at all. The two types of flavoprotein differ in that one-electron steps are possible in the metal flavoproteins. Here, transition to the oxidized state, which implies dissociation of the complex, appears to be difficult. This type of stability was found in the model chelate peracetylriboflavin-Cu(I) [55], which under anhydrous conditions is oxidized very slowly by oxygen.

[95] *V. Massey* and *C. Veeger*, Biochim. biophysica Acta *48*, 33 (1961).

[96] *V. Massey* in [1], Vol. VII, p. 275.

[97] *R. L. Searls, J. M. Peters*, and *D. R. Sanadi*, J. biol. Chemistry *236*, 2317 (1961).

5. Flavin-Metal Contact in Flavoprotein

Metal flavoproteins contain iron and sometimes also molybdenum. The ratio flavin : Mo is generally 1 : 1, while that of flavin : Fe varies between 1 : 1 and 1 : 4 and more [98]. In all iron flavoproteins except succinic dehydrogenase, the flavocoenzyme can be irreversibly detached. The residual iron protein then can no longer be reduced by the flavoprotein substrate but requires an artificial reducing agent ($S_2O_4^{2-}$). As *Handler et al.* [98] have shown, the residual iron proteins retain the optical and ESR properties of the flavoproteins. Hence the red color of the iron flavoproteins in the aerobic resting state is due mainly to the iron protein. In the half-reduced state this is not necessarily so [99], since properties of the protein-free model (cf. Section V) indicate that interaction between Fl_{ox} and Fe_{ox} takes place only after addition of an electron (charge-transfer chelate) or of two electrons (radical chelate).

Only recently direct proof of contact between the flavin and the metal in metal flavoproteins has been obtained from studies of the ESR relaxation of flavosemiquinone in metal-free and metal-containing flavoproteins (Fig. 7) [100].

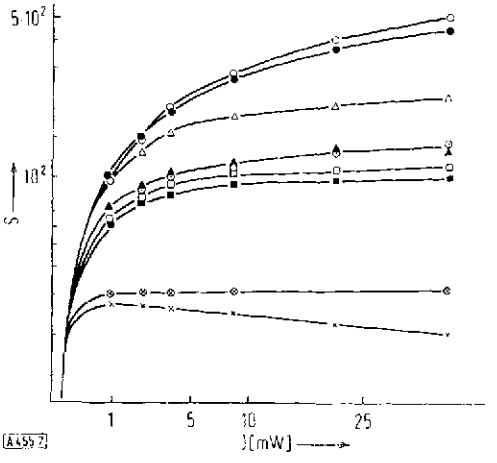


Fig. 7. Spin relaxation of the flavosemiquinone (g = 2.00) in flavoproteins and free flavocoenzymes; taken from [100].
o : Xanthine oxidase
● : dihydroorotic dehydrogenase
△ : NADH dehydrogenase
○ : succinic dehydrogenase
▲ : succinic acid-ubiquinone oxidoreductase
□ : aldehyde oxidase
■ : free flavin + 10 equivalents of Ni^{2+}
⊗ : lipoic dehydrogenase
x : all other metal-free flavoproteins and free flavocoenzymes.
Ordinate: Normalized signal amplitude (S).
Abscissa: Microwave intensity (J).

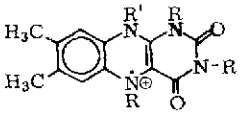
In all metal enzymes the excited spin of the free radical electron (g = 2.00) falls back to the ground state at a rate at least one order of magnitude greater than in any of the metal-free proteins. d-Metal ions affect the spin relaxation in model flavosemiquinones only when N–5 is unsubstituted, *e.g.* in *(63)*, R = H, but not in *(63)*, R = alkyl. The formation of a σ-bond between Fe and Fl, albeit

[98] *P. Handler, K. V. Rajagopalan*, and *V. Aleman*, Federat. Proc. *23*, 30 (1964).

[99] *P. Handler*, personal communication.

[100] *P. Hemmerich* and *H. Beinert*, Biochem. biophysic. Res. Commun. *18*, 212 (1965).

short-lived, is therefore essential; a pure π-type contact is not sufficient.



(63)

Accordingly, the flavin within a metal flavoprotein is only temporarily coordinated, *viz.* during the intermediate stage of the reduction. The equilibrium concentration of the metal-bound flavin fraction may vary widely from enzyme to enzyme.

It is thus the apoprotein which primarily determines the coordination sphere of the flavoprotein iron. For this reason, the influence of the substrate, artificial reducing agents, or inhibitors on the optical properties of metal flavoproteins is exceedingly complicated. An interpretation on a molecular basis is almost impossible in the absence of information about the environment of the iron [101].

6. The Bonding of Non-Heme Iron in Flavoproteins

The only reliable indication for an intact metal coordination sphere in non-heme iron proteins is the characteristic ESR signal appearing on reduction (Fig. 8) [102]. The asymmetry of the signal ($g_z \approx 2.00$, $g_x \approx g_y \approx 1.94$) indicates a coordination polyhedron of no more than rhombic symmetry. In the absence, up to very recently,

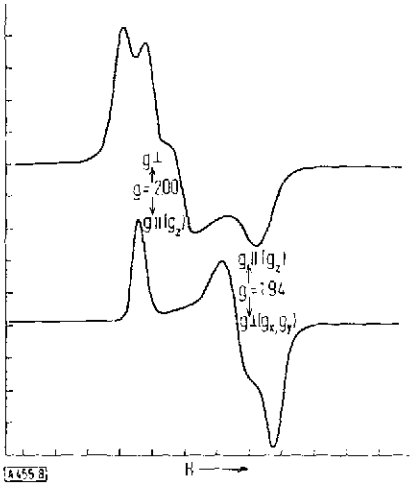


Fig. 8. Comparison of the ESR signals of a reduced non-heme iron protein (Fe-protein from *Azotobacter*, bottom curve), taken from [103], and of the first iron complex of well-defined structure, $Fe(CN)_5NO^{3-}$, with the same g-values; taken from [104].

In the upper curve, $g_\parallel$ shows the ^{14}N-hyperfine structure, due to interaction of the unpaired electron with the nuclear spin $I = 1$ of ^{14}N in the NO ligand of the model.

In contrast, the shoulder in $g_\parallel$ of the iron-protein spectrum must be ascribed to splitting into g_x, g_y which results from the lower symmetry of the natural Fe-coordination polyhedron as compared with the $Fe(CN)_4$ tetragon. Thanks are due to Prof. *Beinert*, Madison, for taking these spectra.

of well defined Fe(II) complexes with g values below 2.00, there was a good deal of doubt about the assignment of the "g = 1.94 signal" to such a complex, particularly since no such spectrum could be expected for Fe(II) in ligand fields of any strength. However, *Beinert et al.* [103] have meanwhile confirmed this assignment by comparison of the ESR spectra of ^{56}Fe- and ^{57}Fe-protein: The preparation containing the ^{57}Fe-isotope exhibited the hyperfine broadening to be expected from the non-zero nuclear spin of the metal.

Accordingly it was to be expected that low-spin Fe(II) with one additional, strongly delocalized electron must be involved in the "g = 1.94"-iron. This calls for the presence of at least one redox-active ligand. Together with *Beinert* and *van Voorst* we found a model of similar field symmetry and electron distribution, namely $[Fe(CN)_5NO]^{3-}$. This compound has a strong field with tetragonal symmetry and an unpaired electron which is so strongly delocalized that a well-resolved ^{14}N-hyperfine structure in addition to the g splitting is observed ($g \approx 1.93$, $g_x = g_y \approx 2.00$) (Fig. 8). The absolute g values are practically the same as in the ESR-active Fe proteins, although here sulfur seems to be the stabilizing acceptor ligand rather than nitrogen (*e.g.* the flavin N–5 atom) [105]. ESR-active Fe-proteins contain stoichiometric amounts of metal and sulfur; the latter can be liberated as H_2S with acid [106], so that normal cyst(e)ine cannot be the source. The chemical nature of this biochemically important "labile" sulfur remains to be explored. Presently it seems that in the non-heme iron four coordination sites are fixed in a strong ligand field, not tetragonally as in heme–Fe but in a (distorted) tetrahedron, so that bidentate redox-active ligands such as disulfides and/or flavin can enter into the reactive cis-positions 5 and 6. The stability of such a configuration must be governed by kinetic or steric factors, so that a good low molecular-weight model will not be easily found. This explains why in aqueous solution Cu(I) serves as a better model for the natural flavin-metal interaction than Fe(II).

Note added in proof: This survey was intentionally completed before the International Symposium on Flavins and Flavoproteins took place at Amsterdam, June 10th–15th, 1965. For the most recent developments as presented at this meeting the reader is referred to the Proceedings of this symposium (*E. C. Slater* and *C. Veeger* ed., Elsevier, Amsterdam, in the press).

The authors gratefully acknowledge the advice or experimental assistance given to them by their co-workers D. Der Vartanian, U. Hartmann, F. Müller, L. Nebel, E. Rommel, and T. Rowan as well as by H. Beinert (Madison), A. Ehrenberg (Stockholm), P. H. Gibson (Philadelphia), O. Gawron (Pittsburgh), M. Klingenberg (Marburg), D. McCormick (Cornell), V. Massey and G. Palmer (Ann Arbor), D. E. Metzler (Iowa State), W. Pfleiderer (Stuttgart), T. Singer (Detroit), E. C. Slater (Amsterdam), J. Spence (Utah State), and J. van Voorst (Amsterdam).

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Translated by Express Translation Service, London

[101] *D. V. Der Vartanian* and *C. Veeger*, Biochem. J. *84*, 65 P (1962).

[102] *H. Beinert* and *R. H. Sands*, Biochem. biophysic. Res. Commun. *3*, 41 (1960).

[103] *Y. I. Shethna, P. W. Wilson, R. E. Hansen*, and *H. Beinert*, Proc. nat. Acad. Sci. U.S.A. *52*, 1263 (1964).

[104] *H. Beinert, P. Hemmerich, D. V. Der Vartanian, C. Veeger*, and *J. D. W. van Voorst*, Biochim. biophysica Acta, in the press.

[105] Cf., for example, *W. A. Pryor*: Mechanisms of Sulfur Reactions. McGraw-Hill, New York 1962, p. 37 *et seq.*

[106] *J. S. Rieske, D. H. McLennan*, and *R. Coleman*, Biochem. biophysic. Res. Commun. *15*, 338 (1964).

The Free-Radical Nature of Nitroso Compounds

By Prof. Dr. W. Theilacker, Dipl.-Chem. A. Knop, and Dr. H. Uffmann

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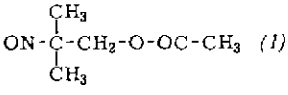
der Technischen Hochschule Hannover (Germany)

Dedicated to Professor F. Micheel on the occasion of his 65th birthday

2-Methyl-2-nitrosopropyl acetate *(1)*, obtained from propene [1], is colorless in the solid state but deep blue in solution; it exhibits paramagnetic resonance absorptions and has therefore free-radical character [2].

We have investigated this phenomenon using 0.1 M solutions in benzene or toluene at room temperature and have found that *N*-nitroso compounds do not give ESR signals; neither do nitrobenzene, azobenzene, azoxybenzene, nor 9,10-diazaphenanthrene-9,10-dioxide. *C*-Nitroso compounds such as *p*-nitrosodimethylaniline, 2-chloro-2-nitrosopropane, and 1-chloro-1-nitrosocyclohexane, which exist only as monomers, also give no ESR signal.

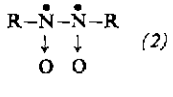
The ESR spectrum of *(1)* exhibits hyperfine structure with three sharp bands of equal intensity and of width 1 gauss with a splitting constant of 14.5 gauss. The splittings in the hyperfine structure in the ESR spectra of aromatic nitroso compounds such as nitrosobenzene, *p*-nitrosotoluene, and *p*-nitrosochlorobenzene are much more complex owing to interaction with the aromatic ring, but here too, resolution into three groups of bands (splitting constant for nitrosobenzene ca. 11 gauss) is apparent. These spectra show free radicals with a high probability for residence of the unpaired electron on the nitrogen to be present.



(1)

A broad band has been observed [3] for nitrosobenzene in ethanol and has been ascribed to a triplet state. We found no such broad band indicative of a triplet state with *(1)* in toluene but only three sharp bands with a g-value of about 2.00; there are no other resonance absorptions on either side of these bands within 2500 gauss, so it is certain that a triplet state is not present.

We assume that *(1)* occurs in the form of a biradical *(2)* in which no interaction occurs between the unpaired electron on one nitrogen atom and the nuclear moment of the other nitrogen and in which the field of each unpaired electron shields the other nitrogen atom. If this is true, 0.1 M solutions in toluene of *(1)* and of nitrosobenzene contain respectively 6 and 0.04% of the biradical form *(2)*. The free radical content increases strongly on passing from the solid (dimeric) nitroso compound to the solution. However, the free radical is not merely an intermediate in the dissociation of the dimer into the monomer, because the formation of the radicals proceeds much more slowly and the equilibrium dimer $\rightleftharpoons$ 2 monomer is attained before the sample is ready for ESR measurement [4].



(2)

The free radicals detected very probably are derived from the dimer, because nitroso compounds which exist as monomers do not give an ESR spectrum, and because the spectrum of 9-nitrosotrypticene, apart from the coupling with the ^{14}N nucleus, shows a further coupling with a *single* proton (hyperfine splitting 3 gauss), which can only be due to steric interaction with a definite proton in one of the aromatic rings. Only in the dimer is the nitroso oxygen sterically fixed in the neighborhood of a single proton.

The ESR spectra of *(1)* and nitrosobenzene in the solid (dimeric) state are more complicated. Although we observed three sharp bands with a splitting constant of 14.5 gauss with *(1)*, the spectrum is overlapped by a broad flat band extending over 50 gauss. Nitrosobenzene exhibits merely a broad unresolved doublet extending over 130 gauss.

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German version: Angew. Chem. 77, 717 (1965)

[1] Another synthesis has been described by *J. R. Schwarz*, J. Amer. chem. Soc. 79, 4354 (1957).

[2] The ESR spectrum observed cannot be due to NO, for the latter gives nine lines with a triplet splitting of 100 gauss and a hyperfine structure constant for ^{14}N of 27 gauss. Moreover, decomposition to free NO does not occur since the ESR spectrum of *(1)* remains constant for a month.

[3] *O. Ristau, H. Rein*, and *F. Jung*, Naturwissenschaften *51*, 262 (1964).

[4] An activation energy of 22.5 kcal/mole for the dissociation of the dimeric form of *(1)* into the monomeric form in toluene can be derived from the rate of dissociation (measured from the rate of disappearance of the dimer using ultraviolet spectroscopy or the rate of appearance of the monomer using visible or ultraviolet spectroscopy). *Schwartz* [1] found a value of 23.5 kcal/mole in benzene. The temperature dependence of the rate of free-radical formation from *(1)* gives a value for the activation energy of this reaction of 1–2 kcal/mole; this value is however doubtful owing to experimental uncertainties.

Synthesis of Diazomethyl Ketones without Using Diazomethane

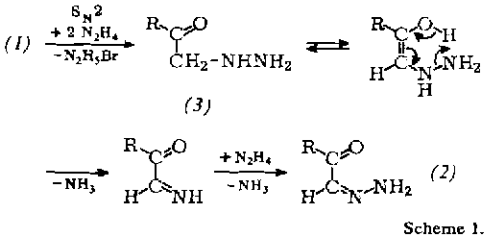
By Prof. Dr. S. Hauptmann, Chem.-Ing. M. Kluge, cand. chem. K.-D. Seidig, and cand. chem. H. Wilde

Institut für Organische Chemie der Universität Leipzig (Germany)

Diazo ketones such as diazomethyl phenyl ketone were previously always made from acid chlorides and diazomethane [1]. We have found that phenacyl bromide *(1)*, R = C_6H_5, reacts with hydrazine in ethanol at 60 °C according to Equation (a) to give a 60% yield of 2-phenylglyoxal monohydrazone *(2)*,

(1) *(2)* (a)

R = C_6H_5. Phenacylhydrazine *(3)*, R = C_6H_5 [2], can be isolated from the reaction mixture below 5 °C. This suggests that the reaction proceeds by the mechanism illustrated in Scheme 1. As in the formation of osazones, the oxidative action of hydrazine is only apparent.



(3) *(2)*

Scheme 1.

The 2-phenylglyoxal monohydrazone can be dehydrogenated by manganese dioxide hydrate [3] in chloroform at 20 °C

to form diazomethyl phenyl ketone *(4)*, R = C_6H_5, in 80% yield. Twenty other known diazo ketones and the

$$\underset{(2)}{R-CO-CH=N-NH_2} \xrightarrow{MnO_2} \underset{(4)}{R-CO-\overset{\ominus}{C}H-\overset{\oplus}{N}\equiv N}$$

unknown diazomethyl ketones listed in Table 1 were prepared in an analogous manner. The yields of the hydrazones

Table 1. New diazomethyl ketones *(4)*

(4), R =	M.p. [°C]	*(4)*, R =	M.p. [°C]
p-C_2H_5-C_6H_4	46–46.5	*p*-CH_3S-C_6H_4	101
p-$(CH_3)_2CH$-C_6H_4	67–68	*p*-$(CH_3)_2N$-C_6H_4	118–119
p-$(CH_3)_3C$-C_6H_4	82.5–83.5	*p*-NC-C_6H_4	142–144
p-Cyclohexyl-C_6H_4	107–108	3-Br-4-CH_3O-C_6H_3	133.5
p-F-C_6H_4	72.5		

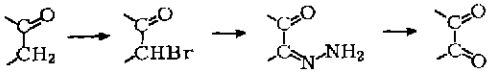
(2) lie between 50 and 70%, and the yields from the dehydrogenations between 80 and 85%.

Diazoketones R–CO–CN_2–C_6H_5 of the azibenzil type can be produced analogously from desyl halides R–C_6H_4–CO–$CH(C_6H_5)X$, but the yields of monohydrazone are only 30–40%. The new α-diazobenzyl phenyl ketones listed in Table 2 have been prepared in this way.

Table 2. New α-diazobenzyl phenyl ketones R–CO–$\overset{\ominus}{C}(C_6H_5)$–$\overset{\oplus}{N}\equiv N$

R	M.p. [°C]	R	M.p. [°C]
p-Cl–C_6H_4	80	*p*-Br–C_6H_4	95
p-CH_3–C_6H_4	87–88	*p*-CH_3O–C_6H_4	93–94

Since the hydrazones *(2)* are readily converted by HNO_2 into the free 1,2-diketones, a new method is available for the oxidation of carbonyl-activated methyl and methylene groups (see Scheme 2).



Scheme 2.

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German version: Angew. Chem. 77, 678 (1965)

[1] *B. Eistert* in *W. Foerst*: Neuere Methoden der präparativen organischen Chemie. Verlag Chemie, Weinheim, 1944. Vol. 1, p. 359.

[2] *M. Busch* and *W. Foerst*, J. prakt. Chem. *119*, 287 (1928).

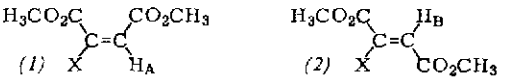
[3] Prepared according to *Houben-Weyl-Muller*: Methoden der organischen Chemie. Georg Thieme Verlag, Stuttgart, 1954. Vol. 7,1, p. 178.

The Stereochemistry of Additions to Acetylenic Triple Bonds

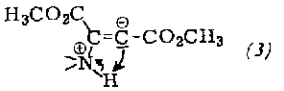
By Priv.-Doz. Dr. E. Winterfeldt and H. Preuss

Organisch-Chemisches Institut der Technischen Universität Berlin (Germany)

It has been observed that the addition of secondary amines to dimethyl acetylenedicarboxylate proceeds *via cis*-addition leading to products of type *(1)* independent of the solvent and basic catalysts used. On the other hand, the addition of alcohols catalysed by tertiary amines such as *N*-methylmorpholine proceeds almost stereospecifically to the *trans*-adducts of type *(2)*. The stereochemistry of the products can be recognized from the chemical shift of the olefinic proton (see Table).



The *trans*-addition can be readily understood in terms of the mechanism formulated by *Truce* [2]. The *cis*-addition can be interpreted as occurring *via* a cyclic electron shift as represented in *(3)*.



(3)

In order to test this hypothesis, the addition of aziridine onto dimethyl acetylene dicarboxylate was studied, because here, owing to the high ring strain in the complex *(3)*, deprotonation might occur readily – perhaps already during the formation of *(3)*. This should then give rise to a *trans*-addition, because a free proton is then added from the reaction medium and not intramolecularly *via* the cyclic mechanism. We found – in agreement with *Dolfini* [1] – that the *trans*-adduct *(2)* is in fact produced in 10% yield alongside 90% *cis*-adduct in ether as solvent. Thermal, non-catalysed addition of alcohols yields *cis*-adduct *(1)* in accordance with the mechanism expressed in *(3)*. Hence the configurational stability of the *trans*-adduct under the conditions of the reaction is assured.

These findings are in agreement with observations of *Jones* and *Whiting* on hydroxyacetylenecarboxylic esters [3] and refute the statement by *Hendrickson* [4] that compounds with mobile hydrogen always afford the *trans*-adducts.

Received: May 20th, 1965 [Z 977/823 IE]
German version: Angew. Chem. 77, 679 (1965)

[1] *J. E. Dolfini*, J. org. Chemistry *30*, 1298 (1965).

[2] *W. E. Truce, H. G. Klein*, and *R. B. Kruse*, J. Amer. chem. Soc. *83*, 4636 (1961).

[3] *E. R. H. Jones* and *M. Whiting*, J. chem. Soc. (London) *1949*, 1423.

[4] *J. B. Hendrickson* et al., J. Amer. chem. Soc. *86*, 107 (1964).

X	$(CH_3)_2N$	$(C_2H_5)_2N$	Piperidino	*N*-Aziridinyl	CH_3O	$(CH_3)_2HCO$	C_6H_5O
τ_A	5.6	5.55	5.42	4.8	4.9	4.9	4.95
τ_B	–	–	–	3.9	3.9	–	3.55

Reversibility of Betaine Formation during the Wittig Reaction

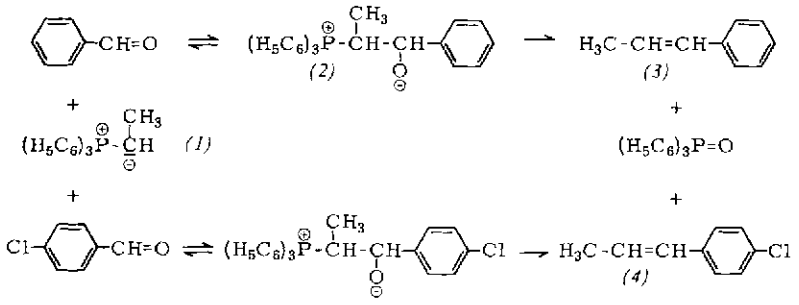
By Dr. M. Schlosser and cand. chem. K. F. Christmann

Organisch-Chemisches Institut der Universität Heidelberg (Germany)

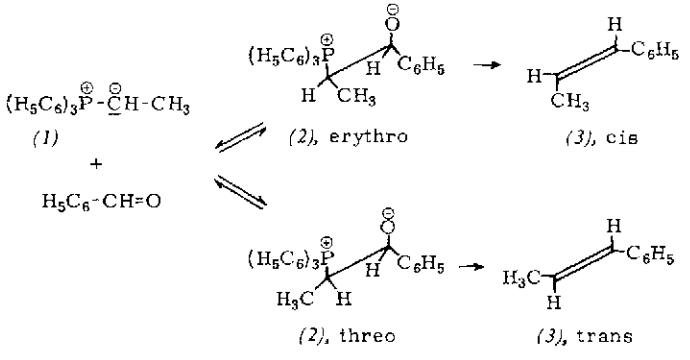
In connection with the stereochemistry of the Wittig carbonyl olefination reaction, the possibility has been discussed [1,2] that even betaines which are derived from non-stabilized phosphorus ylides can redissociate into their components. We have now shown by two different methods that this dissociation takes place.

p-Chlorobenzaldehyde was added to a suspension in benzene or a solution in ether/t-butanol of a mixture of the *threo*- and *erythro*-forms of the betaine *(2)* [3]. The chlorobenzaldehyde trapped some of the ylide *(1)* [3] which together with benzaldehyde is present in equilibrium with *(2)*. When the components were shaken for 16 h at 20 °C, a mixture of *cis*- and

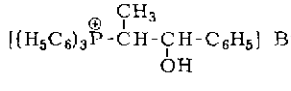
trans-p-chloro-β-methylstyrene *(4)* was obtained in 38% yield in the benzene and in 52% yield in the ether/t-butanol mixture; in addition, 25% and 18% respectively of a mixture of *cis-* and *trans*-β-methylstyrene *(3)* was also formed [4].



Moreover, it proved possible to convert mixtures in which either the *threo-* or *erythro*-forms of *(2)* were enriched, into the normal equilibrium mixture of the diastereoisomers of *(2)*. When *(2)* having a ratio of *threo*-form to *erythro*-form of 90:10 or 99:1 was shaken for 30 h in suspension in benzene at 20 °C, about 50% of *(2)* with the new *threo*:*erythro* composition of 95:5 was recovered in both cases. A 10:90 mixture of the *threo-* and *erythro*-forms of *(2)* had acquired the composition 75% *threo*: 25% *erythro* after the same time.



The ratios of the diastereoisomers were determined by treating *(2)* with HBr in ether, isolating the mixture of the *threo-* and *erythro*-forms of the α-methyl-β-hydroxyphenethyltriphenylphosphonium bromide *(5)* formed, and converting it with potassium t-butoxide into *cis-* and *trans*-β-methylstyrene *(3)*. The salt *(5)* was crystallized from dichloro-



methane in fractions enriched in either the *threo-* or *erythro*-component, *e.g.* with 94% *erythro*-form, m.p. 185–187 °C, or with 90% *threo*-form (solidified oil). Such well-defined mixtures of the diastereoisomeric forms of *(5)* are transformed by phenyl-lithium into the corresponding mixtures of the diastereoisomers of the betaine *(2)*.

Received: May 24th, 1965 [Z 5/832 IE]
German version: Angew. Chem. *77*, 682 (1965)

[1] *L. D. Bergelson, V. A. Vaver, L. I. Barsukov,* and *M. M. Shemyakin*, Tetrahedron Letters *1964*, 2669.

[2] *G. Wittig, H. D. Weigmann,* and *M. Schlosser*, Chem. Ber. *94*, 676 (1961).

[3] For clarity the formulae of *(1)* and *(2)* have been drawn without inclusion of the complexed lithium halide (but cf. [5]).

[4] *A. J. Speziale* and *D. E. Bissing* have carried out similar competition experiments with *m*-chlorobenzaldehyde and a betaine derived from a stable phosphorus ylide; J. Amer. chem. Soc. *85*, 3878 (1963).

[5] *M. Schlosser* and *K. F. Christmann*, Angew. Chem. *76*, 683 (1964); Angew. Chem. internat. Edit. *3*, 636 (1964).

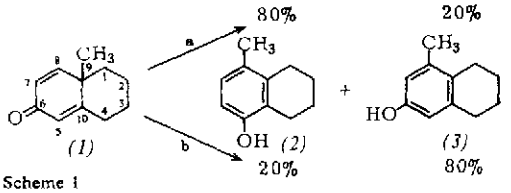
A New Rearrangement of ar-Tetralols with Perchloric Acid [1]

By Dr. med. W. H. Hopff and Prof. Dr. A. S. Dreiding

Organisch-Chemisches Institut der Universität Zürich (Switzerland)

Dedicated to Professor Eugen Müller on the occasion of his 60th birthday

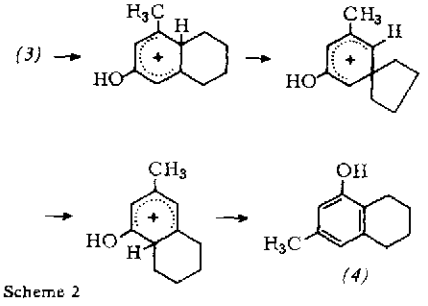
When 1,2,3,4,6,9-hexahydro-6-oxo-9-methylnaphthalene *(1)* was subjected to the dienone-phenol rearrangement by treating it with a little concentrated sulfuric acid in acetic anhydride (conditions a), the only product isolated was 8-methyl-5-tetralol *(2)* [2], whereas with 30–50% aqueous mineral acid (conditions b) the main product was 5-methyl-7-tetralol [3]. Gas-chromatographic analysis of the reaction products has now given the results shown in Scheme 1 [4].



Scheme 1

The carbon skeletons in the phenols *(2)* and *(3)* remain unchanged under both conditions a and b and hence we conclude that both reactions are kinetically controlled [5].

During the course of these investigations we discovered a new thermodynamically controlled rearrangement. On treatment of the dienone *(1)* with 70% perchloric acid, only one rearrangement product is formed, *viz.* 7-methyl-5-tetralol *(4)*, which was shown to be identical with an authentic sample [6]. If the 70% perchloric acid were to convert the dienone *(1)* first into the phenol *(3)* – as does dilute aqueous mineral acid – then the thermodynamic control would have to be ascribed to the rearrangement *(3)* → *(4)*. When *(3)* was treated with 70% perchloric acid at 80 °C for 2 h, the phenol *(4)* was in fact formed in 80% yield. We therefore consider the mechanism shown in Scheme 2 to be applicable to this new "phenol-phenol rearrangement".



Scheme 2

This rearrangement also occurs with *ar*-β- and *ar*-α-tetralol, an approximately 1:1 equilibrium mixture being produced from both substances. In contrast, the equilibrium in the system *(3)* ⇌ *(4)* lies almost entirely on the side of *(4)*.

Received: May 26th, 1965 [Z 999/833 IE]
German version: Angew. Chem. *77*, 717 (1965)

[1] *A. S. Dreiding*, Chemical Society (London) Anniversary Meeting, Birmingham 1964. – We wish to thank Messrs. Sandoz SA., Basel (Switzerland) for generous support of this work.

[2] *R. B. Woodward* and *T. Singh*, J. Amer. chem. Soc. *72*, 494 (1950).

[3] *A. S. Dreiding, W. J. Pummer,* and *A. J. Tomasewski*, J. Amer. chem. Soc. *75*, 3159 (1953).

[4] *G. Sassu* participated in this analytical work.

[5] The same results have been obtained for similar compounds under conditions b by *P. J. Kropp*, Tetrahedron Letters *1963*, 1671.

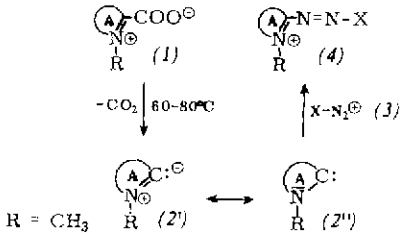
[6] *R. G. Cooke* and *H. Dowd*, Austral. J. Chem. *6*, 53 (1952).

Formation of Nucleophilic Carbenes from Heterocyclic N-Methyl Betaines

By Dr. H. Quast and E. Frankenfeld

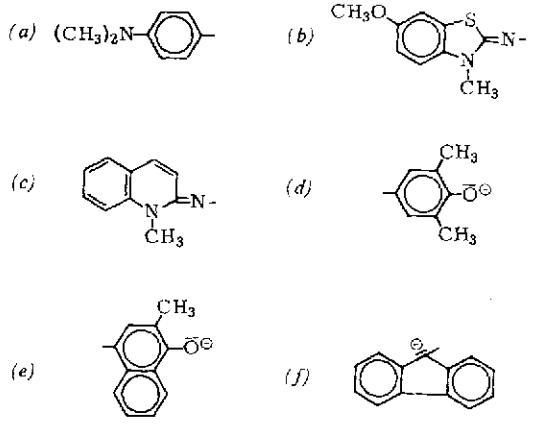
Chemisches Institut der Universität Würzburg (Germany)

We have found that the betaines *(1u)*, *(1v)*, and *(1w)* with the heterocycles A = 2-pyridine [1], 2-quinoline [2], or 1-isoquinoline [3] are decarboxylated by merely warming to 40–80 °C in an aprotic solvent. The ylides *(2)* formed [4] can be trapped by *N*-electrophiles *(3)* to form the colored compounds *(4)*.



X–$N_2^{\oplus}$	Proportion *(3)* : *(1)*	Yield [%] in *N*-methylpyrrolidone of *(4)* from *(1a)* at 80 °C	*(1b)* at 60 °C	*(1c)* at 60 °C
(3a)	1.3:1	11	55–60 [5]	45
(3b)	2:1	26	55	79
(3c)	2:1	—	56	—
(3d)	2:1	—	12–18	—
(3e)	2:1	—	11–17	—
(3f)	3:1	—	1	—

Substituents X in compounds *(3)* and *(4)*:



The rate-determining step in the reaction is apparently the decarboxylation, for the rate of liberation of CO_2 is not affected by the nature of the electrophile *(3)* although the yields of *(4)* depend in a characteristic fashion on the reactivity of the trapping reagent.

The betaines *(1x)*, *(1y)*, and *(1z)* with the heterocycles A = 4-pyridine [1], 4-quinoline [6], and 3-isoquinoline [3] decompose some 50–100 °C higher than *(1u)*, *(1v)*, or *(1w)*. They do not form dyes *(4)* with *(3a)* and *(3b)* under the conditions mentioned above. The greater stability of *(1x)* is in accordance with the results of kinetic experiments [7] where it was found that the rates of decarboxylation of 2-, 3-, and 4-pyridine betaines at 196 °C in ethylene glycol containing 5% quinoline were in ratios of 1600:2.8:1. In order to explain these findings it is assumed that the stabilization of *(2)* is due to an inductive effect of the nitrogen and the mutual steric hindrance of the carboxyl and methyl groups in the ground state of *(1)* [7]. However, comparison of *(1v)* and *(1w)* with *(1z)* reveals that the stability of the ylide *(2)* and hence the activation energy for the decarboxylation are intimately connected with the formation of a low-energy limiting structure *(2'')*.

Received: May 28th, 1965 [Z 1000/825 IE]
German version: Angew. Chem. *77*, 680 (1965)

[1] *E. M. Kosower* and *J. W. Patton*, J. org. Chemistry *26*, 1318 (1961).

[2] *W. H. Mills* and *F. M. Hamer*, J. chem. Soc. (London) *121*, 2011 (1921).

[3] Prepared by methods similar to those described in [2,3].

[4] Nucleophilic carbenes or ylides analogous to *(2')* have already been detected by trapping reactions in the benzthiazole (R = CH_3, C_2H_5), pyridine, quinoline, and isoquinoline series (R = H). See *H. Quast* and *S. Hünig*, Angew. Chem. *76*, 989 (1964); Angew. Chem. internat. Edit. *3*, 800 (1964); Chem. Ber., in press; *H. Balli*, Angew. Chem. *76*, 995 (1964); Angew. Chem. internat. Edit. *3*, 809 (1964); *B. R. Brown*, Quart. Revs. (Chem. Soc. London) *5*, 131 (1951).

[5] *S. Hünig* and *H. Nöther*, Liebigs Ann. Chem. *628*, 69 (1959).

[6] *W. H. Mills* and *R. S. Wishart*, J. chem. Soc. (London) *117*, 587 (1920).

[7] *P. Haake* and *J. Mantecon*, J. Amer. chem. Soc. *86*, 5230 (1964).

Reaction of Allyl Halides with Diazomethane Catalysed by Copper Salts

By Prof. Dr. W. Kirmse and Dipl.-Chem. M. Kapps

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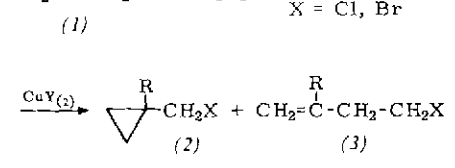
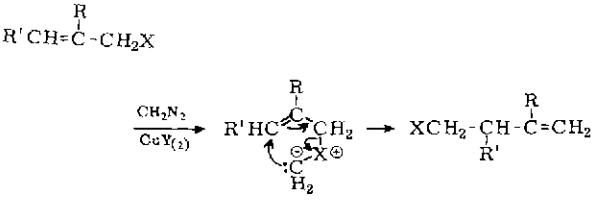
Catalytic decomposition of diazomethane by copper salts in the presence of olefins [1] or aromatic compounds [2] causes insertion of methylene to give cyclopropane or cycloheptatriene derivatives. When this reaction was applied to allyl halides *(1)*, two products were obtained, *viz.* cyclopropylmethyl halides *(2)* and 4-halogenobutenes *(3)*; the total yield based on diazomethane was between 20 and 60%.



When X = Cl, the main product is *(2)*, but when X = Br, preferentially *(3)* is produced. The formation of *(3)* in preference to *(2)* is also promoted when R = Cl. Numerous anhydrous salts of copper(I) and copper(II) can be used as catalysts in this reaction. The use of Cu(I) halides precludes exchange with the halogen of the allyl halide.

The formation of *(2)* is in accordance with known examples [1] and occurs stereospecifically [3]. The 4-halogenobutenes *(3)* are not formed by rearrangement of *(2)*, nor by insertion of H_2C into the C–X bond as in the photolysis of diazomethane in the presence of alkyl halides [4]. It was shown with deuterated and methyl-substituted compounds that the formation of *(3)* is accompanied by a complete allyl rearrange-



ment. We consider this unusual reaction to be due to an electrophilic attack of the H_2C on the halogen with a subsequent S_Ni' reaction.

Received: May 31st, 1965 [Z 1/826 IE]
German version: Angew. Chem. 77, 679 (1965)

[1] *M. F. Dull* and *P. G. Abend*, J. Amer. chem. Soc. *81*, 2588 (1959); *G. Wittig* and *K. Schwarzenbach*, Liebigs Ann. Chem. *650*, 1 (1962); *W. Roth*, ibid. *671*, 10 (1964); *W. v. E. Doering* and *W. Roth*, Tetrahedron *19*, 715 (1963); *E. Vogel*, *W. Wiedemann*, *H. Kiefer*, and *W. F. Harrison*, Tetrahedron Letters *1963*, 673; *R. E. Rincock* and *J. I. Wells*, J. org. Chemistry *29*, 965 (1964).

[2] *E. Müller* et al., Z. Naturforsch. *15b*, 753 (1960); Liebigs Ann. Chem. *661*, 38 (1963); *662*, 38 (1963); *675*, 63 (1964); Tetrahedron Letters *1963*, 1047, 1501; *1964*, 1525.

[3] *W. Kirmse* and *R. B. Hager*, unpublished experiments with *cis*- and *trans*-1,4-dichloro-2-butene; cf. *W. Kirmse*, Angew. Chem. *77*, 3 (1965); Angew. Chem. internat. Edit. *4*, 3 (1965).

[4] *V. Franzen*, Liebigs Ann. Chem. *627*, 22 (1960); *J. N. Bradley* and *A. Ledwith*, J. chem. Soc. (London) *1961*, 1495.

Rearrangement of β-Alkoxyalkylcarbenes

By Prof. Dr. W. Kirmse and Dipl.-Chem. M. Buschhoff

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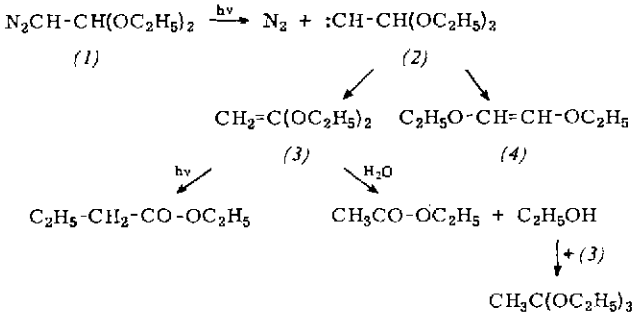
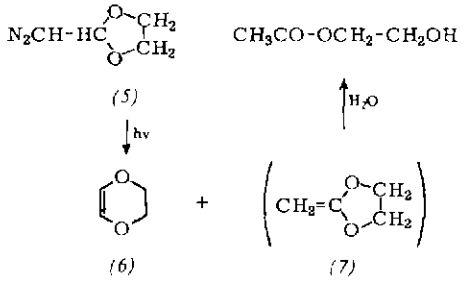
Diazoacetaldehyde diethylacetal *(1)* was obtained in solution by alkaline cleavage of the corresponding nitrosourea. Photolysis or catalytic decomposition of *(1)* with Cu or CuCl leads to ketene diethylacetal *(3)* and 1,2-diethoxyethylene *(4)*, the latter in a *cis*:*trans* ratio of about 1:2. Compound *(3)* was detected only when the solution of *(1)* had been dried over sodium; otherwise ethyl acetate and ethyl orthoacetate are obtained as hydrolysis products of *(3)*. On prolonged irradiation, *(3)* is transformed into ethyl butyrate.

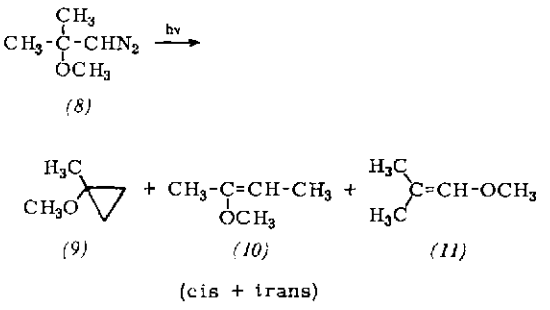


We consider *(3)* and *(4)* to be stabilization products of the carbene *(2)*. No *(4)* is formed by proton-catalysed decomposition of *(1)*. Although carbenes are known to cause hydrogen shifts [1], migration of an alkoxyl group has not been observed previously.

Diazoacetaldehyde ethyleneacetal *(5)* was also prepared and reacted in the same way. Here alkoxyl migration leads to 1,4-dioxene *(6)*. Ketene ethyleneacetal *(7)* is highly reactive and could be procured only in the form of its hydrolysis product, glycol monoacetate.



Irradiation of 1-diazo-2-methoxy-2-methylpropane *(8)* results apart from the usual intramolecular insertion reaction leading to *(9)*, mainly in methyl migration to give 2-methoxy-2-butene *(10)*; only traces of 1-methoxy-2-methylpropene *(11)*, which is formed by a methoxyl shift, were found.



This example demonstrates that the alkoxyl group is not particularly prone to migrate but rather that a β-alkoxyl group tends to promote migration of other β-substituents such as alkyl or alkoxyl [2]. This effect is probably due to the stabilization of a partial positive charge in the transition state [3].

Received: May 31st, 1965 [Z 2/827 IE]
German version: Angew. Chem. 77, 681 (1965)

[1] Cf. *W. Kirmse*: Carbene Chemistry. Academic Press Inc., New York 1964, pp. 47–64.

[2] Little or no alkyl migration is observed with alkyl carbenes such as $(CH_3)_3C-CH$: [1].

[3] An analogous effect involving *intermolecular* insertion is discussed by *W. v. E. Doering*, *L. H. Knox*, and *M. Jones*, J. org. Chemistry *24*, 136 (1959).

Bond Angles in Metal Carbonyl and Metal Nitrosyl Compounds [1]

By Priv.-Doz. Dr. W. Beck, Dr. A. Melnikoff [2], and cand. chem. R. Stahl

Anorganisch-Chemisches Laboratorium der Technischen Hochschule München (Germany)

The angle between equivalent metal-carbonyl and metal-nitrosyl bonds can be determined from the ratio of the absolute infrared intensities I of the symmetric (I_s) and asymmetric

$$I = \lim_{c \cdot d \to 0} \frac{1}{c \cdot d} \int \log (I_0/I)_\nu \, d\nu$$

(I_{as}) carbonyl and nitrosyl valence vibrations. The premise is made that the intensity of a band is proportional to the square of the change in dipole moment occurring during the vibration. This transition moment is derived from the representation of the stretching modes by vector addition of the equivalent changes in dipole moment of the carbonyl or nitrosyl bonds [3]. The angle α between the carbonyl groups and the n-fold axis can be calculated for a series of metal carbonyl complexes using the relationships given in the third column of the Table; β is the calculated angle between two neighboring carbonyl groups and β_{exp} is the value found by X-ray or electron diffraction. Plausible values are also obtained for pentacarbonyl manganese compounds and for $Co(CO)_2(NO)P(C_6H_{11})_3$. This method appears to be applicable to metal carbonyl and metal nitrosyl compounds, in which the carbonyl or nitrosyl stretching vibrations are strictly localized. Since the calculated values for the angles are not sensitive to small changes in I_{as}/I_s, experimental errors in I are relatively unimportant. To a rough approximation the bond angle can be arrived at simply from the ratio of the maximum absorptivities: for

Compound	Symmetry of the $M(CO)_x$ group	$(I_{as}/I_s)_{calc}$	$I_s \times 10^4$	$I_{as} \times 10^4$	α	β	β_{exp}
			[l/mole.cm²]		[°]		
$Co(CO)_3NO$	C_{3v}	$\frac{\sin^2\alpha}{\cos^2\alpha}$	1.39 (A_1)	11.2 (E) [4]	70	109	109.5 [7]
$[Fe(CO)_3NO]$	C_{3v}		1.52 (A_1)	14.3 (E) [4]	72	111	89 [8]
$C_6H_6Cr(CO)_3$	C_{3v}		4,83 (A_1)	8.70 (E) [5]	53	88	91; 94 [9]
$C_5H_5Mn(CO)_3$	C_{3v}		3.17 (A_1)	8.88 (E) [5]	60	96	93; 102 [10]
ButadieneFe$(CO)_3$	„C_{3v}“		2.62	8.69 [6]	61	98	
$C_5H_5V(CO)_4$	C_{4v}		2.18 (A_1)	7.47 (E) [5]	62	77	
$CH_3Mn(CO)_5$ [a]	C_{4v}		0.28 (A_1) [c]	10.6 (E)	81	88	
$CF_3Mn(CO)_5$ [a]	C_{4v}		0.15 (A_1) [c]	11.4 (E)	83	89	
$IMn(CO)_5$ [a]	C_{4v}		0.66 (A_1) [c]	9.45 (E)	75	86	
$Co(CO)_2(NO)P(C_6H_{11})_3$ [b]	C_{2v}		2.5 (A′)	4.4 (A″)	53	106	

[a] Solution in n-heptane. [b] Solution in CCl_4. [c] Totally symmetric radial CO stretching vibration.

example, for gaseous $Fe(NO)_2(CO)_2$, which has a tetrahedral structure [7], a value of 108° is found in this way for the angles CO–Fe–CO and NO–Fe–NO.

Received: June 2nd, 1965 [Z 3/828 IE]
German version: Angew. Chem. 77, 719 (1965)

[1] Spectroscopic Investigations of Complex Compounds, Part 8. Part 7: *W. Beck* and *K. Lottes*, Chem. Ber., in the press.

[2] We wish to thank the Salters' Company, London (England) for a research grant to A. M.

[3] The NC–N–CN angle in the dicyanamide ion was recently determined in this way by *D. Steele*, Quart. Rev. (chem. Soc. London) *18*, 21 (1964).

[4] *W. Beck* and *R. E. Nitzschmann*, Z. Naturforsch. *17b*, 577 (1962).

[5] *R. D. Fischer*, Spectrochim. Acta *19*, 842 (1963).

[6] *K. Noack*, Helv. chim. Acta *45*, 1847 (1962).

[7] *L. O. Brockway* and *J. S. Anderson*, Trans. Faraday Soc. *33*, 1233 (1937).

[8] *P. Corradini* and *G. Allegra*, J. Amer. chem. Soc. *81*, 2271 (1959).

[9] *A. F. Berndt* and *R. E. Marsh*, Acta crystallogr. *16*, 118 (1963).

[10] *O. S. Mills* and *G. Robinson*, Acta crystallogr. *16*, 758 (1963).

Production of Mixed Dicarboxamides from Cyclic Secondary Amines and Cyclic Dicarboximides. Products of the Reaction of Aziridine with Maleimide

By Dr. J. Sambeth and Dr. F. Grundschober

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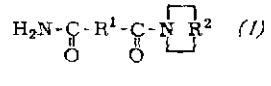
Mixed amides of type *(1)* derived from dicarboxylic acids, ammonia, and a cyclic secondary amine can generally be



(1)

made by aminolysis of the corresponding dicarboxylic ester chlorides ROOC–R^1–COCl *(2)* with a secondary amine and subsequent ammonolysis of the ester group with concentrated aqueous ammonia (Method A).

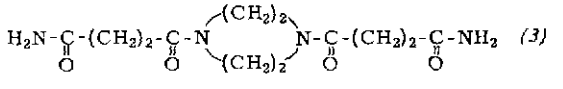
Practical Procedure [1]: A solution of 1 mole of β-methoxycarbonylpropionyl chloride [2] in ether is cooled in ice and 2.2 moles of a cyclic secondary amine is added slowly. The hydrochloride formed is filtered off, and the filtrate is concentrated and vacuum distilled. The resultant β-methoxycarbonylpropionamide is left standing for 4 days with excess 25% aqueous ammonia; the solution is then concentrated and the diamide produced recrystallized from acetone. – In order to procure the aziridine derivative *(1a)*, the ammonolysis must be carried out with anhydrous ammonia in methanol.

It is preferable to treat higher homologues of the cyclic secondary amine (more than 3 carbon atoms) simply with dicarboximides in order to make the mixed dicarboxamides *(1)* [Method B]. In practice, the dicarboximides are heated to boiling with a slight excess (about 10%) of the cyclic secondary amine; the product precipitated on cooling is filtered off and recrystallized from acetone. All the compounds listed in Table 1 are soluble in organic solvents and in water [hot water in the case of *(1e)*].

Table 1. Mixed dicarboxamides *(1)*.

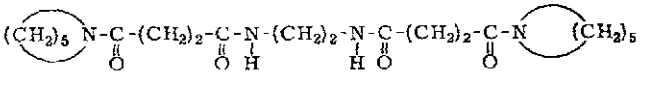
	R^1	R^2	Method A M.p. [°C]	Method A Yield [%]	Method B M.p. [°C]	Method B Yield [%]
(1a)	$(CH_2)_2$	$(CH_2)_2$	85–87	39	–	0
(1b)	$(CH_2)_2$	$(CH_2)_4$	105–108	23	105–107	96
(1c)	$(CH_2)_2$	$(CH_2)_5$	104–105[1]	44	103–105	94
(1d)	$(CH_2)_2$	$(CH_2)_6$	74–76	49	74–78	92
(1e)	$(CH_2)_2$	$(CH_2)_{12}$	–		136–139	85
(1f)	$(CH_2)_2$	$(CH_2)_2$–O–$(CH_2)_2$	–		115–116	95
(1g)	$(CH_2)_3$	$(CH_2)_5$	–		85	90
(1h)	*o*-Phenylene	$(CH_2)_5$	–		120	82

The mixed amide *(3)*, m.p. 200–203 °C, is formed in 50% yield by the reaction of 2 moles of succinimide with 1 mole of



(3)

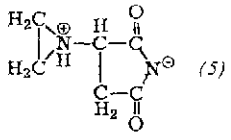
piperazine in triethylene glycol dimethyl ether at 150 °C. *N*-Substituted dicarboximides also react according to Method B. When *N,N′*-ethylenebissuccinimide is heated in a sealed tube at 160 °C with a threefold excess of piperidine, an 85% yield of the mixed amide *(4)* is formed; m. p. 143 to 144 °C.



(4)

Cyclic dicarboximides react at about 80 °C without solvent with aziridine (ethylenimine) by ring opening of both components to give polymers [3]; the reaction of aziridine with maleimide, on the other hand, is strongly exothermic and leads to ill-defined dark products. However, when a solution of aziridine in ether is added dropwise with vigorous stirring to an equimolar amount of maleimide in ether at 25 °C, a white crystalline powder crystallizes out which after recrystallization from acetone melts at 123–125 °C. Its elemental composition and molecular weight indicate it to be 3-(1-aziridinyl)succinimide [4]. Its infrared spectrum contains the bands at 1775 and 1680 cm^{-1} characteristic of the

–CO–NH–CO– group in cyclic imides. Hydrolysis of the compound with dilute acid or alkali releases 1 mole of ammonia. The aziridine ring in the molecule can be determined by acidimetric titration after addition of sodium thiosulfate [5]. The compound is readily soluble in water and on potentiometric titration with 0.1 N NaOH requires 1 mole of sodium hydroxide to neutralize its acidic imide hydrogen. Its aqueous solution has a neutral reaction hence the compound is here probably in the form of an intramolecular salt *(5)*. On melting, the compound undergoes an exothermic reaction to form a strongly cross-linked infusible polymer, which



(5)

is insoluble in organic solvents but swells readily in water; this polymer is hydrolysed by prolonged heating with acids and alkalies and decomposes at 300 °C.

N,N'-Polymethylenebismaleimides with the bridging elements $-(CH_2)_6-$, $-(CH_2)_{12}-$, and $-C_6H_4-CH_2-C_6H_4-$ add on two molecules of aziridine in the same way to give two sirupy products and a crystalline compound that melts at 123–126 °C. On prolonged heating polymerization occurs.

Received: June 3rd, 1965 [Z 10/836 IE]
German version: Angew. Chem. 77, 718 (1965)

[1] *M. Semonsky* and *A. Cerny*, Chem. Listy *47*, 281 (1953).

[2] *J. Cason*, Org. Syntheses Coll. Vol. *3*, 169 (1955).

[3] *J. Sambeth* and *F. Grundschober*, Swiss Patent Applications 1508/64 (Dec. 10th, 1964).

[4] The analogous reaction of maleic esters has been observed by *H. Bastian* et al., German Patent 849407 (Aug. 8th, 1944). It has also been found that piperidine also adds onto the C=C double bond of maleimide: *P. O. Tawny, R. H. Snyder, P. P. Conger, K. A. Leibbrand, C. H. Stiteler*, and *A. R. Williams*, J. org. Chemistry *26*, 21 (1961).

[5] *E. Allen* and *W. Seaman*, Analytic. Chem. *27*, 540 (1955).

Cyclotrimethine Dyes Derived from Squaric Acid

By Prof. Dr. A. Treibs and Dipl.-Chem K. Jacob

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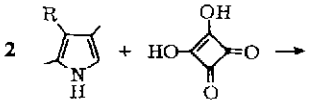
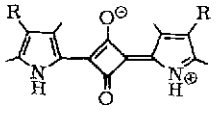
1,2-Dihydroxycyclobutenedione or squaric acid *(1)* [1,2] can be condensed with highly reactive pyrroles [3] to give red-violet dyes which are similar to the cyclotrimethine dyes [4]. Owing to the acidity of squaric acid *(1)*, which is still maintained in the dye bridge, the dyes are intramolecular salts, whereas the dipyrrylmethine and dipyrrylpolymethine dyes known to date are salts of dye bases.



(1)

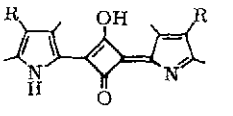


(2)

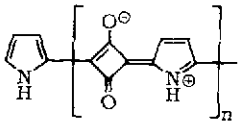
(2a), R = H
(2b), R = $CO_2C_2H_5$
(2c), R = $CO\text{-}CH_3$
(2d), R = C_2H_5

Judging from their mode of formation, elemental composition, and infrared and ultraviolet absorption spectra, the new dyes should have the betaine structure *(2)*, which is stabilized by resonance. The positions and intensities of the absorption bands of the new dyes in particular correspond to the salt form of the trimethine and cyclotrimethine dyes with five- to eight-membered carbo- and heterocyclic rings [4, 5]. The carbonyl absorption in the infrared is at an extremely long wavelength (1620 cm^{-1}) owing to the peculiar bonding arrangement. The possibility of the existence of a tautomeric form *(3)* of *(2)* cannot be excluded; the yellow to red solutions given by the dyes in alkali are probably derived from the form *(3)*. NMR measurements to decide this question could not yet be carried out because of the poor solubility of the new dyes. The dyes *(2a)* and *(2b)* are decolorized rather rapidly by solutions of amines in ethanol. With *(2a)* this reaction is not merely salt formation, for the regeneration of the dye with acid occurs very slowly.

Pyrrole, *N*-methylpyrrole, and pyrrole derivatives with both α-positions free give only blue to blue-green insoluble polymers by polycondensation; these probably have the formula



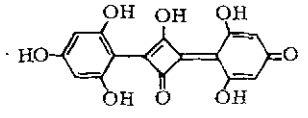
(3)



(4)

(4). Dyestuffs are also formed with 2-substituted indoles, but indole itself undergoes secondary reactions.

Phenols and pyrroles have many reaction features in common. Thus phloroglucinol also condenses smoothly with squaric acid. The resultatet deep red-violet crystalline dyestuff proba-



(5)

bly has the structure *(5)* or a tautomeric polar form of it. The presence of a polar form is not excluded by the position of the absorption due to the carbonyl group on the four-membered ring at 1635 cm^{-1}. Methylation or acetylation dispels the dye character of *(5)* completely. Resorcinol also gives rise to a dye with squaric acid, but phenol does not and can therefore be used as solvent for the reactions described.

Synthesis of (2a): 2,4-Dimethylpyrrole is condensed with squaric acid in a molar ratio of 2:1 in ethanol by heating at 70 °C or by prolonged standing at 20 °C with catalytic amounts of perchloric acid. The violet crystals of *(2a)* are obtained in 65 % yield after washing with ethanol, water, ethanol, and ether, and are recrystallized from chloroform. These crystals release 1 mole of water of crystallization at 90 °C in vacuum and then melt at 240–250 °C (decomp.); the ultraviolet spectrum of *(2a)* in chloroform has $\lambda_{max} = 550 m\mu$ ($\varepsilon = 1.2 \times 10^5$); its infrared spectrum in KBr has ν_{NH} at 3230 cm^{-1} (w) and ν_{CO} at 1635 (vs) and 1610 cm^{-1} (vs).

Synthesis of (5): Quadratic acid is refluxed for 4 h with a twofold molar amount of phloroglucinol in a twentyfold amount of acetic acid. The dye starts to crystallize from the hot solution and is obtained in 67 % yield; it is recrystallized from boiling glacial acetic acid; m.p. 340–345 °C (decomp.) [6]; infrared spectrum in KBr: $\nu_{OH} = 3300–2950$ cm^{-1} (s); $\nu_{CO} = 1635$ cm^{-1} (s); $\nu_{CO(?)} = 1585$ cm^{-1} (s). On drying at 95 °C in vacuum the dye loses 0.5 mole of acetic acid of crystallization.

Received: June 8th, 1965 [Z 998/824 IE]
German version: Angew. Chem. 77, 680 (1965)

[1] *J. D. Park, S. Cohen*, and *J. R. Lacher*, J. Amer. chem. Soc. *81*, 3480 (1959); *84*, 2919 (1962).

[2] *G. Maahs*, Angew. Chem. *75*, 982 (1963); Angew. Chem. internat. Edit. *2*, 690 (1963).

[3] *A. Treibs* and *G. Fritz*, Liebigs Ann. Chem. *611*, 162 (1957).

[4] *A. Treibs* and *E. Herrmann*, Liebigs Ann. Chem. *589*, 207 (1954)

[5] *A. Treibs* and *R. Zimmer-Galler*, Hoppe-Seylers Z. physiol. Chem. *318*, 12 (1960).

[6] Determined on a hot metal block according to *A. Treibs* and *R. Zimmer-Galler*, Chem. Ber. *93*, 2547 (1960).

1,2:3,4:5,6-Tris-(2,2'-biphenylylene)borazole — a Trimer of 9,10-Azaboraphenanthrene

By Dr. R. Köster, Dr. S. Hattori, and Y. Morita

Max-Planck-Institut für Kohlenforschung, Mülheim/Ruhr (Germany)

N,N',N''-Tris-(2-biphenylyl)borazole *(1)* is produced in about 90 % yield by heating 2-aminobiphenyl and triethylamine-borane above 60 °C, hydrogen and triethylamine being liberated.

$$o\text{-}C_6H_5\text{–}C_6H_4\text{–}NH_2 + 3\ H_3B\leftarrow NR_3 \rightarrow [C_6H_5\text{-}C_6H_4\text{–}NBH]_3 + 6\ H_2 + 3\ NR_3$$

(1)

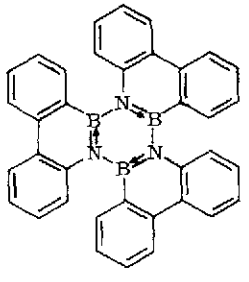
When the colorless crystals of *(1)*, m.p. 179–180 °C, ν_{BH} = 2490, 2510 (shoulder), and 2250 cm^{-1}, ν_{BN} = 1400 and 1425 cm^{-1} [1], are heated to 400–410 °C, hydrogen is evolved; the amount is about 80 % of that to be expected from Equation (a).

$$(1) \rightarrow 3\ H_2 + (C_{12}H_8)_3B_3N_3 \qquad (a)$$

(2)

On cooling, the yellow-brown resin formed deposits an 18 % yield of yellow needles, 1–2 cm long; these are stable in air and are analytically pure after mere washing with benzene; they turn brown above 360 °C and melt at 400–403 °C, ν_{BN} = 1362 cm^{-1} [2]. This compound does not exhibit the infrared bands characteristic of monosubstituted aromatic compounds at 700 cm^{-1} and of the BH bonds between 2480 and 2600 cm^{-1} which appear in the spectrum of *(1)*. Instead, bands for *o*-disubstituted aromatics are observed between 725 and 765 cm^{-1}.

The new product *(2)* is insoluble in benzene, dichloromethane, tetrahydrofuran, sulfolane, and methanol, and slightly soluble in pyridine; its molecular weight was found by mass spectrometry to be 531. The molecular formula for the compound was determined by high-resolution mass spectrometry [3] from the ions $[(2)]^{2\ominus}$ and [9,10-azaboraphenanthrene]$^{\oplus}$ (found 265.618 and 177.073; calc. 265.613 and 177.075). These values indicate a molecular weight of 531.236 or 531.216. Within the range of error, they coincide with the value of 531.226 calculated for $^{12}C_{36}{}^{1}H_{24}{}^{11}B_3{}^{14}N_3$ (^{12}C = 12.0000). The substance sublimes at about 300 °C/0.4 mm and has been assigned the structure of 1,2:3,4:5,6-tris-(2,2'-biphenylylene)borazole *(2)*.



(2)

Received: June 15th, 1965 [Z 11/837 IE]
German version: Angew. Chem. 77, 719 (1965)

[1] ν_{BN} = 1401 cm^{-1} for *N,N',N''*-triphenylborazole, the cyclic trimer of *N*-phenylborazine $(C_6H_5\text{–}NBH)_3$: cf. *K. Niedenzu* and *J. W. Dawson*: Boron-Nitrogen Compounds. Springer, Berlin-Heidelberg-New York 1965, p. 115.

[2] ν_{BN} = 1368 cm^{-1} for hexaphenylborazole: cf. [1], p. 117.

[3] *D. Henneberg*, Mülheim-Ruhr (Germany) kindly carried out these measurements on a CEC 21-110 mass spectrometer.

N-Diazonium Salts of Iminophosphoranes

By Dr. K. Bott [1]

Institut für Organische Chemie der Universität München (Germany)

If a solution of triphenylchlorophosphonium or tri-n-butylchlorophosphonium hexachloroantimonate *(1)* in nitrobenzene is stirred with an equimolar amount of anhydrous sodium azide at room temperature and the sodium chloride which precipitates is filtered off, the iminophosphorane-*N*-diazonium hexachloroantimonates *(2a)*, m.p. 166–169 °C, and *(2b)*, m.p. 155–159 °C, can be obtained in respective yields of 83 and 78 % in pure form by addition of ether or carbon tetrachloride.

$$R_3\overset{\oplus}{P}\text{-Cl}\ \ SbCl_6^{\ominus} \xrightarrow[-NaCl]{+NaN_3} R_3P{=}N\text{-}\overset{\oplus}{N}_2\ \ SbCl_6^{\ominus}$$

(1) *(2)*

$$\xrightarrow[-NaCl]{+NaN_3} R_3P{=}N\text{-}\overset{\oplus}{N}_2\ \ SbCl_5N_3^{\ominus}$$

(3)

(a), R = Phenyl
(b), R = n-Butyl

Both compounds crystallize as almost colorless needles that are stable towards atmospheric moisture; their infrared spectra contain a sharp absorption maximum at 2170 cm^{-1} as is to be expected for the N–N vibration of the diazonium grouping.

Reaction of *(1a)* with 2 moles of sodium azide leads to iminotriphenylphosphorane-*N*-diazonium azidopentachloroantimonate *(3a)*, m.p. 90–94 °C in 85 % yield. The color of *(3a)* and the occurrence of an additional, broad infrared band at 2080 cm^{-1} are in good agreement with the structure proposed.

The reactivity of the central phosphorus atom in chlorotripiperidinophosphonium hexachloroantimonate, m.p. 183 to 186 °C, is reduced to such an extent that replacement of the halogen by an azido group under the above conditions occurs only in the hexachloroantimonate anion.

Received: June 16th, 1965 [Z 6/830 IE]
German version: Angew. Chem. 77, 683 (1965)

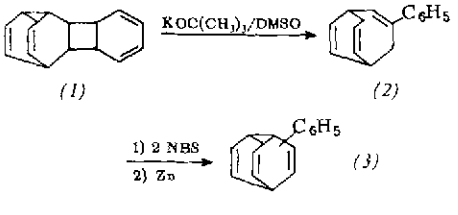
[1] New address: Chemische Werke Hüls AG., Gruppe Forschung, Marl (Germany).

Synthesis and Properties of Phenyltricyclo[3.3.2.0^{4,6}]deca-2,7,9-triene (Phenylbullvalene) [1]

By Priv.-Doz. Dr. G. Schröder

Institut für Organische Chemie der Technischen Hochschule Karlsruhe (Germany)

The dimer *(1)* of cyclooctatetraene, m.p. 76 °C [2], is converted by potassium t-butoxide in dimethyl sulfoxide at about 50 °C within about 50 h into 3-phenylbicyclo[3.3.2]deca-2,6,9-triene *(2)*, m.p. 69 °C, in 70–80 % yield. On catalytic hydrogenation over Pd, *(2)* takes up 3 moles of hydrogen to give $C_{16}H_{22}$, m.p. 74 °C. The ultraviolet spectrum of *(2)* in hexane has a maximum at 242 mμ (ε = 4000); its NMR spectrum has a singlet at 2.87 τ (phenyl protons), a multiplet centered around 4.15 τ (olefinic protons), a multiplet at 7.15 τ (bridgehead protons), and two multiplets centered at 7.45 τ



(1) *(2)* *(3)*

and 7.75 τ (protons of the two methylene groups); the peak areas are in ratios of 5:5:2:2:2.

The hydrocarbon *(2)* reacts smoothly with 2 moles of *N*-bromosuccinimide to give a viscous oil which probably contains a dibromide. Dehalogenation of the oil with zinc powder in refluxing t-butanol in the presence of a trace of solid sodium hydroxide produces phenylbullvalene *(3)* [3] in 5-10% yield [based on *(2)*]. It is advantageous to purify the crude dibromide before dehalogenation by chromatography on silica gel (0.05–0.20 mm grain size) with ether/pentane. The crude phenylbullvalene is purified by distillation in a suitable apparatus, *e.g.* a cold finger, and recrystallization from ethanol/ether, and then melts at 74–76 °C.

On catalytic hydrogenation over Pd, *(3)* absorbs four moles of hydrogen to yield a liquid, $C_{16}H_{22}$. The ultraviolet spectrum of *(3)* in hexane has λ_{max} at 262 mμ (ε = 8500). When heated briefly to 300 °C, *(3)* rearranges to β-phenylnaphthalene.

The NMR spectrum of *(3)* [4] varies with temperature. At −40 °C, 5 phenyl protons can be detected as a singlet at 2.83 τ, 5 olefinic protons as a multiplet at 4.17 τ, and 4 aliphatic protons as multiplets around 7.27 τ and 7.80 τ. It follows from the ratio of 5 olefinic to 4 aliphatic protons that an equilibrium mixture of isomers is present in which the phenyl group is situated on a doubly bonded carbon atom. At 90 °C the NMR spectrum comprises a singlet at 2.85 τ and a singlet (line width 4 cps) at 5.72 τ in area ratios of 5:9. At higher temperatures the nine bullvalyl protons have thus equivalent chemical shifts.

Preliminary experiments have shown that it is possible to synthesize bromophenylbullvalene and t-butoxyphenylbullvalene by a method analogous to that used to prepare bromobullvalene and t-butoxybullvalene [5].

Received: June 16th, 1965 [Z 7/831 IE]
German version: Angew. Chem. 77, 682 (1965)

[1] Molecules which Undergo Fast Reversible Valence-Bond Isomerizations, Part 8. Part 7: *G. Schröder, J. F. M. Oth,* and *R. Merényi,* Angew. Chem., in press.

[2] *G. Schröder,* Chem. Ber. *97,* 3131 (1964). The cyclooctatetraene was kindly supplied by the Badische Anilin- & Soda-Fabrik AG., Ludwigshafen (Germany).

[3] *W. v. E. Doering* and *G. Klumpp* synthesized *(3)* by a different route. The properties of both samples are identical – particularly the NMR properties; personal communication from Prof. *Doering.*

[4] The NMR spectra were taken by Dr. *J. F. M. Oth* and Dipl.-Chem. *R. Merényi,* Union Carbide European Research Associates, Brussels (Belgium).

[5] *G. Schröder, R. Merényi,* and *J. F. M. Oth* Tetrahedron Letters *1964,* 773; *J. F. M. Oth, R. Merényi, J. Nielsen,* and *G. Schröder,* Chem. Ber., in press.

Synthesis of Aryl Iminomethyl Disulfides

By Prof. Dr. W. Walter and Dipl.-Chem. P. M. Heil

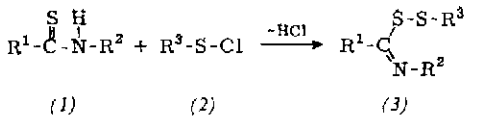
Chemisches Staatsinstitut, Institut für Organische Chemie, Universität Hamburg (Germany)

During the oxidation of thiobenzanilide or thioacetanilide *(1)* with hydrogen peroxide, oxygen adds onto the sulfur atom to form thioanilide *S*-oxides [1].

We have found that the thioanilides *(1)* also react with arenesulfenyl chlorides *(2)* at the sulfur atom to produce aryl phenyliminomethyl disulfides.

In order to establish the constitution of *(3)*, it had to be shown that the R^3S group did not become attached to the nitrogen atom, for it is known that carboxamides react with sulfenyl chlorides at their nitrogen atom to yield *N*-sulfenylcarboxamides [2]. The presence of the disulfide bond was proved by splitting *(3)* with cyanide, when the thioanilides *(1)* were re-formed.

The C=N bond in *(3)* results in a doublet in their infrared spectra in KBr between 1580 and 1640 cm^{-1}; this can be

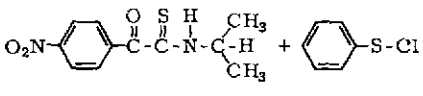


(1) *(2)* *(3)*

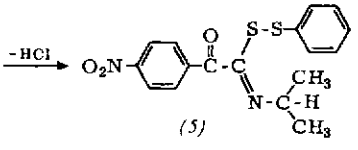
(3a): $R^1 = R^2 = R^3 = C_6H_5$, m.p. 82–83 °C
(3b): $R^1 = CH_3$; $R^2 = R^3 = C_6H_5$, m.p. 28–29 °C
(3c): $R^1 = R^2 = C_6H_5$; $R^3 = o\text{-}O_2N\text{–}C_6H_4$, m.p. 78 °C

assigned to a C=N valence vibration coupled with the remaining groups in the molecule. The peaks for *(3a)* lie at 1608 and 1586 ± 1 cm^{-1}; when *(3a)* is labelled with 97% ^{15}N, the doublet merges to a single intense band at 1574 ± 1 cm^{-1} [3].

Even thioamides which do not form *S*-oxides react with aromatic sulfenyl chlorides. For example, although no *S*-oxide can be detected after oxidation of *N*-isopropyl-*C*-(*p*-nitrobenzoyl)thioformamide *(4)* with H_2O_2 [4], *(4)* does react with benzenesulfenyl chloride to give *N*-isopropylimino-*p*-nitrobenzoylmethyl phenyl disulfide *(5)*, m.p. 97–98 °C. The structure of *(5)* was also proved by cleavage to *(4)* with cyanide and by its infrared spectrum.



(4)



(5)

Phenyl α-Phenyliminobenzyl Disulfide (3a): A solution of 5.33 g of thiobenzanilide in 180 ml of anhydrous ether is cooled to −15 °C, and 2.00 ml of pyridine is added. A solution of 3.61 g of benzenesulfenyl chloride in 50 ml of dry ether is then added to the cold stirred solution over 30 min. The reaction mixture is allowed to warm up to room temperature, and the pyridine hydrochloride which has separated is filtered off and washed with dry ether. Evaporation of the ether from the filtrate leaves an oily residue which crystallizes within a few minutes. Recrystallization from ethanol affords 5.3 g (66%) of pure *(3a)*.

Received: June 18th, 1965 [Z 8/834 IE]
German version: Angew. Chem. 77, 720 (1965)

[1] *W. Walter, J. Curts,* and *H. Pawelzik,* Liebigs Ann. Chem. *643,* 29 (1961).

[2] *J. Goerdeler* and *K. Doerk,* Chem. Ber. *95,* 389 (1962).

[3] In this connection cf. *H. Fritzsche* and *W. Schulze,* Z. Chem. *4,* 105 (1964).

[4] *K. D. Bode,* Doctorate Dissertation, Universität Hamburg 1964.

Isolation of Higher Cyclooligoamides from Polyamides [1,2]

By Dr. P. Kusch and Prof. Dr. H. Zahn

Deutsches Wollforschungsinstitut an der Technischen Hochschule Aachen (Germany)

The cycloamides c[Cap]$_{2-5}$, c[Und]$_2$, c[B–A]$_{1-3}$, and c[B–Seh] have been isolated from nylon-6, nylon-11, nylon-6,6, and nylon-6,10, respectively [3]. We have now isolated the higher cyclic oligoamides c[Cap]$_{6-8}$, c[Und]$_3$, c[B–A]$_4$, c[B–Seb]$_2$, and the c[Dod]$_2$ contained in nylon-12, all on a preparative scale by gel filtration of the polyamide extracts on Sephadex G 25 [Pharmacia, Uppsala (Sweden)] and Bio-Gel P10 [Bio-Rad Laboratories, Richmont, Calif. (U.S.A.)]; some of these compounds had previously been merely detected in the polymers by chromatography [4–6].

	M.p. [°C]	Crystal form
c[Cap]$_6$	260	Needles
c[Cap]$_7$	243	Triangular platelets
c[Cap]$_8$	254	Needles
c[Und]$_3$	184	Needles
c[Dod]$_2$	212	Needles
c[B–A]$_4$	273	Needles
c[B–Seb]$_2$	225	Needles

Shreds of polyamide (nylon-11, nylon-12, nylon-6,6, or nylon-6,10) were extracted with acetic acid/formic acid at about 100 °C; nylon-6 was extracted by precipitation from formic acid/ethanol. The extracts were evaporated, the residues were dissolved in 30–50 % acetic acid and loaded onto a column of gel (4 cm diam., 500 cm long); the fractions were eluted with the same solvent. The cycloamides obtained in this way were recrystallized from 30–40 % acetic acid and identified by comparison on thin-layer chromatograms with authentic synthetic samples and by their elemental analyses. All the cycloamide mixtures could be separated with equal ease on Sephadex G 25 and Bio-Gel P10.

Received: June 21st, 1965 [Z 9/835 IE]
German version: Angew. Chem. 77, 720 (1965)

[1] Oligomers and Pleionomers, Part 42. – Part 41: *H. Zahn, H. Stolper,* and *G. Heidemann,* Chem. Ber., in the press.

[2] The following abbreviations are used:

Cap = $-NH(CH_2)_5CO-$ Seb = $-CO(CH_2)_8CO-$
B = $-NH(CH_2)_6NH-$ Und = $-NH(CH_2)_{10}CO-$
A = $-CO(CH_2)_4CO-$ Dod = $-NH(CH_2)_{11}CO-$.

[3] *H. Zahn* and *G. B. Gleitsmann,* Angew. Chem. 75, 772 (1963); Angew. Chem. internat. Edit. 2, 410 (1963).

[4] *M. Rothe,* J. Polymer Sci. 30, 227 (1958).

[5] *P. Kusche,* Doctorate Dissertation, Technische Hochschule Aachen, 1963.

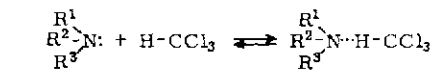
[6] *G. B. Gleitsmann,* Doctorate Dissertation, Technische Hochschule Aachen, 1962.

Investigation of Steric Features by Proton Magnetic Resonance

By Dr. H. J. Friedrich

Chemisches Institut der Universität Würzburg (Germany)

Chloroform exhibits only a single proton magnetic resonance signal in basic solvents owing to the formation of hydrogen bonds with rapid proton exchange; the chemical shift observed depends on the position of the association equilibrium. The shift is especially strong in amines and is hardly affected



by alkyl groups R provided the latter do not cause steric hindrance to the association; for example, δ = 520 cps in methylamine. If the alkyl groups exert a steric effect, characteristic changes in the chemical shift occur.

The proton magnetic resonance of chloroform was measured in various sterically hindered amines. The PMR signal varies according to R within a range of 90 cps at 60 Mc. The resonance frequencies bear a characteristic relationship to the E_S parameters of *Taft* [1], which give a measure of the steric requirements of alkyl groups (see Table). A linear correlation is obtained which is simple to apply in order to determine steric parameters by proton magnetic resonance.

Table 1. Relationship between the chemical shift δ of the PMR signal of $CHCl_3$ in amines and the E_S parameters of *Taft* [1]. The measurements were made with approx. 0.5 % solutions of $CHCl_3$ at 20 °C with tetramethylsilane as internal standard in a Varian A 60 instrument.

$R^1R^2R^3N$			ΣE_S R (cf. [1])	δ [cps at 60 Mc/s [a]
R^1	R^2	R^3		
C_2H_5	C_2H_5	H	+1.1	519
t-C_4H_9	H	H	+0.9	517
n-C_3H_7	n-C_3H_7	H	+0.5	505
n-C_4H_9	n-C_4H_9	H	+0.5	503
i-C_3H_7	i-C_3H_7	H	+0.3	506
CH_3	CH_3	CH_3	0	504
C_2H_5	C_2H_5	C_2H_5	−0.2	495
c-C_6H_{11}	c-C_6H_{11}	H	−0.3	494
i-C_4H_9	i-C_4H_9	H	−0.6	480
c-C_6H_{11}	C_2H_5	C_2H_5	−0.9	480
n-C_3H_7	n-C_3H_7	n-C_3H_7	−1.1	466
n-C_4H_9	n-C_4H_9	n-C_4H_9	−1.2	468
c-C_6H_{11}	n-C_4H_9	n-C_4H_9	−1.6	454
n-C_4H_9	i-C_4H_9	i-C_4H_9	−2.3	435

[a] $\delta \approx$ 430 cps for $CHCl_3$ in indifferent solvents such as hexane.

Received: June 24th, 1965 [Z 12/838 IE]
German version: Angew. Chem. 77, 721 (1965)

[1] *R. W. Taft,* J. Amer. chem. Soc. 74, 3120 (1952).

CONFERENCE REPORTS

Meeting of South-West German Chemistry Lecturers

The meeting took place in Mainz (Germany) from April 28th to 30th. Altogether 110 papers were presented, in part in three parallel sessions. In order to avoid repetition of publication, only those lectures will be summarized the contents of which have not yet been published or submitted for publication. The abstracts are arranged alphabetically according to authors. For a subject index, see page 727 of this issue.

1

The Polymerization of Isoprene Initiated by Organolithium Compounds

F. Bandermann and *H. Sinn,* München (Germany)

At initiator concentrations above 10^{-5} mole/l in n-heptane, ether, or mixtures of both, the concentrations of the undissociated monomeric organolithium compound and of the isoprene are rate-determining. Solvation by ether reduces the reactivity of the initiator. The overall reaction rate in ether is therefore higher or lower than in heptane, depending on the concentration [1] (double-dilatometer technique in the range of low concentrations).

On the basis of the kinetic data and a postulated reaction mechanism, a system of differential equations and equilibrium relations was set up and solved numerically with an analogue computer. The calculated conversion-time curves agreed up to 90 % conversion with the experimental curves within the computing error of 1–3 %.

Solutions of butyl-lithium in n-heptane were found to have the resistances tabulated below (cell constant = 0.01 cm^{-1}):

[1] Cf. *H. Sinn* and *F. Patat,* Angew. Chem. 75, 805 (1963); Angew. Chem. internat. Edit. 3, 93 (1964); Fig. 1.

Conc. [mmoles/l]	Resistance [Ohm]	Conc. [mmoles/l]	Resistance [Ohm]
0.0016	5×10^{11}	3.40	9.2×10^{7}
0.003	3.6×10^{11}	5.70	7.4×10^{7}
0.006	1.7×10^{10}	7.90	6.5×10^{7}
0.009	1.4×10^{10}	12.0	5.8×10^{7}
0.012	1.3×10^{10}	28.8	4.7×10^{7}
0.027	8.4×10^{9}	45.4	4.3×10^{7}
0.043	8.3×10^{9}	69.6	4.1×10^{7}
0.027	8.4×10^{9}	45.4	4.3×10^{7}
0.043	8.3×10^{9}	69.6	4.1×10^{7}
0.065	7.2×10^{9}	93.0	3.9×10^{7}
0.088	6.4×10^{9}	132.0	3.9×10^{7}
0.108	6.0×10^{9}	167	3.7×10^{7}
0.572	2.4×10^{8}	236	3.7×10^{7}
0.595	2.6×10^{8}	358	3.8×10^{7}
1.17	1.4×10^{8}		

The step-like course of the conductance-concentration curve can be explained by ionic interactions. The values show that butyl-lithium is practically undissociated even at the lowest concentrations studied.

2

Infrared Spectra and Frequency Assignment of some Aminoboranes Containing ^{10}B

H.-J. Becher and *H.T. Baechle*, Stuttgart (Germany)

From boric acid having 92 % of the boron present as ^{10}B, boron trichloride was made with aluminium tricbloride *via* boron triphenolate. With the aid of well-known amination reactions, the BCl_3 was converted to $Cl_2BN(CH_3)_2$, $ClB[N(CH_3)_2]_2$, and $B[N(CH_3)_2]_3$, and the corresponding derivatives with diethylamino groups. The infrared spectra of these aminoboranes and of the corresponding compounds with the natural ^{11}B: ^{10}B abundance ratio were measured. Owing to frequency coupling, the introduction of ^{10}B displaces the NC vibration bands and one CH_3 deformation band (per compound) as well as the BCl and BN bands. The band displacements are almost always less than 10 cm^{-1}, and were therefore generally not observed previously in the spectra of aminoboranes without ^{10}B-enrichment. With the present measurements, previous assignements can be completed, and more precise information on the nature of the BN, NC, and CH vibrations in the region 900–1550 cm^{-1} can be given.

3

Fulminato-Metal Complexes

W. Beck, *E. Schuierer*, and *K. Feldl*, München (Germany)

Visible and ultraviolet absorption spectra show that a strong ligand field is produced by the ion CNO^-. This can also be derived from the diamagnetism of Fe(II)[*o*-phenanthroline]$_2$-$(CNO)_2$. The smaller d–d splitting Δ compared to cyano compounds is probably due to a smaller amount of metal → ligand π-back-donation in the fulminato complexes. The fulminate ion should be placed approximately after the cyanide ion in the spectrochemical series [1]. Thus the electronic spectra also indicate the presence of M–CNO bonds in the fulminato complexes; a substantially lower d-d splitting would be expected for structures with M–ONC bonds [1].

Reaction of the tetrafulminato complexes of Ni(II), Pd(II), and Pt(II) with phosphines gives the thermally stable compounds $(R_3P)_2M(CNO)_2$ [2]. The yellow diamagnetic Pd-complexes $[(C_6H_5)_3P]_2PdX_2$ ($X = NCO^-$, NCS^-, $C(CN)_3^-$, N_3^-) are prepared similarly from aqueous solutions of $Pd(NO_3)_2$, the corresponding alkali metal salt, and triphenylphosphine.

The *trans*-compounds $(R_3P)_2M(CNO)_2$ (M = Pd, Pt; R = C_2H_5, C_6H_{11}) react with bromine or iodine to give the yellow, diamagnetic complexes $M(PR_3)_2(CNO)_2X_2$ (X = Br, I). Dipole moment measurements show like ligands to be in *trans*-positions in these six-coordinate compounds, as expected.

In the infrared spectra of various metal fulminates, the ν_1 (νNO) and ν_3 (νCN) frequencies increase in the sequence alkali metal fulminates < complex metal fulminates < non-ionogenic heavy metal fulminates [*e.g.* $Hg(CNO)_2$] < aryl metal fulminates [*e.g.* C_6H_5HgCNO] < organic nitrile oxides. From infrared absorption measurements on ^{15}N-containing metal fulminates the force constants can be determined (CNO^-: $k_1 = 6.8$; $k_2 = 15.5$, $k_{12} = 1.3$ mdyne/Å). Gaseous fulminic acid, which is generally written as CNOH, has the structure of a hydrocyanic acid oxide HCNO according to the infrared spectrum, which contains the following bands: $\nu_1 = 3340$ cm^{-1} (ν C–H), $\nu_2 = 2191$ cm^{-1} (ν CN), $\nu_3 = 1250$ cm^{-1} (ν NO, type B band), $\nu_5 = 538$ cm^{-1} (δ CNO, type A band). On the other hand, bands at 3600 cm^{-1} (ν OH), 1300 cm^{-1} (δ OH, type A band), and 900 cm^{-1} would be expected for CNOH.

[1] Cf. *C. H. Jorgensen*: Absorption Spectra and Chemical Bonding in Complexes. Pergamon Press, Oxford 1962.

[2] *W. Beck* and *E. Schuierer*, Chem. Ber. *98*, 298 (1965).

4

Surface Compounds on Diamonds

H. P. Boehm and *R. Sappok*, Heidelberg (Germany)

On the surface of a diamond crystal, the space lattice of the tetrahedrally linked carbon atoms is interrupted. The "broken" valences are very reactive, since their mutual saturation is possible only at the expense of strong distortion of the tetrahedral arrangement. Surface oxides are formed with oxygen. The surface of a diamond which has been oxidized with oxygen at 400 °C or with aqueous oxidizing agents is weakly acidic and hydrophilic. The higher the oxidation temperature, the more oxygen is bound. Oxygen is slowly absorbed even at room temperature. Continuous combustion to carbon oxides occurs only above about 380 °C.

Attempts to elucidate the constitution of the surface oxides showed the acidity to be due to relatively few carboxyl groups, which are probably attached at the crystal edges. Determinations of the active hydrogen showed that the major part of the oxygen is not bound in the form of carboxyl or hydroxy groups. An infrared absorption band at 1760 cm^{-1} indicates the presence of carbonyl groups; weak bands in the range 1000–1300 cm^{-1} may be ascribed to ether-like groups. Diffraction studies with low-energy electrons [1] showed that the diamond lattice in the oxidized surface is distorted. Only low concentrations of free radicals were detected at the surface.

A hydride surface is formed with hydrogen at 800 °C; C–H absorption is observed at 2850 cm^{-1} in the infrared spectrum. Fluorine and chlorine are also bound at the surface. Bound chlorine is very resistant to hydrolysis. The absorption band at 1410 cm^{-1} indicates a very much stronger bond than in normal organic chloro compounds.

When diamond is heated to 800 °C under low pressure of oxygen (about 0.1 mm), black carbon is formed on the surface [2], whereas in a high vacuum, no transformation occurs even at 1300 °C.

[1] *J. B. Marsh* and *H. E. Farnsworth*, Surface Science *1*, 1 (1964).

[2] *H. P. Boehm*, *E. Diehl*, *W. Heck*, and *R. Sappok*, Angew. Chem. *76*, 742 (1964); Angew. Chem. internat. Edit. *3*, 669 (1964).

5

Fractionation of Polystyrene by Gel Chromatography

D. Braun and *G. Heufer*, Darmstadt (Germany)

For the fractionation of polystyrene, a gel prepared by free-radical polymerization of ethylidene dimethacrylate in isoamyl acetate at 60 °C is particularly suitable; it makes

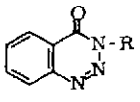
possible separations at room temperature and avoids the difficulties caused by adsorption on cross-linked polystyrene gels. The efficiency of fractionation depends on the network structure of the gel and *inter alia* on the concentration and volume of the sample solution, nature of the swelling and eluting agents, and on column dimensions. Combination of gels of different pore size is necessary for fractionation of polymers having a relatively broad distribution of molecular weights. The distribution curves obtained by gel chromatography agree with those obtained by other methods, *e.g.* fractional precipitation.

6

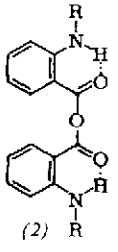
Photolysis of 3,4-Dihydro-4-oxobenzo-1,2,3-triazines Substituted in the 3-Position

G. Ege, Heidelberg (Germany)

3,4-Dihydro-4-oxobenzo-1,2,3-triazines *(1a)–(1c)* having a saturated substituent at N-3 remain unchanged even on prolonged irradiation with a high-pressure mercury vapor lamp (450 W, λ_{max} = 366 mμ). If R is unsaturated, nitrogen is liberated, and various products are obtained depending on the solvent used [1].



(1)



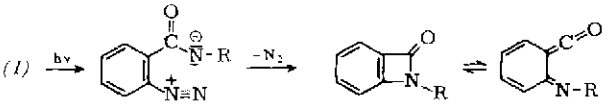
(2)

(a): R = H
(b): CH_3
(c): CH_2–CO–C_6H_5
(d): C_6H_6
(e): 2,4,6-trimethylphenyl (mesityl)
(f): *p*-toluenesulfonyl (tosyl)
(g): benzoyl

Irradiation of *(1d)* in methanol, ethanol, or isopropanol leads to the esters of *N*-phenylanthranilic acid in 90 % yield. In ethyl acetate and in the presence of morpholine, *N*-phenylanthranilic morpholide is formed. In acetone, acridone is obtained, which is also formed in the pyrolysis of *(1d)* [1].

In ethyl acetate, *(1d)* gives rise to the anhydride *(2d)*, m.p. 154 °C; infrared absorptions at 3330 cm^{-1} (NH), 1740 cm^{-1}, and 1680 cm^{-1} (CO). The yield of *(2d)* is 70 % when *(1d)* and 1 equivalent of *N*-phenanthranilic acid in ethyl acetate are irradiated.

In all these reactions *(1)* presumably first dissociates to give *(3)*, from which nitrogen is split off with formation of *(4)* which is valence - tautomeric with *(5)*. Addition of alcohol, morpholine, or *N*-phenylanthranilic acid (formed from *(5)* by addition of water) onto *(5)* then results in the products named above.



(1) *(3)* *(4)* *(5)*

On irradiation of *(1e)*, the anhydride *(2e)* is formed; m.p. 205 °C. In the solvents investigated (dichloromethane, acetone, methanol), *(1f)* gives *N*-tosylbenzamide, together with formaldehyde formed from methanol. In ethyl acetate, *(1g)* yields benzoylanthranil.

To enable the possible empirical formulae of a compound to be determined from C and H analyses, 63000 sum formulae CHNO (S) up to $C_{40}N_6O_{12}$ were tabulated, together with the corresponding molecular weights and percentages of the elements. The table is to be published shortly by Verlag Chemie, Weinheim/Bergstr. (Germany).

[1] *D. H. Hey, C. W. Rees*, and *A. R. Todd*, Chem. and Ind. *1962*, 1332.

7

Isotopic Exchange Reactions of Alkyl Halides

H. Elias, Darmstadt (Germany)

We have investigated the kinetics of homogeneous isotopic exchange reactions between alkyl halides and halide ions

$$R\text{–}X + {}^*X^- = R\text{–}{}^*X + X^-$$

in order to determine the influences of the residue R, the halogen X, and the solvent.

Comparative experiments with ^{36}Cl- or ^{82}Br-labelled 1-chlorohexane *(1)*, 2-chlorohexane *(2)*, 3-chlorohexane *(3)*, 1-bromohexane *(4)*, 2-bromohexane *(5)*, 3-bromohexane *(6)*, chlorocyclopentane *(7)*, chlorocyclohexane *(8)*, chlorocycloheptane *(9)*, chlorocyclooctane *(10)*, and isopropyl chloride *(11)* in anhydrous dimethylsulfoxide (DMSO), dimethylformamide (DMFA), and diethyleneglycol (DEG) gave the following results:

1. In the systems *(1)*, *(2)*, or *(3)*/Cl^-/DMSO and *(4)*, *(5)*, or *(6)*/Br^-/DMSO, the isotopic exchange reaction is bimolecular (S_N2). The rate constants at 25 ° are in the ratios $k_{(1)}$: $k_{(2)}$: $k_{(3)}$ = 28.4:1:0.87 and $k_{(4)}$: $k_{(5)}$: $k_{(6)}$ = 22.7:1:1.30. The bromides *(4)*, *(5)*, and *(6)* react about 100 times faster than the corresponding chlorides.

2. The exchange in the systems *(7)*, *(8)*, *(9)*, *(10)*/Cl^-/DMSO is bimolecular (S_N2). At 25 °C, the rate constants are in the ratio $k_{(7)}$: $k_{(8)}$: $k_{(9)}$: $k_{(10)}$ = 156:1:77.4:8.10.

3. The exchange at 25 °C in the system *(1)*/Cl^-/DMSO is 245 times faster than in the system (1)/Cl^-/DEG, which also reacts bimolecularly.

4. In the system *(11)*/Cl^-/DMFA the exchange is bimolecular (S_N2); a first-order reaction (S_N1) does not occur.

5. At 70 °C, tetrabutylammonium bromide (< 0.03 mole/l) is completely dissociated in DMSO. The dissociation constants in the systems LiCl/DMSO, tetrabutylammonium chloride/DMFA, and LiCl/DEG at 30 °C are 2.4×10^{-2}, 4.1×10^{-2}, and 17.9×10^{-2} mole/l, respectively.

8

NMR-Spectroscopic Conformational Analysis of Menthylamines and Carvomenthylamines

H. Feltkamp, Tübingen

Measurements of conformational equilibria have to date been made almost exclusively on monosubstituted cyclohexanes. In order to test the applicability of the methods to more highly substituted cyclohexanes, we have studied 16 stereoisomeric alcohols of the menthol type and 8 stereoisomeric menthylamines and carvomenthylamines together with the 8 corresponding nitromenthanes.

The menthylamines were prepared by oxidizing menthol with chromosulfuric acid in ether to menthone, which was rearranged to a mixture of menthone and isomenthone with sulfuric acid. The mixture of the oximes was separated by column chromatography on silica gel using a mixture of 25 % ammonia, acetone, benzene, and petroleum ether (1:49:200:750) at 50–70 °C, the pure oximes were reduced with sodium in ethanol, and the mixture of amines was separated by countercurrent distribution. The carvomenthylamines were prepared from carvacrol. The mixture of oximes was separated by chromatography on silica gel with benzene/ethyl acetate/petroleum ether (2:3:20) at 50–70 °C, and the pure oximes reduced as above. The resulting mixture of amines was separated by crystallization of the hydrochlorides, column chromatography, and preparative thin-layer chromatography. The pure amines were oxidized to the nitro compounds with peroxyacetic acid.

The NMR-spectroscopic analysis of the configuration and conformation of the compounds showed that the menthyl and neomenthyl forms are fixed, as are the neoiso forms of the nitro compound and neoisocarvomenthylamine. The functional groups in the menthyl and fixed neoiso forms are equatorial, those in the neo forms axial. Neoisomenthylamine and the iso compounds are conformationally non-uniform.

9

Isomerism of Complexes of the Type $[\pi\text{-}C_5H_5M(CO_2)_2]$

R. D. Fischer and *A. Vogler*, München (Germany)

Dimeric cyclopentadienyl - metal carbonyl complexes $[CpM(CO)_n]_2$ (n = 1–3) can exhibit a considerable dipole moment in solution even when they have a center of symmetry in the crystalline state.

The dependence of the ν(C–O) frequencies of the terminal and bridging CO ligands of the complexes with n = 2 on the solvent, the central metal, and the temperature indicates the presence of four (sometimes coexisting) isomers. Chief characteristics are the presence or absence of a center of inversion and of two CO bridges. A center of symmetry is found only in the solid state. The tendency to bridge formation decreases with increasing atomic number of M. For example, $[CpFe(CO)_2]_2$ exists in the solid state only as the CO-bridged *trans*-form, whereas dissolved $[CpOs(CO)_2]_2$ exists as the pure *cis*-form with a direct Os–Os bond. The Ru complex in solution is an equilibrium mixture of the *cis*-bridged and *cis*-nonbridged isomers.

The preferred existence of the *cis*-isomers in nonpolar solvents is ascribed to weak interactions of, in first approximation, nonbonding electrons of the metal.

10

Proton Magnetic Resonance Measurements on Hydrogen-Bond Associates of Chloroform

H. J. Friedrich, Würzburg (Germany)

The dependence of the proton magnetic resonance frequency of chloroform on the diamagnetic susceptibility of the solvent ($\chi_v = -0.460\times10^{-6}$ to -0.856×10^{-6} EMU/ml) has been studied systematically by measurements in 60 solvents (cylindrical sample tubes, externally standardized). The proton magnetic resonance signals of tetramethylsilane (TMS) in the same solvents were also measured. The TMS-signals were found to occur within a frequency range of 50 c.p.s. (at 60 Mc/sec) and to accurately obey the linear equation for the susceptibility shift $(\Delta H/H)_s$:

$$(\Delta H/H)_s = (2\pi/3)\Delta\chi_v$$

All other effects of the medium can therefore be neglected in comparison to the effect of the susceptibility.

On the other hand, the $CHCl_3$-signal (at 20 °C) varies over the range of 100 c.p.s., since the medium causes association shifts $(\Delta H/H)_A$ by hydrogen-bond formation, in addition to the susceptibility shifts; thus:

$$\Delta H/H = (\Delta H/H)_s + (\Delta H/H)_A$$

For solvents of similar structure and with the same functional groups, the $(\Delta H/H)$ *vs.* χ_v diagrams are still linear with slope $2\pi/3$, since the association shift is specific to structure and functional grouping. Exceptions are the media in which the hydrogen bonding to chloroform is sterically hindered; the degree of hindrance can be obtained from the $(\Delta H/H)$ *vs.* $\Delta\chi_v$ diagram.

The straight lines of $(\Delta H/H)$ *vs.* $\Delta\chi_v$ for the sterically unhindered chloroparaffins, nitriles, ethers, alcohols, ketones, and amines are displaced with respect to those for the paraffins, with which chloroform cannot form H-bond associates, to decreasing fields by the characteristic amounts $(\Delta H/H)_A$ (see Table below). These displacements are a measure of the strengths of the hydrogen bonds, and can according to *W. G. Schneider* be related to the dipole moments of the hybrid atomic orbitals of the proton acceptor atom involved in the bond. These orbital dipole moments were calculated for pure sp, sp^2, and sp^3 atomic orbitals (see Table) according to the AO theory of *C. A. Coulson*. A good

Solvent	$(\Delta H/H)_A$ for $CHCl_3$ [ppm] at 20 °C	Atomic orbital dipole moments μ [Debye]
Paraffins	0	–
Chloroparaffins	0.22	Cl(sp^3): 2.44
Nitriles	0.53	N(sp): 3.74
Ethers	0.70	O(sp^3): 2.78
Alcohols	0.87	O(sp^3): 2.78
Ketones	0.90	O(sp^2): 3.03
Amines	1.53	N(sp^3): 3.25

correlation is obtained, except for the nitriles, when a pure N(sp) atomic orbital is assumed. The deviation can be explained by assuming a higher s-character and by taking into account the magnetic anisotropy of the nitrile triple bond.

11

^{1}H-NMR-Investigations of Organic Platinum and Rhodium Compounds

H. P. Fritz and *K.-E. Schwarzhans*, München (Germany)

In earlier work [1], a π-cyclopentadienyl ligand was postulated to occur in $(CH_3)_2PtC_5H_5$. By comparison with the NMR-spectra of six other platinum cyclopentadienyl complexes and with ultraviolet spectra of σ-cyclopentadienyl compounds it could now be shown that the assumed regular pentagonal ring structure is not correct, but that the conjugated diene system remains intact.

In the synthesis of similar compounds of ^{103}Rh, which is also magnetically active, an intermediate was found, the structure of which was established as

$$Rh_2I_2(CH_3)_4[S(CH_3)_2]_3$$

on the basis of spin-spin coupling in the NMR-spectrum. From this substance, the crystalline, red-brown compound

$$\pi\text{-}C_5H_5Rh(III)(CH_3)_2S(CH_3)_2$$

was isolated. The compound dissolves in organic solvents and is stable in air. Above 100 °C it decomposes with liberation of iodine. Addition of NaC_5H_5 leads to a splitting of the iodo and dimethylsulfide bridges and formation of rhodium cyclopentadienyl compounds.

[1] *S. D. Robinson* and *B. L. Shaw*, Z. Naturforsch., *18b*, 507 (1963).

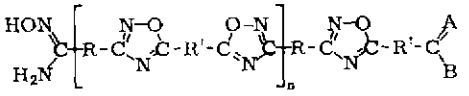
12

Polymers with 1,2,4-Oxadiazole and 1,2,4-Oxadiazoline Rings

W. Funke, Stuttgart (Germany)

Polycondensates from diamide oximes and dicarboxylic dichlorides or dialdehydes were cyclocondensed intramolecularly to yield poly-[1,2,4-oxadiazoles] *(1)* or poly-[1,2,4-oxadiazolines] by heating in dimethylformamide/benzene and distilling off the benzene and the resulting water, or by fusion with $ZnCl_2$.

For the preparation of *(1)*, products obtained by interfacial polycondensation were also cyclocondensed by heating in diphenyl/diphenyl oxide or in *N*-methylpyrrolidone.



(1)

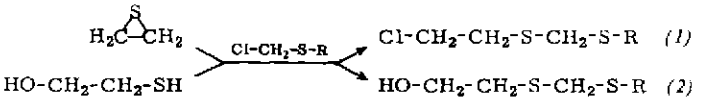
The melting points of the usually powdery products were between 100 and 360 °C. Their molecular weights were found by end-group analysis and cryoscopic measurements to be in the range 1500–2000. The degrees of polycondensation are relatively low because the solubilities of the intermediate polycondensates decrease rapidly with increasing molecular weights.

13

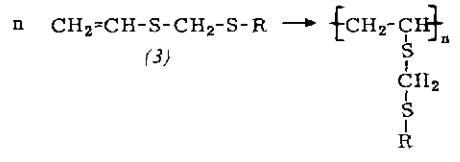
Synthesis and Polymerization of S-Vinylmercaptals of Formaldehyde

K. Gollmer and *H. Ringsdorf*, Marburg (Germany)

From α-chloromethyl thioethers [1] and ethylene sulfide or β-mercaptoethanol, β-chloroethylmercaptals *(1)* and β-hydroxyethylmercaptals *(2)* of formaldehyde were prepared.



By splitting off HCl from *(1)* and H_2O from *(2)* with KOH/NaOH (3:1) at 180–300 °C/3–100 mm Hg, the corresponding formaldehyde-*S*-vinylmercaptals *(3)* were obtained in yields of 50–70 %. The monomers could be polymerized radically with azobisisobutyronitrile and cationically with boron trifluoride.



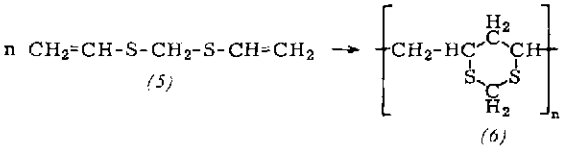
(3)

R = CH_3, C_2H_5, n-C_3H_7, iso-C_3H_7, t-C_4H_9, C_6H_5.

Benzoyl peroxide does not function as initiator, since the –S–CH_2–S– group induces acyl peroxide decomposition with the formation of carboxylic acids and acyloxymercaptals.

The concentration of the free-radical initiator does not influence the degree of polymerization (about 100) to any great extent. This may be explained by the reactivity of the mercaptal group, which acts as a chain-transfer agent. The transfer constants of 15×10^{-4} to 30×10^{-4} found for styrene and saturated mercaptals agree with this explanation.

The polymerization was followed dilatometrically. The influence of the substituent R on the rate of radical polymerization corresponds to a superposition of inductive and steric effects.



(5) *(6)*

Polymerization of formaldehyde-*S*,*S*'-divinylmercaptal *(5)* [2] in toluene leads *via* an intramolecular reaction to soluble polymers *(6)*.

[1] *H. Böhme, H. Fischer*, and *R. Frank*, Liebigs Ann. Chem. *563*, 59 (1949).

[2] *H. Ringsdorf* and *C. G. Overberger*, J. Polymer Sci. *61*, 11 (1962).

14

Five-Membered Heterocycles from Hydrazomethane, Aromatic Aldehydes, and Dipolarophiles

R. Grashey, München (Germany)

The reaction of aromatic aldehydes with *N*,*N*'-dimethylhydrazine gives rise to 1,2,4,5-tetramethyl-3,6-diarylhexahydro-1,2,4,5-tetrazines in high yield. The reaction of these compounds with unsaturated systems gives access to many five-membered heterocycles. It is plausible that the hexahydrotetrazines are first split into two molecules of *C*-aryl-*N*,*N*'-dimethylazomethinimine, which then combines with the dipolarophile; other mechanisms are, however, also possible. When the dipolarophiles used are α,β-unsaturated carbonyl compounds or nitriles, pyrazolidine derivatives are obtained in good yields. Among the phenyl-conjugated alkenes, acenaphthylene was found to be a suitable coreactant.

The reaction of the hexahydrotetrazines with isocyanates and isothiocyanates gives especially high yields. Degradation experiments and spectral data show that this reaction usually leads to 1,3,4-triazolidin-5-ones and triazolidin-5-thiones. Δ^3-1,2,4-Triazolines are accessible through reactions of hexahydrotetrazines with thiocyanates, *e.g.* benzyl thiocyanate. The reactions with CS_2 as dipolarophile run particularly smoothly: 3,4-dimethyl-2-aryl-1,3,4-thiadiazolidin-5-thiones can be isolated in high yields.

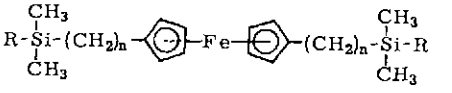
The isolation of the hexahydrotetrazines is not essential. The adducts described can also be obtained directly by heating the three components (aromatic aldehyde, *N*,*N*'-dimethylhydrazine, and dipolarophile). Since, however, side reactions become more important in this procedure, the yields obtained are often poor.

15

Silicon-Organic Polymers Containing Ferrocene

G. Greber and *M. L. Hallensleben*, Freiburg (Germany)

In the H_2PtCl_6-catalysed addition of 1,1'-bis(dimethylhydrosilyl)ferrocene or 1,1'-bis(dimethylhydrosilylmethyl)ferrocene onto acetylene, vinylacetylene, and isopropenylacetylene, 1,1'-disubstituted ferrocene derivatives *(1)*–*(6)* with two functional groups are formed.



(1), R = CH=CH_2, n = 0
(2), R = CH=CH_2, n = 1
(3), R = CH=CH–CH=CH_2, n = 0
(4), R = CH=CH–CH=CH_2, n = 1
(5), R = CH=CH–C(=CH_2)–CH_3, n = 0
(6), R = CH=CH–C(=CH_2)–CH_3, n = 1

Treatment of the divinyl derivative *(1)* with sodium in anhydrous tetrahydrofuran gives a double radical anion capable of initiating the polymerization of vinyl monomers (*e.g.* styrene, methyl methacrylate, acrylonitrile). By transfer of this reaction to products of higher molecular weight with two CH_2=CH–$Si(CH_3)_3$-ferrocene end groups, block copolymers were synthesized.

In contrast to *(1)*, the divinyl derivative *(2)*, in which a methylene bridge separates the ferrocene from the organosilicon group, does not form radical ions.

The bisdiene derivatives *(3)–(6)* can be polymerized by organolithium compounds such as phenyl-lithium or n-butyllithium. The polymers obtained up to 15 % conversion are soluble, and have a "ladder" or double-chain structure, as suggested by their infrared spectra.

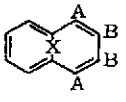
The compounds *(3)–(6)* also undergo Diels-Alder reactions. With difunctional organosilicon philodienes, products with molecular weights around 4000 are obtained in a poly-Diels-Alder reaction. These products contain cyclohexene rings in the main chain in addition to the organosilicon and the ferrocenyl residues. With monofunctional philodienes such as maleic anhydride, difunctional ferrocene derivatives are formed.

16

The Aromatic Character of Systems with Ten π-Electrons: ^{1}H-NMR Spectra of 1,6-Methano- and 1,6-Oxidocyclodecapentaene

H. Günther, Köln (Germany)

1,6-Methanocyclodecapentaene *(1)* [1] and 1,6-oxidocyclodecapentaene *(2)* [2] can be treated NMR-spectroscopically as A_2B_2 systems. For *(1)* the chemical shifts (on the τ-scale) ν_A = 2.73 p.p.m. and ν_B = 3.05 p.p.m. are found. This assignment is supported by a long-range coupling of the A-protons with those of the methylene bridge. For *(2)*, ν_A = 2.54 p.p.m. and ν_B = 2.74 p.p.m. Here the assignment of resonance frequencies is not unambiguous, but in analogy to *(1)* it may be assumed that $\nu_A < \nu_B$. The methylene protons in *(1)* absorb at 10.51 p.p.m.



(1), X = CH_2
(2), X = O

The signals of the peripheral ring protons occur about 1 p.p.m. below those of olefinic protons in comparable structures because of the ring current of the π-electrons. The Pople approximation [3] gives for *(1)* ν_A = 1.80 p.p.m. and ν_B = 2.20 p.p.m., relative to ν = 4.23 p.p.m. for 1,3-cyclohexadiene. The relative chemical shift $\delta\nu$ between the signals of the A- and B-protons is reproduced well by these values, but the absolute values are too low. The presence of a cyclopropane ring in *(1)* can also be excluded on the basis of the ^{13}CH-coupling of the methylene bridge (142 ± 1 c.p.s.) and of the geminal coupling constant (6.9 ± 0.3 c.p.s.) found for the monodeuterated compound.

All HH-coupling constants of *(1)* are very close to those of *(2)*, which indicates that the compounds are stereochemically similar and that the influence of the bridge is not important. The vicinal coupling constants for *(1)* are J_{AB} = 8.97 c.p.s. and J_{BB} = 9.19 c.p.s., for *(2)* J_{AB} = 8.77 c.p.s. and J_{BB} = 9.28 c.p.s. In contrast to cyclic olefins (*e.g.* 1,3-cyclohexadiene, cycloheptatriene) and in agreement with aromatic molecules, the vicinal coupling constants are almost equal. The constants of coupling across more than three bonds are $J_{AB'} \approx 0$ and J_{AA} = 1.46 c.p.s. for *(1)* and $J_{AB'}$ = 0.28 c.p.s. and J_{AA} = 1.13 c.p.s. for *(2)*, departing from the values 1–3 c.p.s. for J_{meta} and 0–1 c.p.s. for J_{para} of classical aromatic compounds, possibly because the relevant CH bonds are not completely coplanar.

The NMR signal of chloroform in a mixture with *(1)* or *(2)* shows an association shift towards higher field, similarly to mixtures of $CHCl_3$ with benzene or its derivatives. Relative to unassociated chloroform the value at infinite dilution is + 1.30 p.p.m. with *(1)* and + 0.97 p.p.m. with *(2)*. The results can be explained by assuming delocalization of the 10 π-electron systems of *(1)* and *(2)*.

[1] *E. Vogel* and *H. D. Roth*, Angew. Chem. *76*, 145 (1964); Angew. Chem. internat. Edit. *3*, 228 (1964).

[2] *E. Vogel* et al., Angew. Chem. *76*, 785 (1964); Angew. Chem. internat. Edit. *3*, 642 (1964); *F. Sondheimer* and *A. Shani*, J. Amer. chem. Soc. *86*, 3168 (1964).

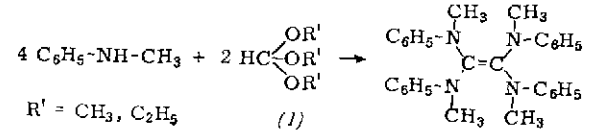
[3] *J. A. Pople*, J. chem. Phys. *24*, 1111 (1956).

17

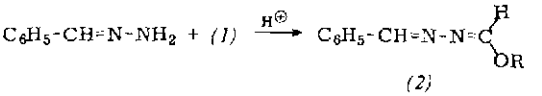
Reactions of Triethyl Orthoformate with some Nitrogen Compounds

Ilse Hagedorn, *K. E. Lichtel*, and *H. D. Winkelmann*, Freiburg (Germany)

1. Triethyl orthoformate *(1)* reacts with *N*-methylaniline to give tetra-(*N*-methyl-*N*-phenylamino)ethylene. *N*-Ethylaniline reacts analogously. The compounds formed are related structurally to bis-(1,3-diphenylimidazolidin-2-ylidene) described by *Wanzlick* [1].

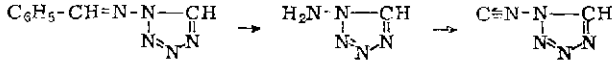


2. Alkoxymethylenazines *(2)* [2] are obtained in excellent yields from *e.g.* benzaldehyde hydrazone and *(1)*.

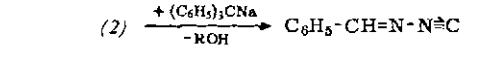


a) Mixed (arylalkyl)azines are obtained from *(2)* by treatment with Grignard reagents, *e.g.*

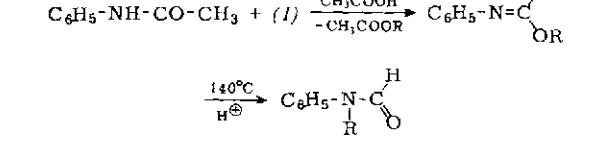
b) Treatment of *(2)* with HN_3 gives 1-benzylidenaminotetrazole, which on hydrolysis leads to 1-aminotetrazole. The latter can be converted to the *N*-isonitrile with $CHCl_3$ and KOH.



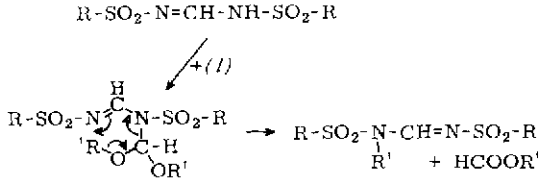
c) Triphenylmethylsodium causes the α-elimination of alcohol from *(2)* with formation of the conjugated *N*-isonitrile [2].



3. Acetanilide reacts with *(1)* in the presence of an equimolar amount of glacial acetic acid to give *N*-phenylformimidic ester and acetic ester. On catalysis with H_2SO_4, an *N*-alkylformanilide, the rearrangement product of the imidic ester, is obtained.



4. *N,N*-(Bisarylsulfonyl)formamidines [3] are alkylated by *(1)*.



[1] *H.W. Wanzlick*, Angew. Chem. *74*, 129 (1962); Angew. Chem. internat. Edit. *1*, 75 (1962).

[2] *I. Hagedorn*, Angew. Chem. *74*, 499 (1962); Angew. Chem. internat. Edit. *1*, 514 (1962).

[3] *H. Etling*, Dissertation, Universität Freiburg, 1963; *I. Hagedorn, U. Eholzer*, and *H. D. Winkelmann*, Angew. Chem. *76*, 583 (1964); Angew. Chem. internat. Edit. *3*, 647 (1964).

18

Acetic Acid Solvates of Nickel and Copper Salts

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Saarbrücken (Germany)

From the tetrahydrate $Ni(O_2CCH_3)_2 \cdot 4H_2O$, the following products were isolated with glacial acetic acid in the pure, crystalline state:

$Ni(O_2CCH_3)_2$	*(1)*
$Ni(O_2CCH_3)_2 \cdot H_2O$	*(2)*
$Ni(O_2CCH_3)_2 \cdot {}^1/_2\ H_2O \cdot {}^1/_2\ CH_3CO_2H$	*(3)*
$Ni(O_2CCH_3)_2 \cdot {}^1/_2\ CH_3CO_2H$	*(4)*
$NiCl_2 \cdot {}^1/_2\ CH_3CO_2H$	*(5)*
$Ni(O_2CCH_3)_2 \cdot CH_3CO_2K$ (in acetic anhydride); μ_{eff} = 3.22–3.97 B.M.	*(6)*

The compound *(4)* cannot be decomposed to *(1)*, and *(1)* cannot be solvated to *(4)*, suggesting the existence of polynuclear complexes in solvate-free nickel acetate.

In contrast to *(5)*, the solvate of $NiBr_2$ is very unstable and decomposes at room temperature. With iodide ions, NiI_2 is obtained directly.

The presence of acetatonickelate ions in *(6)* is concluded from a shift in the absorption bands in the remission spectrum from 400 mμ for *(1)* to 416 mμ for $K[Ni(O_2CCH_3)_3]$ [*(6)*, yellow-green]. A similar shift occurs when solutions of *(1)* or *(4)* in acetic are heated.

From solutions of $Cu(O_2CCH_3)_2$ in glacial acetic acid/CH_3COCl (1:1), $CuCl_2 \cdot 3/2\ CH_3CO_2H$ *(7)* is precipitated. The solvate-free $CuCl_2$ can then be obtained with pure acetyl chloride either directly or *via* the hemisolvate $CuCl_2 \cdot {}^1/_2\ CH_3CO_2H$ *(8)*.

When *(8)* is washed with anhydrous benzene or ether, solvate-free $CuCl_2$ is easily obtained. With anhydrous acetone it yields a trichlorocuprate(II) and a black precipitate which is identical with a modification of the mixed-valence copper(I,II)chloride hemisolvate $Cu_x(CuCl_{2+x}) \cdot {}^1/_2 CH_3CO_2H$ [1].

An analogous mixed-valence compound is obtained by precipitating copper(II) bromide with 10 equivalents of acetyl bromide in glacial acetic acid. The compound decomposes above 75 °C to a heterogeneous mixture of $CuBr_2$ and CuBr and is also decomposed by water.

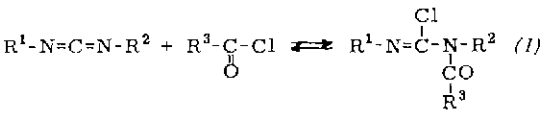
[1] *H. D. Hardt* and *M. Eckle*, Meeting of South-West German Chemistry Lecturers, Freiburg, 1964. Cf. Angew. Chem. *76*, 584 (1964).

19

The Reactions of Carbodiimides with Acid Chlorides

K. Hartke, Marburg (Germany) and
E. Palou, Concepción (Chile)

Carbodiimides react with acid chlorides to give acylchloroformamidines *(1)*, which usually cannot be isolated owing to their thermal instability. The rates of the reactions can be determined by infrared spectrophotometry by following the disappearance of the valence vibration bands of the carbodiimide at 4.7 μ and of the acid chloride at 5.5–5.7 μ, and the formation of two new bands around 6 μ (C=O and −C=N− valence vibrations of the acylchloroformamidines).



Reaction rates and equilibrium constants for aliphatic carbodiimides depend on the size of the substituents R^1 and R^2 and on the reactivity of the acid chloride. If R^1 and R^2 are primary aliphatic residues (such as n-propyl), the reaction with aliphatic carbonyl chlorides is practically instantaneous. The acylchloroformamidines can be isolated by distillation and can be stored for weeks at room temperature.

Inorganic acid chlorides (*e.g.* sulfuryl chloride, thionyl chloride, nitrosyl chloride) react in the course of a few hours. With increasing size of R^1 and R^2, the reaction rate decreases, as does the number of acid chlorides with which the reaction goes to completion. Isopropyl-t-butylcarbodiimide and di-t-butylcarbodiimide do not react with carbonyl halides. Aromatic carbodiimides do not react completely with carbonyl halides, but form equilibium mixtures. Only with phosgene does the reaction go to completion.

20

Structure and Properties of some Salts of Phosphoric Monoesters

K. Hartl, Heidelberg (Germany)

Crystalline salts of divalent cations with phosphoric monoesters exhibit one-dimensional swelling with water and water-like liquids, as well as with long-chain polar n-alkyl compounds [1].

Further insight into this swelling behavior was provided by X-ray analysis of calcium mono-n-alkylphosphate hydrates with the overall formula $CaPO_4R \cdot 2H_2O$. The orthorhombic crystals are composed of electrically neutral, two-dimensionally infinite $Ca(H_2O)PO_4$ layers, between which the ester residues and the molecules of the swelling liquid are arranged.

In the layers of both the methylphosphate and ethylphosphate, the calcium ions are surrounded by four water molecules in square planar coordination, and *vice versa*. The PO_4 tetrahedra are arranged symmetrically on both sides of this plane with one face parallel to it. The calcium ions then have a total of eight coordination sites occupied by oxygen, with mean Ca–O distances of 2.70 and 2.82 Å, respectively. The ester residue is attached to the PO_4-oxygen atom pointing away from the layer, to which the second water molecule of the formula unit is loosely attached.

In the allylphosphate and n-propylphosphate salts, the PO_4 groups alternate on both sides of a $Ca-H_2O$ layer. The calcium ions have six-fold coordination to oxygen; the mean Ca–O distance is 2.55 Å. Ester groups and loosely bound water are accomodated as in the ethyl and methyl derivatives.

The swelling of the allylphosphate and ethylphosphate is particularly uniform in the homologous n-alkylamines and n-alkanols, which are held to the $Ca(H_2O)PO_4$ layers by their polar groups. From the mean increase of the layer distance by 1.26 and 1.20 Å, respectively, per carbon atom of the swelling molecule, their arrangement between the layers can be deduced. The alkyl chains are stretched and have their long axis oblique to the layer planes at an angle of 90° and 73°, respectively. This arrangement agrees with the observed ratio of salt:swelling compound = 2:1.

In the methylphosphate, the unswollen state is favored by van der Waals forces between the closely spaced layers.

Channels are present in the structure of the n-propylphosphate, into which polar compounds can be included, as in zeolite compounds.

Proton magnetic resonance measurements showed that the protons of the ester groups and the water molecules have a restricted mobility similar to that in ice.

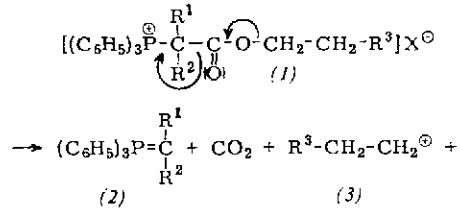
[1] *K. Hartl* and *A. Weiss*, Angew. Chem. *71*, 379 (1959); Z. Naturforsch. *16b*, 844 (1961); *17b*, 11 (1962); Naturwissenschaften *49*, 10 (1962).

21

Thermal Decomposition of Alkoxycarbonylmethyltriphenylphosphonium Halides

H. Hartung, Erlangen (Germany)

Alkoxycarbonylmethyltriphosphonium halides *(1)* decompose on being heated into an alkylidenetriphenylphosphorane *(2)*, carbon dioxide, a carbonium ion *(3)*, and a halide ion.



(1)

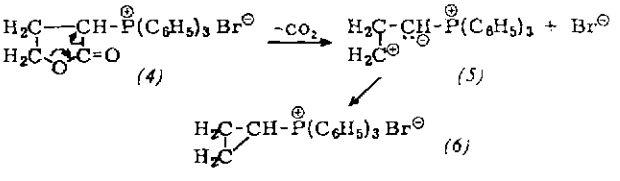
(2) *(3)*

Depending on the nature of the substituents R^1 and R^2, there are three possibilities for the stabilization of the products.

(a) For $R^1 = R^2 = H$, X = Br, a proton is transferred to the alkylidenephosphorane to give a phosphonium salt and an olefin.

(b) When R^1 is an acyl residue and $R^2 = H$, X = Cl, the alkylidenetriphenylphosphorane *(2)* and the alkyl halide corresponding to *(3)* are isolated.

(c) When 2-oxotetrahydrofuran-3-yltriphenylphosphonium bromide *(4)* is decomposed, *(5)* is proposed as intermediate, which is alkylated intramolecularly to cyclopropyltriphenylphosphonium bromide *(6)*.



(4) *(5)*

(6)

22

Protecting Effects in Styrene-Acrylonitrile Copolymers During the Action of Ionizing Radiation

H. Heusinger and *E. J. Weber*, München (Germany)

In order to determine the extent to which the components of a copolymer influence each other during irradiation, the amount of hydrogen evolved on radiolysis of styrene-acrylonitrile copolymere was measured as a function of copolymer composition. A protecting effect was observed which is particulary efficient at low styrene contents. Possible causes are:

Addition of hydrogen onto styrene with formation of hexadienyl radicals; unequal distribution of the energy absorbed between π- and σ-electrons; energy transfer.

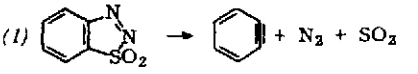
The experimental results show that energy transfer must be primarily responsible for the protecting effect. The occurrence of a maximum in the degree of protection at a styrene content of about 0.05 mole-% shows further that the protecting effect depends not only on the concentration and radiation resistance of the components, but evidently also on the monomer sequence in the polymer chain.

23

Decomposition of 1,2,3-Benzothiadiazole 1,1-Dioxide

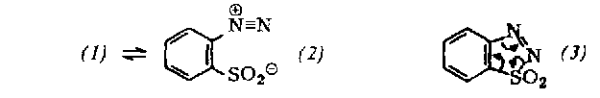
R. W. Hoffmann, *W. Sieber*, and *G. Guhn*, Heidelberg (Germany)

1,2,3-Benzothiadiazole 1,1-dioxide *(1)* is smoothly decomposed in solution at 0–20 °C to dehydrobenzene, sulfur dioxide, and nitrogen [1]. The decomposition in benzene was followed by measurement of nitrogen evolution, and was



(1)

found to have the activation parameters $\Delta H^{\neq} = 27.8 \pm 0.9$ kcal/mole, $\Delta S^{\neq} = 16.6 \pm 1.8$ cal deg^{-1} mole^{-1}. Changing the solvent (*e.g.* from tetrahydrofuran to dimethylsulfoxide) altered the rate of decomposition by at most a factor of 4. Addition of $LiClO_4$ also had only a small effect, which indicates only a small change in polarity in going from reactants to the transition state. Since *(1)* and *(2)* are in a



(1) *(2)* *(3)*

rapidly established equilibrium with each other, it cannot be decided whether the decomposition proceeds from *(1)* or *(2)*. The former is more likely because of the low polarity of the transition state. The substituent effect (10^4 k [sec^{-1}] in benzene at 20 °C for 5-CH_3: 2.75; 5-Cl: 3.82; 5-Br: 5.08; 5-OCH_3: 1.23) can be explained by a concerted decomposition of *(1)* as depicted in *(3)*.

[1] *G. Wittig* and *R. W. Hoffmann*, Chem. Ber. *95*, 2718 (1962).

24

Reactions of Silylamines with Hydrocyanic Acid and Cyanogen Halides

J. Hundeck, München (Germany)

The reaction rate of hydrocyanic acid with organic silylamines [1] is increased by the corresponding organic chlorosilane [2]. Organic cyanosilanes are obtained, *e.g. (1)*.

$$(H_3C)_3Si{-}N(C_2H_5)_2 + (H_3C)_3SiCl + 2\ HCN \rightarrow 2\,(H_3C)_3Si{-}CN + N(C_2H_5)_2H{\cdot}HCl$$

(1)

Organic cyanosilanes are also formed in the reaction of cyanogen iodide with alkyldialkylaminosilanes in yields of up to 60 %.

$$R_3Si{-}NR'_2 + ICN \rightarrow R_3Si{-}CN + NR'_2I$$

The course of the reaction is strongly influenced by the substituents on the silicon and nitrogen as well as by conditions such as temperature, solvent, *etc.*

Triethylsilylamine and bis(trimethylsilyl)amine react with cyanogen iodide at 100 °C in a sealed tube to give bis(trialkylsilyl)carbodiimides:

$$2\,(H_5C_2)_3Si{-}NH_2 + ICN \rightarrow (H_5C_2)_3SiN{=}C{=}NSi(C_2H_5)_3 + NH_4I$$

Cyanogen bromide and chloride react similarly with bis(trimethylsilyl)amine (X = Br, Cl):

$$4\ [(H_3C)_3Si]_2NH + 3\ XCN \rightarrow 3\ (H_3C)_3SiN{=}C{=}NSi(CH_3)_3 + 2\ (H_3C)_3SiX + NH_4X$$

Cyanogen bromide – in contrast to cyanogen iodide (cf. above) – also reacts with trimethyldiethylaminosilane, forming trimethylbromosilane (yield 85 %) and diethylcyanamide:

$$(H_3C)_3Si{-}N(C_2H_5)_2 + BrCN \rightarrow (H_3C)_3SiBr + N(C_2H_5)_2CN$$

Tris(trimethylsilyl)amine reacts only incompletely with cyanogen chloride, even at 200 °C:

$$[(H_3C)_3Si]_3N + ClCN \rightarrow (H_3C)_3SiCl + (H_3C)_3SiN{=}C{=}NSi(CH_3)_3$$

[1] *T. A. Bither, W. H. Knoth, R. V. Lindsey jr.*, and *W. H. Sharkey*, J. Amer. chem. Soc. *80*, 4151 (1958).

[2] *J. Hundeck*, Doctorate Dissertation, Universität München, 1961.

25

Intermolecular Interactions in the Heat-Induced Aggregation of Globular Proteins in Solution

R. Jaenicke, Frankfurt/Main (Germany)

The heat-induced aggregation of dissolved globular proteins is generally brought about by coagulation and exchange processes. The types of bonds formed can be determined by the use of specific inhibitors or by degradation of the aggregates.

Coagulation by non-covalent bonds in principle seems to be the precursor reaction of the exchange mechanism; it exceeds the covalent aggregation by disulfide- and lanthionine-bonds under all conditions of experiment.

Ion-pair attractions can be excluded as a cause of coagulation, since guanidinium chloride and urea are equally effective in dissociating the aggregates. The behavior of dinitrophenylated and acetylated proteins also provides an indication against ion-pair binding. Inhibitors can be used to distinguish between hydrogen bonds and hydrophobic interactions: the aggregation is inhibited at all pH values by formaldehyde, dioxane, 2-chloroethanol, and ionic detergents. Together with measurements of optical rotatory dispersion, these results show that when the native conformation is retained (λ_c = const.), only hydrogen bonds take part in the coagulation. A partial denaturation, on the other hand, gives rise in addition to hydrophobic bonding among the particles forming the aggregates.

The results verify the principle of tertiary structure derived from X-ray analysis in the case of the protein in solution.

26

The System Lithium Oxide/Uraninium(V) Oxide

Sibylle Kemmler, Tübingen (Germany)

The compounds $LiUO_3$, 0.5 $Li_2O{\cdot}U_2O_5$, and 0.15 $Li_2O{\cdot}U_2O_5$ exhibit paramagnetism with an anomalous temperature dependence. The strong influence of the ligand field on the magnetic moment indicates less effective shielding of the 5f electrons compared to the 4f electrons. Similar behaviour was found for other ternary uranium(V) oxides ($NaUO_3$; KUO_3; $RbUO_3$; $MgO{\cdot}U_2O_5$; $CdO{\cdot}U_2O_5$; 2 $PbO{\cdot}U_2O_5$; 2.5 $PbO{\cdot}U_2O_5$; $La_2O_3{\cdot}U_2O_5$; $Sc_2O_3{\cdot}U_2O_5$). None of these compounds obey the Curie or the Curie-Weiss laws. The experimental data were found to obey the equation

$$\chi_M = (N\beta^2\mu_{eff}^2/3\ kT) + N\alpha = (C/T) + A$$

When the molar susceptibility χ_M was split up into a temperature-independent part A and a temperature-dependent part C/T, then A was found to be almost constant for the various compounds studied ($A \approx 400\times10^{-6}$), and the Curie constants C were found to be distributed about two means depending on the coordination number N of the uranium, *viz.* C = 0.05–0.07 for N = 6, and C = 0.13–0.16 for N = 8. The Curie constants calculated for the electronic configuration $5f^1$ with the ligand field theory have similar values. This agreement shows the electronic configuration of uranium in the U(V) compounds to be $5f^1$.

Triuranium octoxide U_3O_8 has magnetic properties similar to those of 0.15 $Li_2O{\cdot}U_2O_5$, and should therefore probably be formulated as $U_2O_5{\cdot}UO_3$.

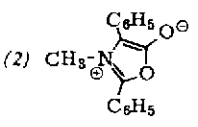
27

Mechanism of the Dakin-West Reaction

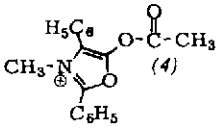
R. Knorr, München (Germany)

The decarboxylating acetylation of α-amino acids with acetic anhydride/pyridine, known as the Dakin-West reaction, occurs *via* cyclic intermediates. The intermediate formation and acylation of azlactones from glycine derivatives has been described [1]; the reaction requires the presence of base and of acetic acid.

The azlactone-analogous intermediate formed from *N*-benzoyl-*N*-methyl-α-phenylglycine *(1)* is anhydro-2,4-diphenyl-5-hydroxy-3-methyloxazolium hydroxide *(2)*, a mesoionic compound [2]. In the presence of acetic acid (> 0.4 mole/l), *(1)* gives, *via (2)*, CO_2 and *N*-benzoyl-*N*-methyl-α-amino-α-phenylacetone *(3)* in 75 % yield. The second intermediate *(4)* can be isolated as the perchlorate; in acetic

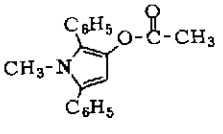


(2)

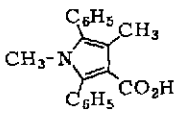


(4)

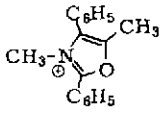
anhydride it is found by ultraviolet absorption measurements to be present to about 1 %. It reacts further by nucleophilic attack in position 2 of the oxazole ring; effective nucleophiles are acetate, the carbanion *(5)* of acetic anhydride occurring in the Perkin cinnamic acid synthesis, or chloride ions. In the absence of acetic acid or in the presence of only small amounts (< 0.2 moles/l), *(5)* is converted by O → C acetyl migration to position 4 of the oxazole ring and subsequent 1,3-dipolar CO_2-elimination into the pyrroles *(6)* and *(7)*, and acetate is converted into the enol acetate of *(3)* and the oxazolium ion *(8)*. The branching of the



(6)



(7)



(8)

reaction starting from *(4)*, manifested in these products, can also be shown from kinetics: thus acetic acid inhibits the reaction by removal of *(5)*. No base catalysis occurs; the salt effect is positive.

The reaction of acetyl chloride with *(2)* is a new variant o, the Dakin-West reaction: by attack of chloride ions on *(4)*f the product *(8)* is obtained in 70 % yield. It is assumed that all Dakin-West reactions in which cyclic intermediates occur take place according to this mechanism.

[1] *G. H. Cleland* and *C. Niemann*, J. Amer. chem. Soc. *71*, 841 (1949).

[2] *R. Huisgen, H. Gotthardt, H. O. Bayer*, and *F. C. Schaefer*, Angew. Chem. *76*, 185 (1964); Angew. Chem. internat. Edit. *3*, 136 (1964).

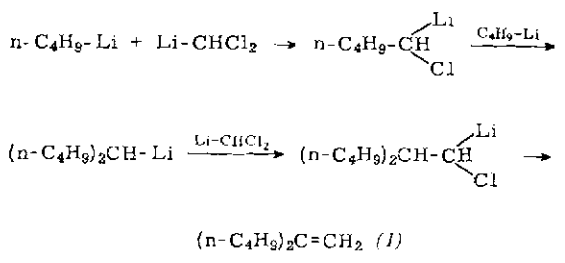
28

Stability and Reactivity of α-Halogen-Carbanions

G. Köbrich, K. Flory, H. R. Merkle, and *H. Trapp,*
Heidelberg (Germany)

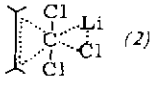
Compounds of the type $>C(Hal)Li$ are more stable at low temperatures in tetrahydrofuran (THF) as solvent than in diethyl ether. Substances in which β-elimination is possible behave exceptionally: trichlorovinyl-lithium decomposes more rapidly in THF than in diethyl ether.

Organic α-halogeno lithium compounds, besides possessing the nucleophilic character expected for organolithium compounds, also have electrophilic properties: dichloromethyl-lithium reacts smoothly at −74 °C with an equimolar amount of n-butyl-lithium to give 1-chloro-1-pentyl-lithium, which yields mainly 1,1-di-n-butylethylene *(1)*.



$$(n\text{-}C_4H_9)_2C{=}CH_2 \quad (1)$$

At −74 °C, dichloromethyl-lithium does not react with cyclohexene, and even on being heated above the decomposition temperature (−60 °C) forms only traces of chloronorcarane. Trichloromethyl-lithium in THF at −100 °C is stable and inert to cyclohexene. On short-term heating to −72 °C, partial decomposition is observed (mean: 36 %). Since the decomposition is increased by addition of cyclohexene (mean: 54 %), and the yield of dichloronorcarane (mean: 16 %) corresponds to this increase within the limits of error, it is concluded that the cyclopropane is formed by the trichloromethyl-lithium in a reaction competing with the thermal decomposition. The substituent effect in the cycloaddition to other olefins (tetramethylethylene, α-methylstyrene, vinyl ethyl ether) suggests that this reaction takes place by an electrophilic attack at the double bond without the occurrence of significant partial charges on the olefin carbon atoms.



(2)

The transition state is therefore best represented by the formula *(2)*, which corresponds to the transition state of the Simmons-Smith reaction.

These examples show that organic α-halogeno lithium compounds are capable of electrophilic reactions with olefins and organolithium compounds, reactions which were previously regarded as typical carbene reactions.

29

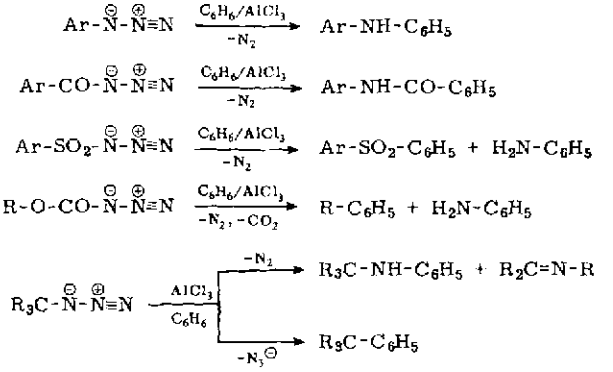
Reactions of Organic Azides under the Conditions of the Friedel-Crafts Reaction

R. Kreher and *G. Jäger,* Darmstadt (Germany)

Organic azides split off N_2 or $N_3^{\ominus}$ under the influence of aluminum trichloride. The ionic intermediates expected are stabilized by reaction with benzene or by rearrangement.

Whereas aryl, acyl, sulfonyl, and alkoxycarbonyl azides react primarily with evolution of N_2, alkyl azides also split off significant amounts of $N_3^{\ominus}$.

The behaviour of azides depends also on the solvent. For example, alkoxycarbonyl azides in cyclohexane react with elimination of N_2 and CO_2, presumably *via* alkyl azides, to give azomethines.



30

Trifluorophosphine Complexes of Nickel, Cobalt, and Iron

Th. Kruck, K. Baur, W. Lang, and *A. Prasch,*
München (Germany)

Tetrakis(trifluorophosphine)nickel, $Ni(PF_3)_4$, can be prepared from metallic nickel, as well as from nickel(II) iodide in the presence of copper powder under pressure of PF_3.

The PF_3 ligands can be substituted by triphenylphosphine, triphenylphosphite, or carbon monoxide, to give $Ni(PF_3)_{4-n}[P(C_6H_5)_3]_n$ (n = 1 and 2), $Ni(PF_3)[P(OC_6H_5)_3]_3$, and $Ni(CO)_4$, corresponding to the different donor-acceptor properties of these substituents. The shift of the P–F valence absorptions to longer wavelenghts for phosphine- and phosphite-substituted nickel trifluorophosphines is ascribed to an increase in the Ni → PF_3 back donation and the related decrease of the π-bonding character of the P–F bond.

The reaction of PF_3 with $ReCl_5$ and copper powder in an autoclave gives the colorless, crystalline chloropentakis(trifluorophosphine)rhenium, $Re(PF_3)_5Cl$ [1]. Deep red $Fe(PF_3)_4I_2$ and orange $Fe(PF_3)_4Br_2$ are obtained from pentakis(trifluorophosphine)iron and iodine in petroleum ether and from $Fe(PF_3)_5$ and bromine vapor, respectively. Iodotetrakis(trifluorophosphine)cobalt, $Co(PF_3)_4I$, is formed from a mixture of CoI_2 and copper powder even at temperatures as low as 20 °C and PF_3 pressures of less than 50 atm, or from $HCo(PF_3)_4$ and iodoform. All halogenotrifluorophosphine-metal compounds are as volatile as the metal trifluorophosphines, and are readily soluble in nonpolar solvents. These properties indicate an essentially nonionic metal-halogen bond, with the resonance structure $\overset{\oplus}{X}{-}\overset{\ominus}{M}{\leftarrow}PF_3$ probably having a considerable weight.

[1] Work carried out with collaboration of *A. Engelmann.*

31

Synthesis of 3'-Aminonucleosides

F. W. Lichtenthaler, H. P. Albrecht, G. Olfermann, and *J. Yoshimura,* Darmstadt (Germany)

The dialdehyde-nitromethane cyclization can be extended to "nucleoside dialdehydes" resulting from nucleosides by periodate oxidation [1]. On condensation with nitromethane/sodium methoxide in methanol and subsequent neutralization, mixtures of 3'-deoxy-3'-nitronucleosides

are obtained, which can be separated by fractional crystallization, by preparative layer chromatography in chloroform/methanol, or on silica gel columns with butanol/water. The main product is the *gluco*-isomer. Catalytic hydrogenation leads to the corresponding 3'-amino-3'-deoxynucleosides. The configurational proof was derived from the NMR spectra of the *N*-acetates and tetraacetates, and by characterization of the amino-sugars formed on acid hydrolysis.

Nitromethane cyclization of "inosine dialdehyde" gives a mixture of 9-(3'-deoxy-3'-nitroglucopyranosyl)hypoxanthine (38 %) and 9-(3'-deoxy-3'-nitrogalactopyranosyl)hypoxanthine. "Adenosine dialdehyde" analogously gives two 3'-nitronucleosides with D-*gluco* and D-*manno* configurations respectively [2]. By deamination with sodium nitrite/acetic acid, 9-(3'-deoxy-3'-nitroglucopyranosyl)adenine and 9-(3'-deoxy-3'-nitromannopyranosyl)adenine can be converted to the hydroxylamine derivatives. Cyclization of "xanthosine dialdehyde" with nitromethane also gives two 3'-nitronucleosides which have *gluco* (35 %) and *galacto* (22 %) configuration.

1-(β-D-Glucopyranosyl)thymine can be converted by periodate oxydation into "thymine dialdehyde", which on nitromethane cyclization gives 1-(3'-deoxy-3'-nitroglucopyranosyl)thymine in 45 % yield.

[1] *F. M. Lichtenthaler, H. P. Albrecht,* and *G. Olfermann,* Angew. Chem. *77*, 131 (1965); Angew. Chem. internat. Edit. *4*, 147 (1965); *K. A. Wanatabe* and *J. J. Fox,* Chem. pharmac. Bull. (Tokyo) *12*, 975 (1964).

[2] *J. J. Fox* et al. obtained 3-amino-3'-deoxyhexosyladenine by the same reaction as a mixture of the D-*gluco*, D-*manno*, and D-*galacto* isomers (personal communication).

32

Binding of Actionomycin on Apyrimidinic Acid

M. Liersch and *G. Hartmann*, Würzburg (Germany)

The antibiotic actinomycin associates with deoxyribonucleic acid (DNA), thereby blocking its biological function in the synthesis of nucleic acids. According to a hypothesis of *Hamilton* et al. [1], the helix structure of DNA is necessary for the binding of the antibiotic. We have therefore investigated the binding of actinomycin on apyrimidinic acid [2], which cannot have a helix structure because of its base composition.

On addition of apyrimidinic acid to an aqueous solution of actinomycin, similar changes of the ultraviolet spectrum are observed as with thymus DNA. In the presence of excess actinomycin, the apyrimidinic acid becomes saturated with it. Calculation from the extinction coefficients shows that under these conditions one actinomycin molecule is bound per 5.7 base residues of apyrimidinic acid. The value obtained is almost the same as for the associate of thymus DNA and actinomycin.

Optical measurements at concentrations between 10^{-5} and 10^{-6} M of actinomycin and nucleic acid show that the affinity of apyrimidinic acid for the antibiotic is not much lower than that of native DNA.

Addition of urea leads to dissociation of the associates, as of the complex with thymus DNA. Evidently the bonding is similar in the two different associates.

These experiments, and similar ones with single-stranded DNA from the phage fd, show that the helix structure of DNA is not necessary for the association of actinomycin with DNA.

[1] *L. Hamilton, W. Fuller,* and *E. Reich,* Nature (London) *198*, 538 (1963).

[2] Apyrimidinic acid was prepared from thymus DNA by hydrazinolysis of the pyrimidine bases.

33

The Action of Diazooxonorleucine and Albizziin on the Biosynthesis of Aromatic Amino Acids in Saccharomyces Cerevisiae and Escherichia Coli

F. Lingens and *Gerhard Müller,* Tübingen (Germany)

The biosynthesis of aromatic amino acids occurs *via* the ether of 3-enolpyruvic acid with *trans*-3,4-dihydroprotocatechuic acid, also known as chorismic acid. We detected this compound in culture media of tryptophane-deficient mutants (try$^-$) and phenylalanine-tyrosine-deficient mutants (phen$^-$,tyr$^-$) of *Saccharomyces cerevisiae*. Chorismic acid accumulates in particular when 6-diazo-5-oxo-L-norleucine or *p*-fluorophenylalanine is added to the try$^-$-mutant, or when 6-diazo-5-oxonorleucine, albizziin (L-α-amino-β-ureidopropionic acid), or 4-methyltryptophane is added to the phen$^-$, tyr$^-$-mutant. Diazooxonorleucine and albizziin inhibit the amine transfer from glutamine in the biosynthesis of anthranilic acid. *p*-Fluorophenylalanine acts as a feedback inhibitor in the transformation of chorismic acid into prephenic acid. 4-Methyltryptophane presumably inhibits the first step in the conversion of chorismic acid to anthranilic acid. Mutants having a genetic block behind a metabolic branching point accumulate mixtures of substances, the composition of which can be influenced by the inhibitors mentioned above. Diazooxonorleucine causes the accumulation of *p*-hydroxybenzoic acid and of phenylpyruvic acid in wild strains of *S. cerevisiae* and *Escherichia coli*. A (try$^-$) mutant of *E. coli* normally accumulating anthranilic acid also produces, on addition of diazooxonorleucine, *p*-hydroxybenzoic acid and phenylpyruvic acid, which are postulated to be formed enzymatically from chorismic acid.

34

The Behavior of Neptunium and Various Uranium Fission Products in Heterogenous Reactions of Neutron-Irradiated Uranium Compounds with Complexing Agents

F. Lux and *F. Ammentorp-Schmidt,* München (Germany)

Uranium dioxide was irradiated with neutrons. Lattice transformations were produced in the product by alternating treatment with air (or N_2O) and ethanol vapor in a nitrogen stream at 200–450 °C which contained a complexing agent (acetylacetone or phthalodinitrile). In other experiments, a phthalodinitrile melt with or without phthalocyanine was used as complexing agent.

With acetylacetone, Np and Ru are separated as volatile complexes. With phthalocyanine, Np does not form volatile complexes, but Ce, Nd, Zr, and Ru are partially separated. The partial separation of Mo and Tc observed with both acetylacetone and phthalocyanine can also be explained by the formation of the oxides. The yields of the fission products separated were generally below 1 %.

Instead of the system uranium/oxygen (which is unfavorable from the point of view of complex formation) the system uranium/uranium hydride was chosen for further experiments. The neutron-irradiated uranium was converted to uranium hydride, which was heated with phthalocyanine in a terphenyl melt to 300–400 °C. Subsequently the terphenyl was sublimed off, then the phthalocyanine at 450–500 °C in a high vacuum. In the phthalocyanine sublimate, 3–7 % of Np was present, and only 0.1–0.01 % of the fission products Ce, Nd, Zr, and Ru. Since the specific activity of Np in the phthalocyanine is unchanged by re-sublimation, an Np-phthalocyanine complex subliming at 450–500 °C in high vacuum must be formed. Zone melting experiments support this conclusion. To our knowledge, a volatile Np complex has not been described previously. If the Np sublimes in the form of an iodide formed from fission-produced iodine, the

sublimate would contain ^{133}I or ^{131}I, which however is not the case.

From UCl_4 and Li_2pc (pc = phthalocyanine residue), $U(pc)_2$ was prepared, which presumably has a bipyramidal structure in analogy with $Sn(pc)_2$ [1]. $U(pc)_2$ cannot be sublimed.

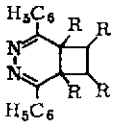
[1] *F. H. Moser* and *A. L. Thomas*: Phthalocyanine Compounds. Reinhold, New York 1963, p. 127.

35

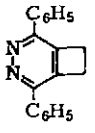
Attempts to Prepare Compounds with the 3,4-Diazabicyclo[4.2.0]octa-2,4-diene and 3,4-Diazabicyclo-[4.2.0]octa-2,4,7-triene Ring Structure

G. Maier, Karlsruhe (Germany)

In connection with the investigation of the valence-tautomeric system diazanorcaradiene ⇌ diazacycloheptatriene [1] we are interested in the structural relationships between compounds of the types *(1)* and *(3)* and their monocyclic valence tautomers [*e.g. (2b)*].



(1a) R = H
(1b) R = CH_3



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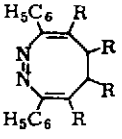
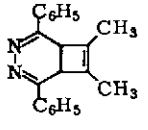
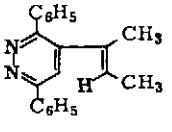


(2b) R = CH_3



(3)



(5)

Compound *(1a)*, prepared from 5-oxo-2-phenyl-3,4-diazabicyclo[4.2.0]oct-2-ene with phenyl-lithium, cannot be isolated, but is transformed spontaneously with elimination of hydrogen into 3,6-diphenyl-4,5-cyclobutenopyridazine *(4)*.

The reaction of 1,2-dimethyl-*cis*-3,4-dibenzoylcyclobutene with hydrazine also does not lead to the desired bicyclic compound *(3)* but its rearrangement product *(5)*.

If dehydration is made impossible by substitution, derivatives of *(1)*, *e.g.* the compound *(2b)*, can be isolated [2]. At present we have no indication for the existence of *(2b)*. We assume that *(1b)* is in valence-tautomeric equilibrium with *(2b)*, but that the concentration of the monocyclic tautomer is too low for direct detection.

[1] *G. Maier*, Angew. Chem. *75*, 920 (1963); Angew. Chem. internat. Edit. *2*, 621 (1963); Chem. Ber., in press.

[2] With collaboration of *F. Seidler*.

36

The New Europium Isotopes ^{142}Eu and ^{143}Eu

H. Münzel, Karlsruhe (Germany)

The Eu isotopes formed by bombardement of ^{144}Sm with high-energy deuterons were investigated. Analysis of the decay curve of the chemically separated europium fraction showed the presence of 5 components with half-lives of 1.1 min, 2.5 min, 8.8 min (^{143}Sm), 72 min (^{142}Sm) and >10 h. The two short-lived components were identified as the as yet unknown nuclides ^{142}Eu and ^{143}Eu. The following data on the decay of these nuclides were obtained:

	$T_{1/2}$ [min]	E_γ [MeV]	β^+ [MeV]
^{142}Eu	1.1	0.77; 1.03	> 3
^{143}Eu	2.5	1.11; 1.55	> 3

To separate the europium from the radioisotopes of other rare earth elements, the target material was dissolved in 1 N HCl and extracted with sodium amalgam. The separation is complete after about 50 sec.

37

Structural Relationships between Basic Mercuric Chloride, $HgCl_2 \cdot 4\,HgO$, and the Modifications of Mercuric Oxide, HgO

G. Nagorsen and *A. Weiss*, Heidelberg (Germany)

The orthorhombic and the hexagonal modifications of mercuric oxide are composed of infinite —Hg—O—Hg— chains. In the former, the chains are zig-zag and parallel; in the latter, they are spirally coiled. The Hg—O bond length is about 2.03 Å in each case; the O—Hg—O bond angle is almost 180°, and the Hg—O—Hg angle roughly tetrahedral.

Our previous suggestion [1] that $HgCl_2 \cdot 4\,HgO$ has a layer lattice is in disagreement with new results. For the interpretation of the lattice parameters of the isostructural bromide, as well as of the lattice defects observed for the chloride when crystallized at low temperature, other positions must be assumed for the oxygen atoms. The mercury and chloride lattices of the previous model are retained, but a new pattern is assumed for the —Hg—O—Hg— chains in the c-direction. The Hg—O bond length is about 2.03 Å, the angle at the oxygen atom around 114°. From the interatomic distances it must be concluded that the $HgCl_2$ is present in the ionic form in the lattice. The lattice defects are probably false chain links of the type found in the orthorhombic modification of HgO; the defects occur in the same plane in all chains and affect the diffraction pattern like a stacking fault of a layer lattice with a displacement vector a/2. From the line broadening of the (310) reflection of a single crystal it was deduced that the ordered regions in the c-direction are on the average about 8 times the thickness of the unit cell.

[1] *A. Weiss, G. Nagorsen*, and *A. Weiss*, Z. Naturf. *9b*, 81 (1954).

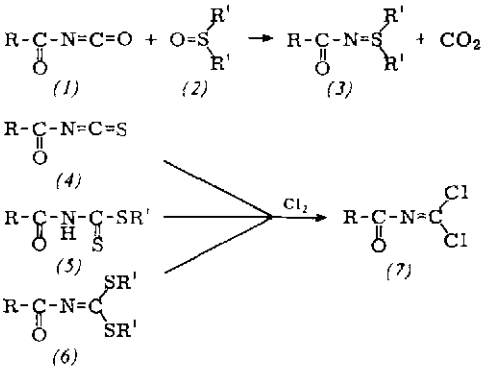
38

Syntheses and Reactions of N-Acylisonitrile Derivatives

R. Neidlein and *W. Haussmann*, Marburg (Germany)

The reaction of phosphorus pentachloride with aroyl isocyanates leads to α-chloroalkylidenecarbamidic chlorides. In contrast, aliphatic acylisocyanates, such as mono-, di-, or tri-chloroacetyl isocyanate, under the same conditions give mixtures of α,α-dichloroalkyl isocyanates and α-chloroalkylidinecarbamoyl chlorides. The structures of these compounds were ascertained from their infrared spectra.

Acyl isocyanates *(1)* react with dialkyl sulfoxides *(2)* to *N*-acylsulfimines *(3)*, the structures of which were proved by synthesis *via* other routes [1].



N-Acylisonitrile dichlorides *(7)*, of which previously only the benzoylisonitrile dichloride [2] was known, were prepared by chlorination [3] of *N*-acylisothiocyanates *(4)* or of *N*-acyldithiocarbamates *(5)*; in some cases ultraviolet light or heating were necessary.

The cleavage of *N*-acyliminodithiocarbonates *(6)* [4] with chlorine also led to *N*-acylisonitrile dichlorides *(7)*.

N-Acylisonitrile dichlorides react with primary and secondary amines, thiols, dithiols, and ethanolamines to give *N*-acylguanidines, *N*-acyliminothiocarbonate chlorides, *N*-acyliminodithiocarbonates, and β-hydroxyethylformamidinium chlorides, respectively. From phosphorus pentachloride and acylisonitrile dichlorides, α,α-dichloroalkylisonitrile dichlorides are formed.

[1] *D. S. Tarbell* and *C. Weaver*, J. Amer. chem. Soc. *63*, 2939 (1941).

[2] *I. B. Douglass* and *T. B. Johnson*, J. Amer. chem. Soc. *60*, 1486 (1938).

[3] *E. Sell* and *G. Zierold*, Ber. dtsch. chem. Ges. *7*, 1228 (1874).

[4] *N. Kreuzkamp*, Naturwissenschaften *55*, 474 (1963).

39

The Induced Decomposition of Acyl and Alkyl Peroxides

W. P. Neumann, *K. Rübsamen*, and *R. Sommer*, Gießen (Germany)

Free-radical decomposition of diacetyl and dibenzoyl peroxide is induced strongly by organic tin hydrides, *e.g.* triethyl- or tributyltin hydride [1]. The attacking species are stannyl radicals. The same is true for dilauryl peroxide and t-butyl perbenzoate, but not for di-t-butyl and cumyl t-butyl peroxide. The presence of at least one carbonyl group besides a peroxy bridge is thus required for induction to occur; the different dissociation energy of the O–O bond in the various compounds does not play a significant part.

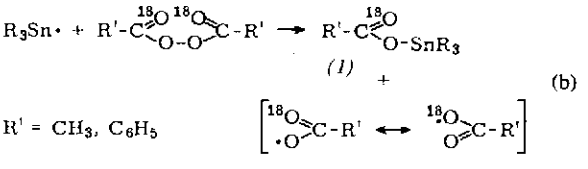
All free radicals formed are captured by excess organotin hydride (usually 3–4 moles per mole of peroxide). Thus t-butanol is formed quantitatively from di-t-butyl peroxide.

$$(CH_3)_3C{-}O{-}O{-}C(CH_3)_3 + 2\ R_3SnH \rightarrow 2(CH_3)_3C{-}OH + R_3Sn{-}SnR_3 \qquad (a)$$

The further decomposition of the t-butoxy radicals into acetone and methyl radicals, which other radical scavengers do not suppress completely, does not take place here.

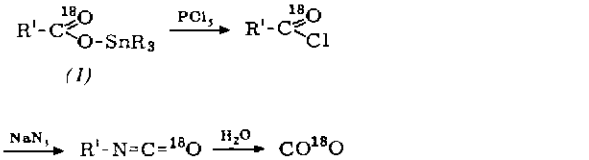
From cumyloxy radicals also, no acetophenone is formed. Only lauryloxy radicals decompose partly to CO_2 and undecane.

It was shown by ^{18}O-labelling of the carbonyl groups that stannyl radicals induce the decomposition of dibenzoyl and diacetyl peroxide by a synchronous mechanism. In the course of the reaction they become attached to one of the peroxy oxygen atoms [Eq. (b)].



(b)

By degradation of the stannyl ester *(1)* to the acid chloride transformation to the isocyanate, and hydrolysis to CO_2 it



was shown that 75 % of the ^{18}O remained in the carbonyl group. This means that only half of the peroxide molecule occurs as a free acyloxy radical.

Further evidence for (b) is given by the $^{18}O{=}C$ band at 1622 cm^{-1} ($R{=}C_2H_5$, $R'{=}CH_3$ in CCl_4).

[1] *W. P. Neumann*, *R. Sommer*, and *H. Lind*, Angew. Chem. *76*, 597 (1964).

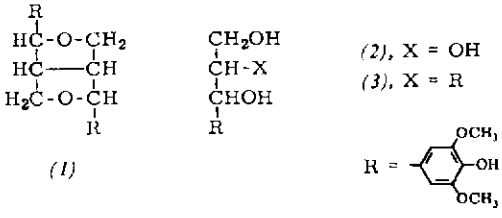
40

The Structure of Beech Lignin

H. Nimz, Heidelberg (Germany)

When pre-extracted beechwood powder is percolated with water at 100 °C for several weeks, 40 % of the wood and of the lignin go into solution; mild hydrolysis with almost complete suppression of condensation reactions, which always occur in the presence of mineral acids, takes place. After fractionation of the concentrated extract by countercurrent distribution, at least 20 low-molecular weight phenols can be detected by chromatography, including D,L-syringaresinol *(1)*, dimethylpyrogallylglycerol *(2)*, and 1,2-bis-(3,5-dimethoxy-4-hydroxyphenyl)propane-1,3-diol *(3)*.

The degradation product *(2)*, which is present in the largest amount, indicates the presence of β-aryl ethers of arylglycerol, which are the most important compound types in spruce lignin as well. The compound *(3)* is of a type not previously encountered in lignin. On being heated with sodium hydroxide solution, it gives rise to hydroxystilbene. Another hydroxystilbene is obtained from spruce under similar conditions [1]. Therefore the presence of 1,2-diarylpropane units can be assumed for spruce lignin, too.



(1) *(2)*, X = OH; *(3)*, X = R

[1] *H. Richtzenhain* and *C. v. Hofe*, Ber. dtsch. chem. Ges. *72*, 1890 (1939).

41

Cleavage of the Si-N Bond of Silazanes by Phosphorus Halides

H. Nöth, *L. Meinel*, and *H. Madersteig*, München (Germany)

Silazanes usually react with acid halides EX according to Equation (a). Chlorodiphenylphosphine Ph_2PCl and hexamethyldisilazane in boiling toluene or trimethylchlorosilane give rise to bis(diphenylphosphino)amine, m.p. 146 °C [Eq. (b)]; in *e.g.* petroleum ether at room temperature the adduct $(Ph_2P)_2NH{\cdot}PH_2PCl$ is formed preferentially, [Eq. (c)]. In acetonitrile, NH_4Cl is precipitated [Eq. (d)]. The $(Ph_2P)_4NCl$ simultaneously formed is obtained in high purity according to Eq. (e) in petroleum ether.

$$EX + R_3Si{-}NR'_2 \rightarrow E{-}NR'_2 + R_3SiX \qquad (a)$$

$$2\ Ph_2PCl + (Me_3Si)_2NH \rightarrow (Ph_2P)_2NH + 2\ Me_3SiCl \qquad (b)$$

$$3\ Ph_2PCl + (Me_3Si)_2NH \rightarrow (Ph_2P)_2NH{\cdot}Ph_2PCl + 2\ Me_3SiCl \qquad (c)$$

$$12\ Ph_2PCl + 4\ (Me_3Si)_2NH \rightarrow NH_4Cl + 3\ (Ph_2P)_4NCl + 8\ Me_3SiCl \qquad (d)$$

$$3\ Ph_2PCl + Ph_2PN(SiMe_3)_2 \rightarrow (Ph_2P)_4NCl + 2\ Me_3SiCl \qquad (e)$$

The formation of $[Ph_3P{-}N(PPh_2)_2]Cl$ from Ph_2PCl and $Ph_3P{=}NSiMe_3$ is closely related to Reactions (d) and (e).

A simple synthesis of triphenylphosphine-*N*-trimethylsilylimine was devised according to Eqs. (f) and (g). Reactions (f) and (g) were carried out in acetonitrile, Reaction (h) in toluene or ether.

$$Ph_3PBr_2 + (Me_3Si)_2NH \rightarrow [Ph_3P{-}NHSiMe_3]Br + Me_3SiBr \quad (f)$$

$$[Ph_3P{-}NHSiMe_3]Br + (C_2H_5)_3N \rightarrow Ph_3P{=}NSiMe_3 + (C_2H_5)_3N{\cdot}HBr \quad (g)$$

$$2\ Ph_2PCl + Ph_3P{=}NSiMe_3 \rightarrow [Ph_3P{=}N(PPh_2)_2]Cl + Me_3SiCl \quad (h)$$

NMR-Spectroscopic investigations on $(Ph_2P)_4NCl$ and $[Ph_3P{-}N(PPh_2)_2]Cl$ can be reconciled with the structures

$[Ph_2P{-}PPh_2{=}N{=}PPh_2]Cl$ and $[Ph_3P{=}N{=}PPh_2{-}PPh_2]Cl$

respectively.

42

Dichloroborazide

P. I. Paetzold, München (Germany)

Dichloroborazide *(1)* is a model substance which allows the explosive decomposition of borazides to be compared with the kinetically controlled thermal decomposition.

Borazides tend the more to explosion-like decomposition the stronger the Lewis acid BX_3, *i.e.* the tendency to explode increases in the sequence $NR_2 < Ar < CH_3 < Cl < Br < N_3$ for X. The tendency of the X_2BN_3 molecules to associate *via* the azide α-nitrogen with formation of B–N–B bridges runs parallel to this sequence. The trimeric (at room temperature), crystalline compound *(1)* was shown to have D_{3h} symmetry by vibrational analysis [1], *i.e.* the structure of *(1)* is a regular six-membered B–N ring. At low temperatures, $(CH_3)BN_3$ also is associated.

The controlled thermal decomposition of X_2BN_3 is determined by anchimeric assistance given by the residue X which migrates from the B atom to the α-N atom. Kinetic measurements showed increasing decomposition rates for $X = NR_2 < Cl < Ar$. The controlled decomposition of *(1)*, which leads to hexachloroborazole as main product [2], is therefore – in contrast to the explosive decomposition – less favored than that of Ar_2BN_3. The strengths of the B–X bonds broken and of the N–X bonds formed in the transition state are a basis for satisfactory explanation of this result.

[1] *P. I. Paetzold, M. Gayoso*, and *K. Dehnicke*, Chem. Ber. *98*, 473 (1965).

[2] *P. I. Paetzold*, Z. anorg. allg. Chem. *326*, 47 (1963).

43

Cis-Trans-Isomeric Mixed-Ligand Complexes of Iridium and Osmium

W. Preetz, Saarbrücken (Germany)

On treatment of the hexachloro complexes of the platinum elements with a mixture of HCl and HBr, mixed-ligand complexes $[MCl_xBr_{6-x}]^{2-}$ (M = Ir(IV), Os(IV); x = 0,1,2,..6) [1–3] are formed. The seven complexes possible are present in an equilibrium mixture. They have different mobilities in an electric field. High-voltage electrophoresis gives approximately equidistant, cleanly separated zones of different colors.

Cis-trans-isomers are possible for $[MCl_2Br_4]^{2-}$, $[MCl_3Br_3]^{2-}$, and $[MCl_4Br_2]^{2-}$, but cannot be separated electrophoretically. Their preparation is effected by utilizing the different *trans*-effects [4] of the ligands Cl^- and Br^-. From the hexachloro complexes and HBr, the *trans*-isomers are obtained; from the hexabromo complexes and HCl, the *cis*-forms are obtained by directed (stereospecific) ligand exchange. They are separated from the equilibrium mixture by high-voltage electrophoresis, eluted from the paper strips, and precipitated as the Rb or Cs salts.

The isomers have different colors; the absorption spectra contain many bands and exhibit systematic shifts. The spectra of the Ir complexes agree with those of the Os complexes except for a shift of about 6000 cm^{-1} to longer wavelengths. The previously obtained [3], not characteristic spectra of the mixed-ligand complexes $[MCl_xBr_{6-x}]^{2-}$ (x = 2,3,4) are superpositions of the spectra of the *cis*- and *trans*-isomers.

[1] *W. Preetz* and *E. Blasius*, Z. anorg. allg. Chem. *332*, 140 (1964).

[2] *E. Blasius* and *W. Preetz*, Z. anorg. allg. Chem. *335*, 1 (1965).

[3] *E. Blasius* and *W. Preetz*, Z. anorg. allg. Chem. *335*, 16 (1965).

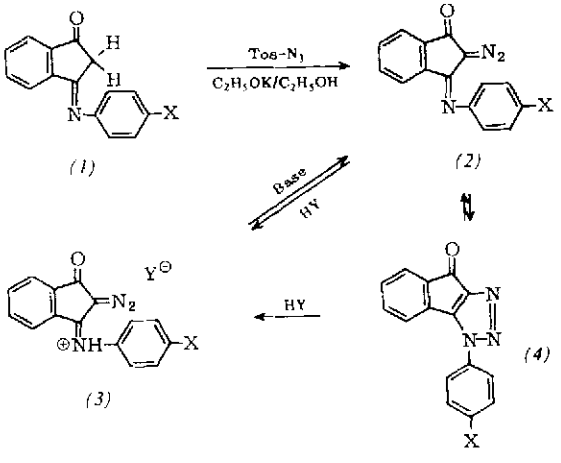
[4] *F. Basolo* and *R. G. Pearson*, Prog. Chemistry *4*, 381 (1962).

44

Synthesis of 1,2,3-Triazoles and Isomeric α-Diazoimines by Diazo-Group Transfer with Tosyl Azide

M. Regitz, Saarbrücken (Germany)

If a diazo group is introduced into compounds of general formula $-CO-CH_2-\overset{|}{C}=N-$ with tosyl azide, cyclization occurs to 1,2,3-triazoles [1]. On the other hand, stable α-diazoimines *(2)* are formed on diazo-group transfer from the carbanions of *(1)*, X = H or Cl.



Substituents X with (–E)-effect (*e.g.* CH_3, I, OCH_3) here also effect the triazole ring closure to *(4)*. On brief fusion and cooling, *(4)* gives back the isomeric α-diazoanils *(2)*. With strong mineral acids HY (Y = Cl, Br, ClO_4), *(4)* or *(2)* give rise to the stable α-diazoimonium salts *(3)*. The α-diazoimines *(2)* recyclize to 1,2,3-triazoles *(4)* on being recrystallized from high-boiling solvents, if $X = CH_3$, I, or OCH_3.

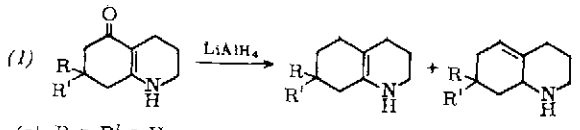
[1] *M. Regitz*, Angew. Chem. *77*, 428 (1965); Angew. Chem. internat. Edit. *4*, 431 (1965).

45

Reduction of Vinylogous Amides with Lithium Aluminum Hydride

H. Reinshagen, Darmstadt (Germany)

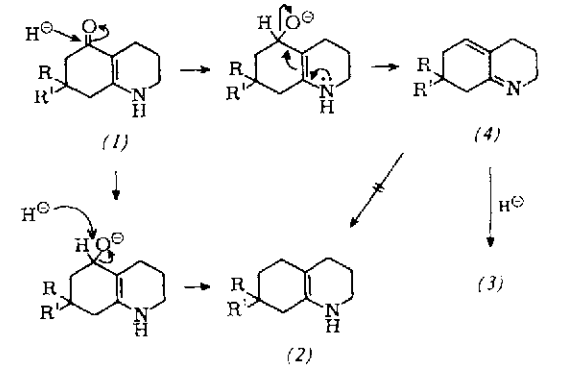
Octahydroquinoline ketones *(1)* are reduced by $LiAlH_4$ in boiling THF. Thus *(1a)* gives the enamine (2), and *(1b)* and *(1c)* give the allylamines *(3)*.



(a), R = R' = H
(b), R = H, R' = CH_3
(c), R = R' = CH_3

The reduction is independent of the solvent, but not of the temperature. The compounds *(1b)* and *(1c)* are redueed in boiling dioxane to mixtures of *(2)* and *(3)*. The ratio enamine:allylamine is similar in both cases.

In the reduction of vinylogous amides with $LiAlH_4$, one equivalent of hydride attacks at the carbonyl group. In the reaction leading to allylamines, there follow oxygen elimination and reduction of the C = N double bond of the intermediate hexahydroquinoline *(4)*. Since *(2a)* is not formed by reduction of *(4a)*, the enamines must be formed by another route. Evidently oxygen is displaced here in a nucleophilic substitution by a second equivalent of hydride. The fact that the reduction to the enamine is favored at higher temperatures shows that a high energy barrier must be surmounted in this reaction.

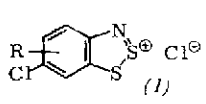


46

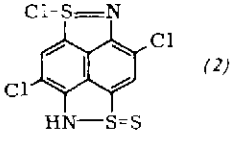
The Herz Reaction with 1,5-Diaminonaphthalene

W. Ried and *J. Valentin*, Frankfurt/Main (Germany)

The action of excess S_2Cl_2 on primary aromatic amines leads to "thiazthionium chlorides" of the general formula *(1)*.



By the action of S_2Cl_2 on 1,5-diaminonaphthalene, *M. Schubert* obtained a beautifully violet compound of the composition $C_{10}H_3N_2Cl_3S_3$, which has properties different from those of thiazthionium chlorides. The structure *(2)* is proposed for this substance.



The structure is based on the following evidence:

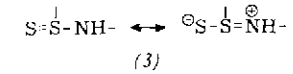
1. Compound *(2)* is also formed from 2,6-dichloro-1,5-diaminonaphthalene.

2. One of the three sulfur atoms can be split off by thermolysis, or by silver nitrate or zinc dust in glacial acetic acid, giving pale yellow products.

3. Reductive degradation gives, depending on the conditions, derivatives of 1,5-diaminonaphthalene or of dimercapto-1,5-diaminonaphthalene, proving the presence of two N–S and two C - S bonds.

4. Introduction of one or two atoms of oxygen imparts the character of sulfochlorides on *(2)*. Together with the infrared spectral data, this result indicates the presence of the group –N=S–Cl.

More vigorous oxidation leads to substitution of one sulfur atom by an oxygen atom. Together with the infrared spectra and the behavior mentioned under 2. above, this suggests a thiosulfinic amide grouping *(3)*.



47

A New Indole Synthesis

P. Rosenmund, *W. Haase*, and *D. Sauer*, Frankfurt/Main (Germany)

From *o*-nitrophenylacetyl chloride and 1-(*N*-morpholino)-cyclohexene *(1)*, -cyclopentene *(2)*, and -1-phenylethene *(3)*, 1,3-diketones are obtained in good yields according to the method of *Hünig* [1]. 2-(*o*-Nitrophenyl)cyclohexanone is formed from *(1)*. With the exception of the diketones from *(2)*, the products crystallize readily. All products give the $FeCl_3$ reaction of enolizable compounds and show in their infrared spectra a characteristic band, strongly shifted to longer wavelengths, of a chelated carbonyl group. On reduction with $SnCl_2$ in ether, mainly indoles are obtained, identified by analysis, by the cinnamaldehyde reaction, and by their ultraviolet spectra. By condensation of the aromatic amino group, which results from reduction of the nitro group, with the δ-carbonyl group, the isomeric benzazepines are formed as by-products. They can be quantitatively and preparatively separated on silica gel columns with chloroform/ethyl acetate. The azepines contain a vinylogous amide structure which is conjugated to the aromatic ring and which explains their ultraviolet spectra (λ_{max} = 335 mμ).

Reduction of 2-(2-oxocyclohexyl)indole with $NaBH_4$ or Raney nickel gives alcohols with different *cis-trans* ratios. By hydrogenation in the presence of ammonia or methylamine, the corresponding primary and secondary amines, respectively, are obtained. Benzaldehyde reacts smoothly with 2-(2-aminocyclohexyl)indole to give 3,4-tetramethylene-1-phenyl-1,2,3,4-tetrahydro-5*H*-pyrido[4,3-*b*]indole. From 2-(2-methylaminocyclohexyl)indole and ethyl bromoacetate, 2-(*N*-ethoxycarbonylmethyl-*N*-methyl-2-aminocyclohexyl)indole is obtained, which can be hydrolysed to the acid. Cyclization at 110 °C with polyphosphoric acid gives rise to a basic compound, the ultraviolet spectrum of which (λ_{max} = 298 mμ) corresponds to that of indole-3-carboxaldehyde and to that of 3-acetylindole. Possibly a new seven-membered ring is formed by elimination of water and condensation with the 3-position of indole, in which case a part of the structure of the iboga alkaloids would have been built up by total synthesis.

[1] *S. Hünig*, *E. Benzing*, and *E. Lücke*, Chem. Ber. *90*, 2833 (1957).

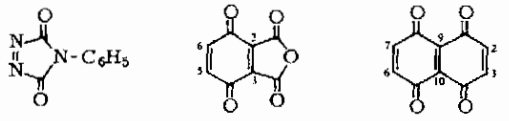
48

Reactivity of Dienophiles and Ability to Form Charge-Transfer Complexes

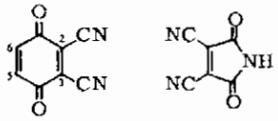
J. Sauer and *B. Schröder*, München (Germany)

The dienophiles *(1)*–*(5)* were studied in preparative and kinetic experiments. The rate constant k for the addition of *(1)* onto *trans,trans*-1,4-diphenylbutadiene, 2-chlorobutadiene, and hexachlorobutadiene exceeds that of tetracyanoethylene by a factor of 10^2–10^4 (at 20 °C in dioxane). Solu-

tions (10^{-3} M) of the Diels-Alder adducts of *(1)* with 9,10-dialkoxyanthracenes partially decompose at 20 °C into the

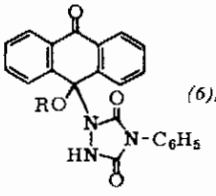


(1) *(2)* *(3)*



(4) *(5)*

original components. In the presence of traces of acid they are converted in good yield into anthrone derivatives *(6)*. Compounds *(2)* and *(4)* take up isoprene, 2,3-dimethylbutadiene, and cyclopentadiene at the more strongly activated 2,3-double bond; *(3)* adds the dienes at the central 9,10-double bond. With butadiene, *(2)* also reacts at the 2,3-bond, but *(3)* gives a 1:1 adduct (addition of the diene at the 9,10 position) besides a 2:1 adduct (addition of the diene at the 2,3- and 6,7-bonds).



(6), R = CH_3, C_2H_5

The rates of Diels-Alder reaction of *(2)* and *(5)* with 2,3-dimethylbutadiene, anthracene, and 2-methylbutadiene exceed, in part considerably, those of tetracyanoethylene, which in turn are higher than those of *(4)*.

No clear relationship is obvious between the reactivity of the dienophiles *(2)*, *(4)*, *(5)*, and tetracyanoethylene and the formation of charge-transfer complexes of these compounds with hexamethylbenzene, durene, pyrene, naphthalene, and anisole.

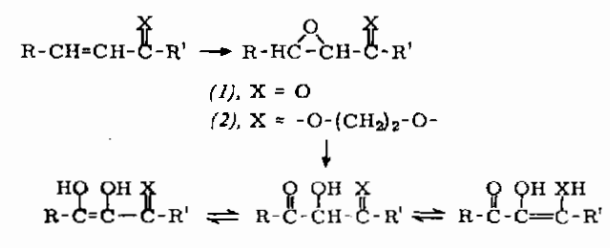
49

A New, General Synthesis of Reductones and Their "Ketals"

K. Schank and *D. Wessling*, Saarbrücken (Germany)

Aci-reductones [1] were previously prepared by *reduction* from 1,2,3-triketones or by *exchange* of halogen, acyloxy, or diazo groups in α-monosubstituted β-dicarbonyl compounds or β-monosubstituted α-dicarbonyl compounds for hydroxy groups.

We have now discovered an *oxidative* reductone synthesis. Acyloxiranes *(1)* or their ketals *(2)*, which are readily accessible from α,β-unsaturated carbonyl compounds and their ketals, respectively, by epoxidation, can be oxidized to the



(1), X = O
(2), X = -O-$(CH_2)_2$-O-

(3), X = O
(4), X = -O-$(CH_2)_2$-O-

R, R' = Alkyl, H

reductone stage *(3)* with dimethylsulfoxide/boron trifluoride [2]. The free reductones *(3)* and their "ketals" *(4)* were obtained in yields of 20 % and 15 %, respectively. The compounds *(4)* are stable in the pure state, and even in aqueous solution in the absence of acid.

[1] *H. von Euler* and *B. Eistert*: Chemie und Biochemie der Reduktone und Reduktonate. Enke, Stuttgart 1957.

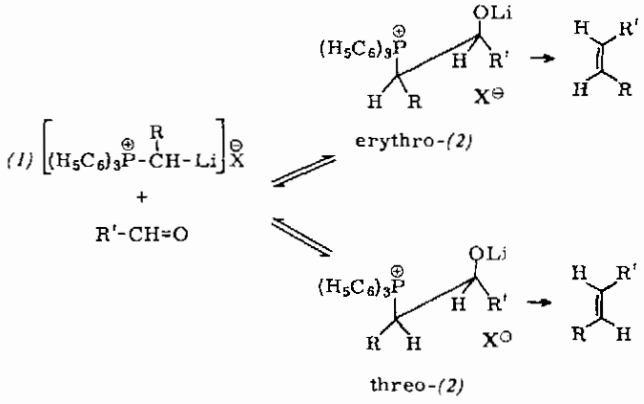
[2] *Th. Cohen* and *T. Tsuji*, J. org. Chemistry *26*, 1681 (1961).

50

Stereoselective Wittig Reactions

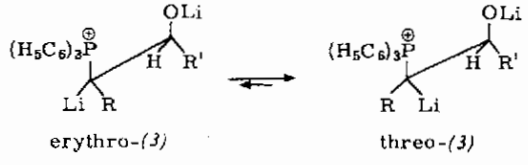
M. Schlosser and *K. F. Christmann*, Heidelberg (Germany)

Cis-selective Wittig reactions are brought about by kinetic control: the phosphorus ylide-LiX adduct *(1)* reacts with the aldehyde primarily to the *erythro*-betaine-LiX adduct *(2)*; this must be rapidly transformed to the *cis*-olefin before it can isomerize to *threo-(2)* [1]. With thermodynamic control, the olefinations are *trans*-selective: if the equilibrium between *erythro-(2)* and *threo-(2)* is rapidly established, but the olefins [2] form only slowly, the more stable *trans*-olefin is obtained preferentially.



(1) erythro-*(2)* threo-*(2)*

These principles can however be applied only occasionally with success. We have found that *trans*-olefins are obtained in high yields if the betaine-LiX adducts are again treated with phenyl-lithium. The resulting derivatives *(3)*, which are both P–O betaines and P–C ylides, are interconverted extremely rapidly, and the equilibrium lies considerably on the side of the *threo*-form.



erythro-*(3)* threo-*(3)*

By Li^+–H^+ exchange, *threo-(3)* gives the betaine *threo-(2)* and thence the *trans*-olefin. The *trans*:*cis* ratio in the product usually is higher than 95:5.

[1] *L. D. Bergelson* and *M. M. Shemyakin*, Angew. Chem. *76*, 113 (1964); Angew. Chem. internat. Edit. *3*, 250 (1964).

[2] *H. O. House* and *G. R. Rasmusson*, J. org. Chemistry *24*, 4278 (1961).

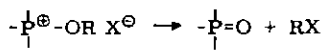
51

Alkylation of Phosphine Chalcogenides and Phosphinylamines

A. Schmidpeter, *Barbara Wolf*, and *Krista Düll*, München (Germany)

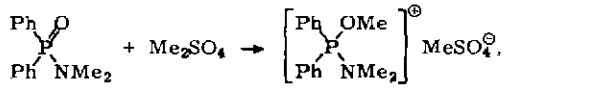
Compounds having an alkoxyphosphonium structure *(1)* occur as unstable intermediates in a number of reactions (*e.g.* Michaelis-Arbusow reaction, phosphine oxidation with di-

alkyl peroxides). They decompose with cationic transfer of the alkyl residue and formation of the phosphine oxide.



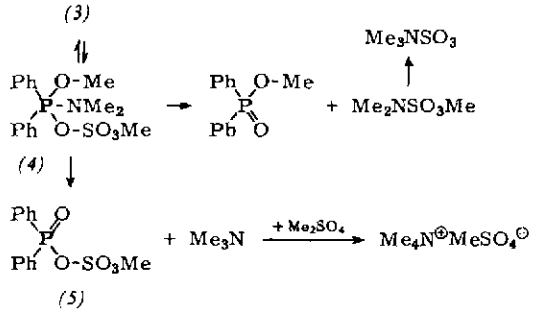
(1)

Stable members of the class of compounds *(1)* were obtained by the reverse reaction, *viz.* by alkylation of phosphine oxides. From triphenylphosphine oxide with dimethyl sulfate and $PF_6^{\ominus}$ or $SbCl_6^{\ominus}$, or directly from trialkyloxonium salts, triphenylalkoxyphosphonium salts are formed. Their stability depends on the alkyl residue as well as on the anion present. Triphenylphosphine sulfide reacts analogously and yields the very stable triphenylalkylthiophosphonium salts $Ph_3\overset{\oplus}{P}S\overset{\ominus}{R}X$. In the reaction of diphenylphosphinyldimethylamine *(2)* with dimethyl sulfate, diphenyl(dimethylamino)methoxyphosphonium methyl sulfate *(3)* is formed at first by methylation of the oxygen atom; it was identified by NMR spectroscopy.



(2) *(3)*

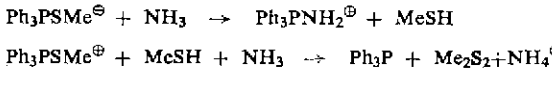
Trimethylamine sulfur trioxide, tetramethylammonium methyl sulfate, methyl diphenylphosphinate, and probably diphenylphosphinyl methyl sulfate *(5)* are subsequently formed from *(3)*. It is assumed that these products arise *via* a pentacovalent form *(4)* which is in equilibrium with *(3)*.



(5)

All products were isolated, with the exception of *(5)*, which was hydrolysed to diphenylphosphinic acid during work-up. Methylation of diphenylthiophosphinyldimethylamine stops after the formation of the diphenyl(dimethylamino)methylthiophosphonium ion.

Ammonolysis of triphenylmethylthiophosphonium salts takes place according to:



52

Mixed-Crystal Formation of Lithium Indium Oxide with Magnesium Oxide, and a Contribution to the "Gadolinium Corner"

H. Schwarz and *D. Bommert*, Karlsruhe (Germany)

Because of the ordered distribution of the Li and In ions, $LiInO_2$ crystallizes with the tetragonal superstructure of the NaCl lattice. All attempts to crystallize $LiInO_2$ in a cubic form with random distribution of the cations have been unsuccessful. Cubic mixed crystals are however formed with MgO. In samples quenched from 1000 °C, mixed crystals are formed in the range from 0 to about 95 mole-% of $Li_{0,5}In_{0,5}O$. In this range the lattice parameters lie on a Vegard straight line. This range borders on a two-phase region from 95 to about 99 mole-% in which the cubic and tetragonal phases coexist. A very narrow region of mixed-crystals with tetragonal structure follows. With decreasing temperature the coexistence curve between the mixed-crystal region and the two-phase region shifts towards the MgO-rich side of the system, and the two-phase region becomes broader (750 °C: 78 mole-%; 675 °C: 72 mole-%; 600 °C: 53 mole-% $Li_{0,5}In_{0,5}O$).

The so-called gadolinium corner, *i.e.* the discontinuity at Gd in the dependence of certain properties of the triply charged rare earth ions Ln^{3+} on the atomic number Z, is now well established. Crystallographic data of isostructural compounds frequently however do not show this discontinuity. For example, no discontinuities are observed for numerous compounds [Ln_2O_3 (C-type), $Ln_2Sn_2O_7$, $LnVO_4$, $LnCrO_4$, LnOCl, LnF_3, LnOF, Ln_2O_2S] in the unit-cell volume of the lattice. For some other compounds, however, [*e.g.* LnN, LnAs, LnSb, LnC_2], in which the Ln^{3+} ions occupy a particularly high proportion of the total lattice volume, a more or less pronounced effect is observed. That the occupation of a large fraction of the lattice volume by Ln ions does not alone determine the occurrence of the gadolinium corner is shown by the discontinuities observed at Gd in the graph of cell volume against Z, for the compounds $SrO \cdot Ln_2O_3$ and $BaO \cdot Ln_2O_3$ [1] (rhombic $CaO \cdot Fe_2O_3$ type). The effect appears to depend strongly also on the structural type.

[1] *H. Schwarz* and *D. Bommert*, Z. Naturforsch. *19b*, 955 (1964).

53

Stability and Coordination of Alkali Chlorometalates(II) of the Light Transition Elements

H. J. Seifert, Giessen (Germany)

The phase diagrams of some systems (alkali metal chloride)/(dichloride of a light transition metal) were determined by differential thermal analysis. The number and compositions of compounds formed, as well as their relative stabilities were investigated. The coordination numbers C.N. of the transition metal ions were determined by X-ray analysis. The occurence of the C.N. 6 was confirmed for all the ions except Zn^{2+} but the C.N. 4 was also found for some of the metals. Tetracoordination in the compounds of Mn^{2+} to Zn^{2+} is due the smaller radii compared to the first half of the group (Ca^{2+} to Cr^{2+}) and the polarizing action of the ions, which increases towards Zn^{2+}. In addition, the site-preference energy of the crystal field theory has the effect that *e.g.* in the system $CsCl/NiCl_2$, the only stable compound formed is $CsNiCl_3$ with 6-coordinate nickel. For the double chlorides $AMCl_3$, which crystallize with a perovskite-like lattice, the decrease in stability, with decreasing radius of the alkali metal ions A, is due to the increasing difference in radius between alkali metal ions and chloride ions. It is evident from the phase diagrams and was confirmed for the chloromanganates(II) by calometric measurements in solution.

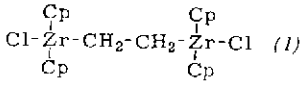
54

The Reaction of Triethylaluminum with Biscyclopentadienyltitanium(IV) and Zirconium(IV) Compounds

H. Sinn and *E. Kolk* [1], München (Germany)

Biscyclopentadienyltitanium(IV) chloride is reduced by excess triethylaluminum within several tenths of a second to Ti(III) compounds. A gas is liberated consisting of 50% ethane, 45% ethylene, and 5% C_4-hydrocarbons. If the gas is collected in fractions, excess ethane is found in the early fractions, and excess ethylene in the later ones. The corresponding zirconium compound also reacts with triethylaluminum; however only ethane is present in the reaction gas. The reaction is slow and results in a yellow, diamagnetic compound, which can be freed from aluminum by extraction with

tetrahydrofuran. The Al-free compound takes up one mole of HCl per mole of Zr and liberates half a mole of ethane. It is therefore thought that the structure *(1)* is present (Cp = cyclopentadienyl).



(1)

With the assumption of an analogous titanium compound, which decomposes to ethylene and Ti(III) compounds, the slower evolution of ethylene compared to ethane can be explained.

The ethane split off on reduction is formed from an ethyl group which obtains the sixth hydrogen atom from the methyl part of another ethyl group, not from the methylene part.

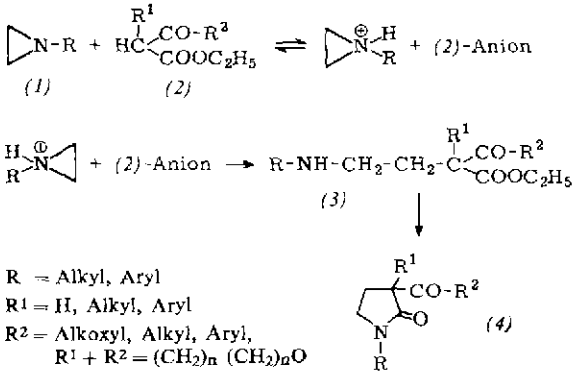
[1] Extract from the Doctorate Dissertation of *E. Kolk*, Technische Hochschule München, 1964.

55

β-Aminoethylation of Malonic Esters and of β-Keto Esters with Aziridines

H. Stamm, Marburg (Germany)

The ring opening with substitution of aziridines *(1)* by the anions of malonic esters or β-keto esters *(2)* takes place above 100 °C in the presence of a large excess of ester, which makes *(1)* reactive by protonation.



(1) *(2)* *(2)*-Anion *(3)*

R = Alkyl, Aryl
R^1 = H, Alkyl, Aryl
R^2 = Alkoxyl, Alkyl, Aryl,
$R^1 + R^2 = (CH_2)_n\ (CH_2)_nO$

(4)

The yields are poor because the preceding equilibrium is unfavorable and because the anion of *(2)* also undergoes other reactions with free ester. If, however, this anion is used in the form of the almost undissociated Li salt (the system being diluted with aromatic hydrocarbons), and at the same time the protonation equilibrium is shifted to the right by the addition of lithium salts as Lewis acids satisfactory yields of *(4)* (up to 70 %) are obtained at 80–145 °C. The excess of ester *(2)* can be recovered almost quantitatively. Open-chain amides are formed as by-products from *(3)* and *(2)*. In 2,2-dimethylaziridines, the anion of *(2)* attacks in the unsubstituted 3-position.

The primary product *(3)* can be isolated when R is bulky (*e.g.* t-butyl or tolyl).

56

Activation of Molecular Vibration Bands by Lattice Disorders

W. Sterzel, Frankfurt/Main (Germany)

Of the possible normal modes of vibration of a highly symmetrical molecule, the modes in which no change in dipole moment occurs are usually inactive in the infrared. The symmetry of such molecules (or complex ions) can be retained on crystallization, or previously inactive vibration bands can be activated by a lowering of the symmetry class by the crystal field. In crystals which do not lower the symmetry of the constituent molecules or ions, local lattice defects should effect activation of vibration bands.

Such an effect was observed in experiments on calcite, cadmium carbonate, and sodium nitrate. The infrared-inactive, symmetrical valence vibration ν_1 of the CO_3^{2-} anion in calcite and cadmium carbonate was activated by intense plastic deformation. The new band caused by lattice disorders occurs at 1085 cm^{-1} for calcite and 1076 cm^{-1} for cadmium carbonate. Formation of defects was confirmed by X-ray diffraction data. The lattice deformations also give rise to a broadening of the normal vibration bands to different extents, the effect being particularly pronounced for the symmetrical valence vibration band of aragonite, which also gains in total intensity; *i.e.* this vibration is activated by lattice defects in addition to the normal activation by the crystal field. Otherwise the intensity of the ν_1 band of aragonite would decrease on deformation, since partial transformation to calcite occurs.

Lattice defects were also produced by doping of crystals and by mixed-crystal formation. $BaSO_4$–$PbSO_4$ mixed crystals show a weak band at 450 cm^{-1} which is present in neither of the pure components. This band probably corresponds to the symmetrical deformation vibration ν_2 of the SO_4^{2-} anion, which is infrared-inactive in crystals of pure $PbSO_4$ and $BaSO_4$.

57

Synthesis and Properties of 4-Pyridyl Phosphate

A. Stock, Frankfurt/Main (Germany)

Nicotinamide adenine dinucleotide (NAD) phosphorylated in the pyridine ring possibly plays a part as an energy-rich intermediate in the respiratory chain phosphorylation. Therefore 4-pyridyl phosphate was synthesized as a model substance from 4-pyridone and phosphorus oxide chloride in chloroform with subsequent hydrolysis with a solution of potassium hydrogen carbonate. On electrophoresis at pH 7 the compound migrates to the anode. It is completely hydrolysed within 10 min in 1 N acid at 90 °C to pyridone and phosphoric acid. The pH-dependence of the ultraviolet spectrum is similar to that of 4-chloropyridine and of 4-methoxypyridine, but different from that of *N*-methyl-4-pyridone. These results show that the phosphorylation has taken place at the O atom, and not the N atom. The values obtained are:

pH > 7: $\lambda_{max} = 253$ mμ, $\varepsilon_{max} = 1000$
pH 5.5–7: $\lambda_{max} = 241$ mμ, $\varepsilon_{max} = 9400$
pH 1: $\lambda_{max} = 230$ mμ, $\varepsilon_{max} = 8000$

The first H^+ion therefore adds onto the N atom (around pH 7).

The crude product (25 % 4-pyridone, 75 % phosphorylated compound) is cleaved to an extent of 50 % in 3 h at 25 °C and pH 0, in 17 h at pH 3.5, in 14 days at pH 7, in 24 h at pH 14; no decomposition is detected at pH 10.5.

On chromatography of 4 mmoles of the crude product on 600 g of Dowex 1X8 (carbonate-bicarbonate form), 1.2 mmole of 4-pyridone was eluted with water, and by a $KHCO_3$/K_2CO_3 solution (pH 10) of concentration increasing up to 1 M $KHCO_3$, various phosphorylation products of 4-pyridone are obtained:

70 μmoles of 4-oxo-1-pyridyl phosphate ($\lambda_{max} = 262$ mμ, $\varepsilon_{max} = 16000$)

150 μmoles of di-(4-pyridyl) phosphate ($\lambda_{max} = 253$ mμ, $\varepsilon_{max} = 2000$)

240 μmoles of 4-pyridyl phosphate

40 μmoles of an *O*-phosphorylated compound (presumably 4-pyridyl pyrophosphate), the hydrolysis of which yields 4-pyridone and phosphoric acid in the ratio 1:2.

7 µmoles of a compound containing 2 pyridine groups, of which one is phosphorylated at the N atom and the other at the O atom.

Altogether 45% of the substance was recovered by elution.

Analogously the potassium salt of 2-pyridyl phosphate was obtained from 2-pyridone and phosphorus oxide chloride/pyridine in benzene with subsequent hydrolysis by $KHCO_3$ solution. This salt decomposes at 25 °C and pH 7 to 2-pyridone and phosphoric acid to the extent of 50% in 15 min.

58

Nucleophilicity and Basicity of Amines

H. Suhr, Tübingen (Germany)

The nucleophilic character of an amine in reactions with various types of aromatic and aliphatic coreactants is almost constant. It is therefore possible to express the nucleophilicity n_a of an amine by the logarithms of the rate constants of nucleophilic reactions with aromatic substances. The reaction with 4-fluoronitrobenzene at 50 °C in dimethyl sulfoxide was chosen as standard. The validity of these n_a values within wide limits raises the question of their relation to basicity. Both parameters are determined by polar and steric effects. Strongly basic amines often are weakly nucleophilic because steric effects are of secondary importance for basicity, but of considerable importance for nucleophilicity. In sterically equivalent compounds, such as the substituted anilines, the basicities and the rate constants of nucleophilic substitution follow the Hammett equation with roughly equal values of ρ. The relation between nucleophilicity and basicity of aliphatic amines also can be described with the aid of polar and steric constants. The basicities can be represented by the equation [1]

$$pK_a = -3.1\ \Sigma\sigma^* + 13$$

The nucleophilicities of all groups of sterically equivalent amines show a similar dependence on the polar constant σ*, whereas the differences between these groups are a function of the steric constant E_s. The n_a values of primary and secondary amines can therefore be represented by the equation

$$n_a = -2.0\ \Sigma\sigma^* + 2.1\ E_s + 5.4$$

In sterically little hindered aliphatic amines, basicity and nucleophilicity are simply related by $n_a - ApK_a + b$, where the constants depend on the halogen compound and the solvent used.

[1] *H. K. Hall*, J. Amer. chem. Soc. *79*, 5441 (1957).

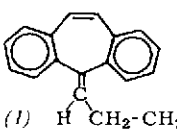
59

Intramolecular Mobility of Di- and Tribenzocycloheptatriene Derivatives

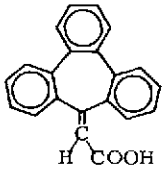
W. Tochtermann, H. Küppers, and *A. Mannschreck*, Heidelberg (Germany)

As shown by the ^{1}H-NMR spectra, the energy barrier for the inversion of the seven-membered ring of tribenzocycloheptatrienone dimethylacetal ($\Delta G^{\neq}$ above 180 °C > 23 kcal/mole) is considerably higher than in the analogous 2,3;6,7-dibenzo compounds ($\Delta G^{\neq}$ at 30 °C = 14.9± 0.2 kcal/mole) [1].

Since the amine *(1)* [2] and the carboxylic acid *(2)* [3] can be resolved into optical antipodes, the influence of the third benzene ring on the ring inversion can also be estimated from a comparison of the rates of racemization of *(1)* and *(2)*.



(1) H CH_2-CH_2-$N(CH_3)_2$



H COOH *(2)*

From the result that *(1)* racemizes even at 20 °C (E_A = 22 kcal/mole) [2], but *(2)* only at 139 °C with comparable rate ($\Delta G^{\neq}$ at 139 °C = 32 kcal/mole), an energy difference similar to that found for the acetals by NMR spectroscopy is obtained.

[1] *W. Tochtermann, U. Walter*, and *A. Mannschreck*, Tetrahedron Letters *1964*, 2981.

[2] *A. Ebnöther, E. Jucker*, and *A. Stoll*, Chimia *18*, 404 (1964); *E. Jucker* and *A. Ebnöther*, personal communication.

[3] *W. Tochtermann* and *H. Küppers*, Angew. Chem. *77*, 173 (1965); Angew. Chem. internat. Edit. *4*, 156 (1965).

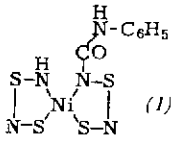
60

Preparation and Structure of a Monophenyl Isocyanate of $Ni(HN_2S_2)_2$

J. Weiss and *U. Thewalt*, Heidelberg (Germany)

When $Ni(HN_2S_2)_2$ is heated at about 65 °C for about 3 h with a 3-fold excess of phenyl isocyanate in THF, a dark olive-green solution is obtained. The residue obtained on evaporation is washed with small amounts of acetone and benzene, and recrystallized from acetone to give black crystals of the compound $Ni(C_7H_7ON_5S_4)$., m.p. 170 °C (decomp.), yield ca. 40%, which dissolve in organic solvents to give olive-green solutions.

The structure was determined by X-ray analysis. The compound crystallizes in the monoclinic system with the space group C^5_{2h}–$P2_1/a$, with four molecules in the unit cell; a = 14.08 Å, b = 5.11 Å, c = 17.77 Å, β = 98.3 °. The positions of the nickel and the four sulfur atoms were determined from the 3d Patterson synthesis. Fourier projections ρ(xz) and 3d Fourier syntheses gave the positions of all atoms. The R-value (B = 3.5) after the last Fourier synthesis was 0.151 for all of the 921 observed F(hkl). Subsequent "back-shift" correction improved the R-value to 0.146. The structure obtained is shown as *(1)*.



(1)

61

The Chemistry of Bis(trimethylsilyl)halogenoamines

N. Wiberg, F. Raschig, and *K. H. Schmidt*, München (Germany)

Reaction of bis(trimethylsilyl)amine with *N*-bromosuccinimide or of lithium bis(trimethylsilyl)amide with chlorine or iodine chloride gives brown $(Me_3Si)_2NBr$, b.p. 176 °C, yield 65%; light yellow $(Me_3Si)_2NCl$, b.p. 145 °C, yield 60%; deep brown $(Me_3Si)_2NI$, b.p. 196 °C, yield 55%.

Bis(trimethylsilyl)halogenoamines react with cleavage of either the *N*-halogen bond or the N-Si bond. Thus bis(trimethylsilyl)sodamide reacts with bis(trimethylsilyl)chloroamine or bromoamine to give the radical *(1)*. This abstracts

$$(Me_3Si)_2N\text{–}Hal + NaN(SiMe_3)_2 \rightarrow NaCl + 2\,(Me_3Si)_2N\cdot \quad (1)$$

hydrogen atoms from diethyl ether or toluene with formation of bis(trimethylsilyl)amine. In benzene solution *(1)* undergoes the following reaction:

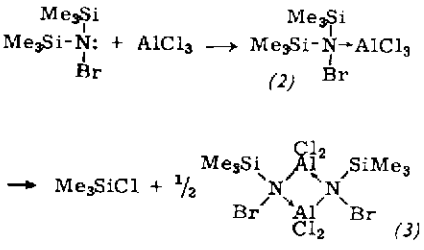
$$4\ (1) \rightarrow$$

$$(Me_3Si)_2NH + (Me_3Si)_2N\text{–}Si(Me_2)\text{–}N(SiMe_3)\text{–}CH_2\text{–}N(SiMe_3)_2$$

Dimerization of *(1)* to the hypothetical tetrakis(trimethylsilyl)hydrazine $(Me_3Si)_2N$–$N(SiMe_3)_2$ was not observed.

The cleavage of the N–Si bond of bis(trimethylsilyl)chloroamine and bromoamine occurs with Lewis acids. From the chloroamine and boron trichloride, hexachloroborazole is formed in over 60% yield. Aluminum trichloride reacts with the bromoamine to give a dark yellow compound *(3)* which decomposes at about 80 °C. The Lewis acid probably first

adds on to the lone electron pair at the nitrogen atom in *(2)*; trimethylchlorosilane is then split off. The intermediate *(2)*



was isolated in the reaction of bis(trimethylsilyl)amine with aluminum or gallium trichloride in the form of $(Me_3Si)_2NH{\rightarrow}MCl_3$ (M = Al, Ga.).

62

NMR-Spectroscopic Determination of the Configurations of Carbohydrates and Cyclanols Using Their Trimethylsilyl Ethers

J. Yoshimura and *F. W. Lichtenthaler*, Darmstadt (Germany)

The trimethylsilyl ethers (trisylates) of cyclanols and sugars were prepared by the reaction of the hydroxy compounds with trimethylchlorosilane in pyridine at 130 °C. Better results were obtained from the reaction with hexamethyldisilazane in dioxane in the presence of boron trifluoride. Under these conditions (3h at 100 °C), di-*N*-acetyl-*neo*-inosa-1,4-diamine gives the tetratrisylate in 72% yield; 1,4-dideoxy-1,4-dinitro-*neo*-inosite *(1)* in 100% yield already at 25 °C. Analogously, cyclohexane-1,3-diol, 2-nitrocyclohexane-1,3-diol, α-methyl-D-xyloside, and α-benzyl-*N*-acetyl-D-glucosamide give the completely trisylated compounds in yields of 50 to 85%. In the reaction of *(1)* with hexamethyldisilazane in dioxane (100 °C without catalyst), selective trisylation occurs with the formation of 2,3,6-tris(trimethylsilyl)-1,4-dideoxy-1,4-dinitro-*neo*-inosite in 20% yield. The NMR spectra obtained in $CDCl_3$ showed sharp signals around 9.7–10 τ due to the methyl protons of the trisyloxy group. The exact value depends on the orientation of this group. In the cyclanol series the signals occur at 9.73–9.86 τ for axial and at 9.83 to 9.96 τ for equatorial trisyloxy groups, in the sugar trisylates at 9.80–9.88 τ for equatorial orientation.

The use of trisylates for the NMR-spectroscopic determination of conformation has the following advantages over the use of acetyl compounds: The $(CH_3)_3SiO$ signals are in a region where no other protons absorb; they are three times as strong as the CH_3CO signals; and they allow an unambiguous assignment of configuration particularly for aminocyclanols and amino sugars by NMR analysis of the *N*-acetyl-*O*-trisyl compounds.

[VB 925/240 IE]

German version: Angew. Chem. 77, 721 (1965)

Modern Analytical Methods in the Chemistry of Foodstuffs and in Biological Chemistry

The "Analytical Chemistry" and "Foodstuffs Chemistry and Forensic Chemistry" Groups of the Gesellschaft Deutscher Chemiker, as well as the Gesellschaft für Physiologische Chemie and the Deutsche Gesellschaft für Klinische Chemie organised a symposium in Heidelberg from 17th to 19th March 1965.

From the lectures:

Quantitative Determination of β-Aminoisobutyric Acid by Thin-Layer Chromatography

H. W. Goedde, H. Brunschede, and *R. Hoffbauer*, Freiburg/Br. (Germany)

β-Aminoisobutyric acid can be extracted by ether after quantitative reaction with 1-fluoro-2,4-dinitrobenzene. Routine chromatography involves a single rising development on silica gel G in chloroform/pyridine/glacial acetic acid [1] (50:50:1; v/v), elution of the (dinitrophenyl-β-amino)isobutyric acid (DNP-β-AIB) with 10% (v/v) acetic acid, and measurement of the optical density at 366 mμ. The calibration curve is linear over the region 10–700 mμmoles; the standard deviation of a measurement is less than ± 5%. Rechromatography affords 80% of the DNP-β-AIB extracted with ether. Repeated chromatography after removal of protein (best by ultrafiltration) is required for more sensitive detection of this amino acid in plasma and organ homogenates. After development in pyridine/chloroform/n-heptane/acetic acid (50:25:25:1; v/v) and drying for 3 hours in a desiccator, further separation is effected by the rising method with chloroform/glacial acetic acid (100:1;v/v) in a chamber with a very small volume (BN-Kammer, Messrs. Desaga). To improve the separation and shorten the running time in this process, the silica gel is scraped off from the starting point to about 1 cm below the β-AIB band [2]. If separation is still incomplete, a further run can be made, after short drying, with the same liquid phase. 4–300 mμmoles of β-aminoisobutyric acid (purity > 98·5%) can be detected with a yield of 80–90%. Absorption spectra show that the pH value has no effect on the position or height of the maximum at 360 mμ ($\varepsilon_{366} = 15{\cdot}0\times10^3$ cm² mole^{-1}). Dinitrophenyl derivatives of β-amino acids appear to be insensitive to light, in distinction from the derivatives of α-amino acids.

[1] The chloroform contains 1% absolute alcohol.

[2] *H. Brunschede, R. Hoffbauer*, and *H. W. Goedde*, Z. analyt. Chem., in press.

Detection and Determination of Amines on the 10^{-10} Molar Scale. Separation of 5-Dimethylamino-1-naphthalenesulfonamides on Thin-Layer Chromatograms

N. Seiler, Frankfurt/Main (Germany)

Quantitative reaction of primary and secondary amines and phenols with 5-dimethylamino-1-naphthalenesulfonyl chloride (DANS-Cl) permits detection and determination of these compounds in the 10^{-10} molar region by means of the intense fluorescence of the amide and phenol esters of the corresponding acid. Two-dimensional thin-layer chromatography is suitable for separation of 25 biologically important amines. Development is effected on silica gel (Kieselgel G) plates in the first direction with ethyl acetate/cyclohexane (75:50; v/v) and, after reactivation of the plates by heat at 100°, in the second direction with either benzene/methanol/cyclohexane (85:5:10; v/v) or benzene/triethylamine (100:20; v/v). The chromatograms are readily reproducible, so that the amides can be identified by their position and, in some cases, by the color of their fluorescence. DANS-amino acids remain on or near the starting point, so that they do not disturb chromatography of the amines. Only very little decomposition or autoxidation occurs during this treatment. For quantitative determination of the DANS-amides on

thin-layer plates, removal of the spots and extraction of the silica gel with methanol containing 5 % of concentrated ammonia solution are recommended. After excitation with the 365 mμ Hg line, the intensity of fluorescence of the extract is determined at 520 mμ for DANS-amides and at 530 mμ for phenol- and pyrocatechol-amine derivatives. Reproducibility is 3–5 % for concentrations of 2×10^{-10} mole/cm³.

Use of Chromatography on Anion-exchangers for Determination of Low Phosphate Contents

J. Wernet, *J. Ebert*, and *R. Adrian*,
Knapsack bei Köln (Germany)

The usual methods of paper-chromatographic separation and determination of condensed phosphates require concentrations of 1 to 5 g/l of each phosphate. In samples of water or foodstuffs, and in biological chemistry, the phosphate contents to be determined are usually considerably less than this. Concentration by evaporation would, *inter alia*, alter the form of the phosphates as a result of hydrolysis. Chromatography on anion-exchangers is suitable for determination of phosphates in these circumstances. It permits dissolved ionogenic phosphates to be separated and indications of the distribution of dissolved, non-ionogenic, inorganic and organic phosphates to be obtained. Dissolved, ionogenic, condensed phosphates can be separated and determined in concentrations down to less than 1 mg of total P_2O_5 per litre. In phosphate-treated drinking water, in river water, and in effluent water seven forms of phosphate could be determined in presence of each other: dissolved, non-ionogenic, highly condensed, inorganic and organic phosphates – dissolved ionogenic compounds, separated into mono-, di-, tri-, total > tri- and meta-phosphates – and highly condensed phosphates. [VB 923/230 IE]

German version: Angew. Chem. 77, 683 (1965)

Mode of Action of the Thiamine Antagonists Pyrithiamine and Oxythiamine in Rat Brain

C. J. Gubler, Freiburg/Breisgau (Germany)

Thiamine in the form of its pyrophosphate ester is involved as coenzyme in the decarboxylation of pyruvate and α-oxoglutarate. Prolonged deficiency of thiamine can lead to damage of the nerves.

Injection of the thiamine antagonist pyrithiamine into rats causes polyneuritis and a large decrease in the content of thiamine in the brain. Injections of oxythiamine do not affect the thiamine content. These findings were clarified by experiments *in vitro*. Inactive thiamine can be phosphorylated in brain tissue to give the active pyrophosphate [1]. The activating enzyme, thiamine pyrophosphokinase, was concentrated by a factor of 12. Pyrithiamine inhibits this enzyme 1000 times more strongly than oxythiamine ($K_{i\ (pyrithiamine)} = 1.3\times10^{-7}$; $K_{i\ (oxythiamine)} = 1.5\times10^{-4}$). Hence thiamine is not phosphorylated in the presence of pyrithiamine; instead, it is catabolized and excreted.

In contrast to pyrithiamine but like thiamine, oxythiamine is phosphorylated by thiamine phosphokinase, and the phosphate then inhibits the enzymes transketolase and pyruvate and α-oxoglutarate dehydrogenase.

Experiments with thiamine antagonists labelled with ^{14}C and ^{35}S revealed that the oxythiamine injected penetrates into the brain but in concentrations too low to prevent phosphorylation of the thiamine, and that pyrithiamine suppresses the production of thiamine phosphate in the brain.

[GDCh-Ortsverband Hamburg (Germany).
April 6th, 1965] [VB 934/236 IE]

German version: Angew. Chem. 77, 684 (1965)

[1] *L. R. Johnson* and *C. J. Gubler*, Federat. Proc. *24*, 481 (1965).

The Stereochemistry of Sulfoxides

K. Mislow, Princeton, N.J. (U.S.A.)

Three major problems in sulfoxide stereochemistry are: the absolute and relative configuration of optically active sulfoxides, the relation between structure and optical rotatory power of sulfoxides, and the inversion of the sulfoxide pyramid.

The absolute configuration of menthyl *p*-iodobenzenesulfinate *(1)* was established by X-ray diffraction [1]. The configurations of menthyl *p*-toluenesulfinate *(2)* and of *(1)* were correlated, utilizing an asymmetric synthesis of the esters from (–)-menthol and an excess of the corresponding sulfinyl chloride. Reaction of *(2)* with a variety of alkyl- and arylmagnesium halides by an inversion mechanism led to optically active *p*-tolyl alkyl and aryl sulfoxides of known absolute configuration. Reaction of diastereomerically enriched menthyl 1-butanesulfinate (which had been prepared by asymmetric synthesis from (–)-menthol and 1-butanesulfinyl chloride) with methylmagnesium bromide led to optically active methyl n-butyl sulfoxide of known absolute configuration. This constitutes the first preparation of an optically active dialkyl sulfoxide lacking other functionalities. The optical rotatory dispersions of the abovementioned sulfoxides were measured and could be conveniently discussed from the viewpoint that the C_6H_5SO- moiety represents an inherently dissymmetric chromophore whose chirality determines the signs of the Cotton effects above 200 mμ.

Optically active sulfoxides containing aromatic nuclei may be racemized (a) thermally, by heating at temperatures near 200 °C (depending on the structure), (b) photochemically by irradiation (at room temperature) in the wavelength region above 285 mμ, and (c) chemically, by the catalytic action of hydrogen chloride in non-aqueous solvents.

[GDCh-Ortsverband Marburg (Germany),
May 15th, 1965] [VB 938/241 IE]

German version: Angew. Chem. 77, 684 (1965)

[1] In collaboration with *E. Fleischer*, University of Chicago.

Erratum

"Inorganic Ring Systems with Silicon and Nitrogen Atoms as Ring Members" by *U. Wannagat*, Angew. Chem. internat. Edit. *4*, 605 (1965).

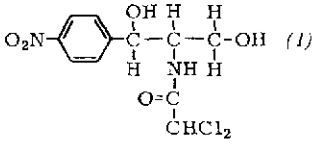
The last sentence of this lecture summary should begin: "Compound *(6)* with R = CH_3....."

SELECTED ABSTRACTS

A table of the masses of molecules and molecular fragments for help in identifying compounds by high-resolution mass spectrometry has been compiled by *D. D. Tunnicliff*, *P. A. Wadsworth*, and *D. O. Schissler*. An electronic computer was used to arrange the sum formulae of all possible combinations of elements (and their commonest isotopes) into two tables in order of increasing masses. The first table (215781 entries) gives combinations of the elements C, H, O, and N up to mass numbers of 600, the second (545017 entries) gives selected combinations of the elements C, H, O, N, F, Cl, Br, I, S, P, Si, B, Ga, Fe, Sn, and Al up to mass numbers of 400./Analytic. Chemistry *37*, 543 (1965)/–Hz. [Rd 311/520 IE]

Cyanamide formation under primaeval conditions was observed by *A. Schimpl, R. M. Lemmon*, and *M. Calvin*: on irradiating ammoniacal solutions of $NH_4{}^{14}CN$ with ultraviolet light, a 3.5 % yield of dicyanamide, the product of dimerization of cyanamide, was obtained. Irradiation of a methane/ammonia/water mixture also led to dicyanamide. Since dicyanamide and cyanamide effect the formation of pyrophosphate from orthophosphate, of glucose 6-phosphate from glucose and orthophosphate, and of adenosine 5'-phosphate from adenosine and H_3PO_4 (1–3 % yield at room temperature after several hours), they possibly are key compounds in chemical evolution. / Science (Washington) *147*, 149 (1965) / –De. [Rd 244/453 IE]

Chloramphenicol can serve as sole source of nitrogen for algae; this follows from experiments by *F. C. Czygan* with *Ankistrodesmus braunii* and *Chlorella ellipsoidea* in normal, low-nitrogen, and nitrogen-free culture solutions. The algae convert the chloramphenicol *(1)* into 1-(*p*-aminophenyl)- and 1-(*p*-nitrophenyl)-2-amino-1,3-propanediol, ethanolamine, *p*-aminobenzoic acid, and *p*-aminobenzaldehyde. The last three compounds can also be used as nitrogen sources by both species of algae. The *p*-amino analogue of chloramphenicol does



(1)

not occur in the culture medium but was produced from *(1)* with a hydrogenase from *A. braunii*. / Naturwissenschaften *51*, 541 (1964) / –De. [Rd 231/439 IE]

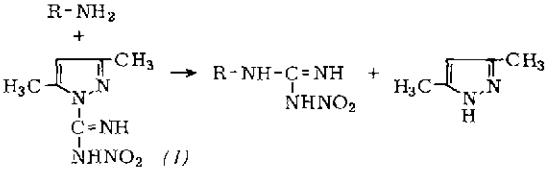
Reversible changes in the conformation of myoglobin from the sperm whale and in that of apomyoglobin were detected by *S. C. Harrison* and *E. R. Blout* using optical rotatory dispersion (ORD). The haem group can be removed from the myoglobin (Mb) by treating it with acetone at a low pH, the helix content being thereby reduced from 60 % (Mb) to 51 % (apo-Mb). It follows from results of ORD measurements that the major portion of the apo-Mb helical regions behave as though they were in an organic solvent and not in water, the medium in which the measurements were carried out. Consideration of the structural model for Mb proposed by *Kendrew* confirms that the helical regions are partly engulfed in a hydrophobic environment owing to inclusion inside the globular protein. Apo-Mb is completely unfolded in 8 M urea and has no helical regions. The ORD values then correspond to those for a peptide chain immersed completely in an aqueous medium. Removal of the urea by dialysis restores a 48 % helix content. The apo-Mb re-formed in this way combines completely with haem to give Mb which is indistinguishable from native Mb. The reversibility of the changes in conformation is particularly interesting because Mb has no disulfide bridges or thiol side chains. These results support the "thermodynamic" hypothesis of the formation of the tertiary structure of the protein. / J. biol. Chemistry *240*, 299 (1965) / –Hö. [Rd 302/511 IE]

The diffusion of boron in graphite has been investigated by *G. Hennig*. Boron is probably the only element that can be accomodated in lattice sites of graphite. The mobility of boron atoms in single crystals of graphite was measured as follows. The single crystals were etched and subsequently shadowed with gold, which condenses preferentially on the etched sites, rendering them visible in the electron microscope. The mobility of the boron atoms is largely independent of the concentration between B:C atom ratios of 10^{-2} and 10^{-8}. The diffusion constants between 1700 and 2400 °C can be represented by the expressions $6320\exp(-157000/RT)$ for motion parallel to the lattice layers and $7.1\exp(-153000/RT)$ for motion normal to the lattice layers. / J. chem. Physics *42*, 1167 (1965) / –Hz. [Rd 310/519 IE]

Dissociation constants of acidic hydrocarbons in the pK range 18–34 have been measured in cyclohexylamine by *A. Streitwieser, J. I. Brauman, J. H. Hammons*, and *A. H. Pudjaatmaka*. The equilibrium concentrations of the hydrocarbons and their carbanions were measured for the transanionization by spectrophotometry (the Beer-Lambert law is fulfilled). The equilibria were adjusted so that measureable concentrations of all four components were present. The technique can be applied whenever the anion and the corresponding acid (*i.e.* the hydrocarbon) can be distinguished by spectroscopy. 9-Phenylfluorene was taken as a standard with a known pK value (18.5 ± 0.1 in aqueous sulfolane). pK values of 22.9, 32.5, and 34.1, reproducible to within ±0.2 pK units, were found for fluorene, triphenylmethane, and diphenylmethane, respectively. / J. Amer. chem. Soc. *87*, 384 (1965) / –Eb. [Rd 273/482 IE]

$$C^{\ominus}M^{\oplus} + C^1H \rightleftharpoons CH + C^{1\ominus}M^{\oplus}\ (M = Li \text{ or } Cs)$$

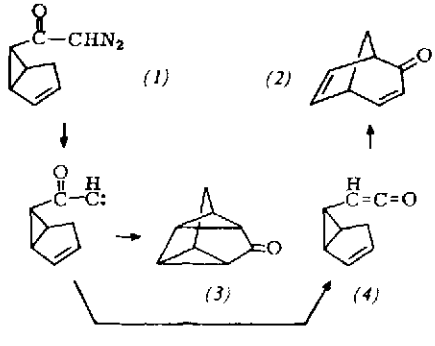
A new reagent for nitroguanylating proteins has been discovered by *A. Habeeb*. It is 1-nitroguanyl-3,5-dimethylpyrazole *(1)*. For example, the free amino groups in a 1 % aqueous solution of bovine serum albumin are almost completely nitroguanylated by a 0.025 M solution of *(1)* at pH 9.5 and room temperature without attack of the functional



(1)

groups in tyrosine, tryptophan, or histidine residues. Nitroguanylation is an important reaction for intentional modification of enzyme molecules. Hitherto *S*-methyl-1-nitroisothiourea was used instead of *(1)*, but the former does not react as completely as *(1)* with the free amino groups. The new reagent is made from nitroaminoguanidine and acetylacetone. / Biochim. biophysica Acta *93*, 533 (1964) / –Hö. [Rd 261/470 IE]

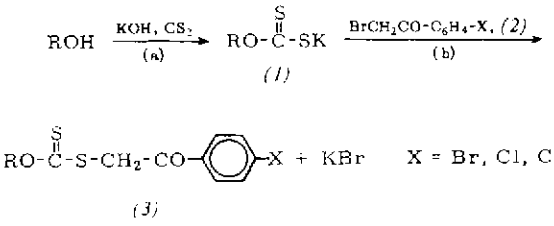
An unusual valence-bond isomerism was observed by *P. K. Freeman* and *D. G. Kuper*. Photolysis of a 1.5 % solution in tetrahydrofuran of *endo*-6-diazomethylcarbonylbicyclo[3.1.0]hex-2-ene *(1)*, which is obtained from bicyclo[3.1.0]hex-2-ene-6-*endo*-carbonyl chloride and diazomethane, affords the bicyclic ketone *(2)* resulting from valence-bond isomerization of the ketene intermediate *(4)*, which arises by Wolff rearrangement of *(1)*. The main product obtained is bicyclo[3.2.1]octa-3,6-dien-2-one *(2)*, but the tetracyclic ketone



(1) *(2)* *(3)* *(4)*

tetracyclo[3.3.0.0^{4,6}0^{2,8}]octan-3-one is formed as a by-product by intramolecular carbenoid addition to the double bond in competition to the Wolff rearrangement; the total yield of ketones is 50 %. The ketone *(3)* was recently synthesized by *Lebel*, and can also be prepared in 30 % yield from *(1)* by heating its solution in benzene with copper powder. / Chem. and Ind. *1965*, 424, 425 / –Ma. [Rd 285/494 IE]

Characterization of primary and secondary alcohols as their *O*-alkyl *S*-phenacyl dithiocarbonates *(3)* is described by *J. Berger* and *J. Uldall*. The potassium xanthates *(1)* are converted into the phenacyl derivatives *(3)*, which – contrary to the xanthates – crystallize well and have sharp melting points



(3)

In acetone, the KBr formed precipitates out and Reaction (b) goes almost to completion. When water is added, the KBr redissolves, and *(3)* precipitates out. In practice, 4 mmoles of *(1)* are dissolved in 10 ml of acetone plus 1–3 ml of water, and 3.6 moles (1.0 g) of *p*-bromophenacyl bromide *(2)*, X = Br, in 10 ml of acetone are added. After 5 min, water is added, and the whole is shaken vigorously. The precipitate consisting of *(3)*, X = Br, is sucked off and recrystallized from ethanol, the melting points and elemental analysis then being satisfactory. ROH = methanol leads to *(3)*, R = CH_3, of m.p. 94–95 °C. Polymorphism is occasionally observed. The technique can be applied on the micro scale down to 5 mg of *(1)*. / Acta chem. scand. *18*, 1353 (1964) / –Eb.

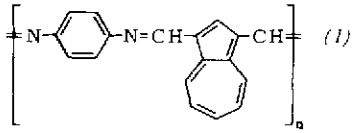
[Rd 235/443 IE]

Biological C-methylation by methionine was studied by *E. Lederer* et al., who found that only 2 hydrogen atoms of the methyl group are transferred to the acceptor. The origin of the 10-methyl group of tuberculostearic acid and of the 28-methyl group of ergosterol from methionine is known. *Lederer*'s group cultivated *Mycobacterium smegmatis* in the presence of 100 mg/l of methionine that was trideuterated at the methyl group. The tuberculostearic acid was separated from the cultures and examined by mass spectrometry for its deuterium content. It was found to contain only two deuterium atoms. This result was in agreement with that of the mass spectrographic analysis of ergosterol isolated from analogous cultures of *Neurospora crasse*. The analyses reflected the content of only two deuterium atoms per molecule so precisely that isotope exchange or dilution is cannot be an explanation for the deuterium loss. In addition, the methionine synthesis by the bacteria is almost completely suppressed by the high methionine content of the culture medium. It is not known which intermediate of the transmethylation reaction undergoes the loss of a deuteron. / Biochemistry *4*, 347 (1965) / –Hö. [Rd 304/513 IE]

Separation of lactic dehydrogenase isoenzyme bands into sub-bands by electrophoresis in polyacrylamide gels has been observed by *P. J. Fritz* and *K. B. Jakobson*. The separation of lactic dehydrogenase (LDH) into 5 bands (isoenzymes) with different rates of migration in electrophoresis has already been closely studied. It now appears that the isoenzymes in turn also consist of up to five components with only small differences in their mobilities, but there is a striking constancy in the distances between the sub-bands. The separation of the sub-bands depends on the pH (the optimum separation for LDH from mouse skeletal muscle occurs at 8.6) and on the concentration of 2-mercaptoethanol in the buffer. Separation is also observed in two-dimensional electrophoresis. Reversal of the current causes reunification of all the components at the starting point. These phenomena were observed with LDH from mouse skeletal muscle, mouse heart muscle, and rabbit skeletal muscle. The results do not depend on the purity of the LDH. The isoenzyme with the lowest mobility ("band 5") was generally found to be split into the largest number of sub-bands. / Biochemistry *4*, 282 (1965) / –Hö.

[Rd 305/514 IE]

Polyazomethines with azulene residues inserted in the main chain were prepared by *S. S. Stivala, G. R. Sacco*, and *L. Reich* from azulene-1,3-dicarboxaldehyde and 1,6-hexamethylene diamine, 1,4-diaminobenzene, 4,4'-diaminobiphenyl, 1,5-diaminonaphthalene, *etc.* The reagents are heated together, first in dimethylformamide at 100 °C for 8 h and then, after removal of the solvent, for a further 4 h at 250 °C. The polymers, *e.g. (1)*, are only slightly soluble in concentrated sul-



(1)

furic acid or formic acid and are stable *in vacuo* to 400 °C. This confirms the expectation that because of its resonance energy, which is of the same order of magnitude as that of benzene, azulenylene residues confer the same thermostability on the polymers as the phenylene residue. / Polymer Letters *2*, 943 (1964) / –Hl. [Rd 270/479 IE]

Pure phenyldifluorophosphine $C_6H_5PF_2$ was prepared by *R. Schmutzler* from $C_6H_5PCl_2$ with a suspension of sodium fluoride in tetramethylene sulfone at 180 °C and separated by vacuum distillation (b.p. 31 °C/11 mm). The compound does not etch glass and has a pleasant odor; it is oxidized slowly in air to $C_6H_5POF_2$ but does not ignite spontaneously. In contrast to CH_3PF_2 [cf. Equation (a)], it does not disproportionate under normal conditions. The compound was identified as $C_6H_5PF_2$ by elemental analysis and by its ^{31}P and ^{19}F nuclear magnetic resonance spectra. Being a strong π-electron donor, $C_6H_5PF_2$ reacts with metal carbonyls according to Equation (b). The redox reaction shown in Equation (c) proceeds completely stoichiometrically.

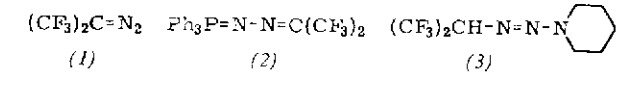
$$10\ CH_3PF_2 \rightarrow 5\ CH_3PF_4 + (CH_3P)_5 \quad (a)$$

$$Ni(CO)_4 + 4\ C_6H_5PF_2 \rightarrow Ni(C_6H_5PF_2)_4 + 4\ CO \quad (b)$$

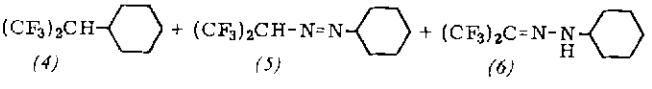
$$3\ C_6H_5PF_2 + 2\ SbF_3 \rightarrow C_6H_5PF_4 + 2\ Sb \quad (c)$$

A compound of b.p. 64–70 °C previously described as $C_6H_5PF_2$ [1] must obviously have a different composition. / Chem. Ber. *98*, 552 (1965) / –Gn. [Rd 271/480 IE]

Bistrifluoromethyldiazomethane *(1)*, the first perfluorinated diazo compound, was synthesized by *D. M. Gale, W. J. Middleton*, and *C. G. Krespan* by oxidation of the hydrazone of benzonitrile with lead tetraacetate. It is a pale yellow compound, b.p. 12–13 °C, and can be stored at –78 °C, but decomposes slowly at room temperature with release of nitrogen. It reacts with triphenylphosphine to give the phosphazine *(2)* and with piperidine to give the triazene *(3)*. When heated with benzene for 8 h at 200 °C, *(1)* yields 7,7-bistrifluoromethyl-1,3,5-cycloheptatriene (88 %) and hexafluoroisopropylbenzene (12 %) at 70 % conversion. On



(1) *(2)* *(3)*

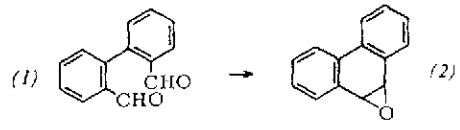


(4) *(5)* *(6)*

pyrolysis at 150–200 °C over quartz in an atmosphere of helium *(1)* gives hexafluoropropene and tetrakis(trifluoromethyl)ethylene. On heating in cyclohexane for 8 h at 150 °C, *(1)* yields 12 % hexafluoroisopropylcyclohexane *(4)* plus 52 % *(5)* and 36 % *(6)*; the latter two compounds have probably been formed by a radical chain reaction. / J. Amer. chem. Soc. *87*, 657 (1965) / –Ma. [Rd 291/500 IE]

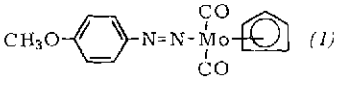
[1] Zhur. obshch. Khim. *29*, 3957 (1959).

A new cyclization reaction leading to epoxides of aromatic hydrocarbons has been discovered by *M. S. Newman* and *S. Blum*. Treatment of *o,o'*-diformylbiphenyl *(1)* with trisdimethylaminophosphine causes exothermic formation of 87 % 9,10-dihydro-9,10-epoxyphenanthrene *(2)*, m.p. 104 to



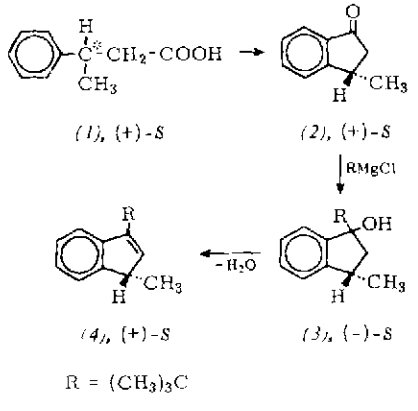
105 °C. 3,4-Dihydro-3,4-epoxybenz[*a*]anthracene, m.p. 119 to 120 °C (decomp.) and 3,4-dihydro-3,4-epoxy-10-methylbenz[*a*]anthracene, m.p. 117–120 °C, were obtained analogously. The three compounds are the first examples of epoxides of aromatic hydrocarbons; on treatment with acids, they isomerize to phenols. / J. Amer. chem. Soc. *86*, 5598 (1964) / –Ma. [Rd 253/462 IE]

An arylazo derivative of molybdenum, the first compound with an arylazo group attached directly to a transition metal, has been synthesized by *R. B. King* and *M. B. Bisnette*. *p*-Anisyldiazonium tetrafluoroborate was treated with excess $NaMo(CO)_3C_5H_5$ in tetrahydrofuran at room temperature; evaporation of the solvent and extraction of the residue with CH_2Cl_2 afforded a 20 % yield of *(1)*, which forms orange-red crystals, m.p. 78–79 °C, from pentane. The complex de-



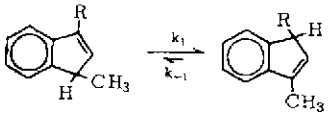
composes within a few hours on exposure to air. The structure *(1)* is reconcilable with the NMR spectrum of the compound. The complex is diamagnetic. / J. Amer. chem. Soc. *86*, 5694 (1964) / –Ma. [Rd 254/463 IE]

Optically active indenes have been obtained from β-phenylbutyric acid *(1)* by *A. M. Weidler* and *G. Bergson* by ring closure in a Friedel-Crafts reaction, conversion of the resultant indanone *(2)* with t-butylmagnesium chloride into *(3)*, R = t-butyl, or with $LiAlH_4$ into *(3)*, R = H, and dehydration of *(3)* with acid. Racemic *(1)* was resolved with optically



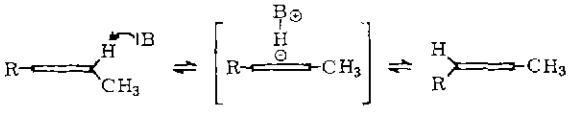
active α-phenylethylamine, the ammonium salts precipitated being recrystallized from aqueous ethanol, m.p. 135–140 °C. Three more recrystallizations raised the m.p. to 144.5–146 °C. The acid released from this product had a specific rotation $[\alpha]_D^{25}$ of +52.2 ° in benzene. The *(S)*-configuration of the (+)-acid *(1)* was already known. Since both antipodes of α-phenylethylamine were available, both enantiomorphic β-phenylbutyric acids could also be prepared. It is assumed that the acids (+)-*(1)* and (–)-*(1)* were optically almost pure and that the subsequent operations involved in the ring closure effected at the most only partial racemization. (+)-*S*-*(4)*, R = H, was also obtained with $[\alpha]_D^{25}$ = +182.1 ° in benzene, and (+)-*S*-*(4)*, R = t-butyl, with $[\alpha]_D^{25}$ = +110.2 °. / Acta chem. scand. *18*, 1483 (1964) / –Eb. [Rd 236/444 IE]

An ion-pair mechanism for the tautomerization of substituted indenes was discovered by *A. M. Weidler* and *G. Bergson*. 1-Methylindene *(1)* is stable in pyridine, but on addition of triethylamine or other aliphatic amines, it isomerizes to 3-methylindene *(2)*. This tautomerism can be followed by measuring the increase in intensity of the NMR signal of the olefinic methyl group. The isomerization is practically irreversible ($k_1 \gg k_{-1}$) and is pseudomonomolecular. k_1 is proportional to the concentration of amine catalyst. With (+)-1-methylindene *(1)*, the addition of catalyst causes the specific rotation to fall off to zero at the same rate as is observed for the isomerization. When R = t-butyl, the specific rotation attains a



(1), R = H *(2)*, R = H

limiting value with a sign opposite to that of the original rotation. The rate constants derived by polarimetry, too, are always the same as those measured by NMR spectroscopy. The stereospecificity of the reaction and the lack of deuterium-hydrogen exchange during the isomerization in the presence of D_2O can be explained by a mechanism involving prototropy *via* an intramolecular ion pair; a synchronous mechanism was shown not to occur. In dimethyl sulfoxide, the race-



mization of (+)-1-methylindene *(1)* was faster than the isomerization. Here the ion pair appears to dissociate partially to the free carbanion and $BH^{\oplus}$, and thus the stereospecificity of the preceding intermediate is lost. / Acta chem. scand. *18*, 1487 (1964) / –Eb. [Rd 237/445 IE]

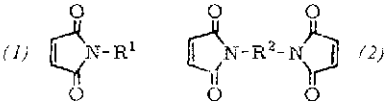
Dipeptide phosphates are intermediates of enzymatic tripeptide syntheses; this was shown by *J. S. Nishimura*, *E. A. Dodd*, and *A. Meister*. γ-L-Glutamyl-L-α-aminobutyryl phosphate is an intermediate in the synthesis of ophthalmic acid (γ-glutamyl-α-aminobutyrylglycine), which is catalysed by the glutathione synthetase from yeast. The reaction takes place in two steps:

$$\text{Dipeptide} + \text{ATP} \rightleftharpoons \text{Dipeptide phosphate} + \text{ADP} \quad (1)$$

$$\text{Dipeptide phosphate} + \text{Glycine} \rightleftharpoons \text{Tripeptide} + \text{Phosphate} \quad (2)$$

Both reactions are catalysed by the enzyme, and the intermediate remains attached to the enzyme protein. Four reactions catalysed by glutathione synthetase reveal the overall process: (a) formation of dipeptide hydroxamic acid from the dipeptide, ATP, and hydroxylamine; (b) formation of dipeptide hydroxamic acid from the tripeptide and hydroxylamine in the presence of phosphate or arsenate; (c) exchange between free glycine and that bound in the tripeptide; and (d) cleavage of the tripeptide into the dipeptide in the presence of arsenate. The Reactions (a)–(d) require catalytic amounts of ADP, which appears to be an essential part of the active enzyme-substrate complex. γ-L-Glutamyl-L-α-aminobutyryl phosphate was synthesized from *N*-carbobenzoxy-α-benzyl-γ-L-glutamyl-L-α-aminobutyric acid and phosphoric acid in the presence of dicyclohexylcarbodiimide. Its role as an intermediate was proved by its introduction during the enzyme reaction: in the course of Reaction (2), it condenses with glycine to form the tripeptide, while the reverse of Reaction (1) leads to the formation of ATP and the dipeptide when ADP is added. / J. biol. Chemistry *239*, 2553 (1964) / –Hö. [Rd 265/474 IE]

Vulcanization of styrene/butadiene copolymers with maleimides of types *(1)* and *(2)* can be carried out according to *P. O. Tawny, W. J. Wenisch, S. van der Burg*, and *D. I. Relyea* with peroxides and sulfur-containing accelerators of the thiazole type. The cross-linking activity of *(1)* and *(2)* depends



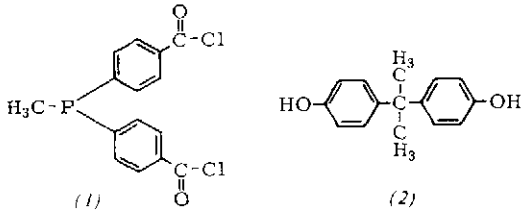
(1) *(2)*

largely on the nature of the substituents R^1 (*e.g. p*-ethoxyphenyl > *m*-chlorophenyl > *o*-nitrophenyl) and R^2 (*e.g. m*-phenylene > 1,2-(*p,p'*-diphenylene)ethylene > *p,p'*-biphenylyl). For example, 100 g of a 24:76 styrene/butadiene copolymer can be vulcanized by treatment with 0.85 g of *N,N'*-phenylenebismaleimide and 0.7 g of dicumyl peroxide (40 % activity) for 22 min at 155 °C. The physical properties of the vulcanized product are independent of the vulcanization temperature. In contrast to vulcanization with sulfur, the maleimide vulcanization systems have no significant effect on the crystallizability of the elastomers on stretching. Maleimides of type *(1)* in which $R^1 = SCCl_3$ or *p*-$HOOC-C_6H_4$, for example, are suitable as self-accelerating vulcanizing agents or as adhesives. / *J. appl. Polymer Sci. 8*, 2281 (1964) / –Hl. [Rd 268/477 IE]

The origin of the nitrogen in quinoline made by the Skraup synthesis was investigated by *M. Wahren*. He studied how the nitrogen from the coreagents aniline and nitrobenzene is distributed in the reaction products. It is generally accepted that the nitro compound used as dehydrogenating agent for the intermediate dihydroquinoline is reduced to the aniline derivative, which then acts as additional "starting material." – Nitrobenzene or aniline was labelled with ^{15}N, and the reaction products were processed in five fractions: unreacted nitrobenzene, aniline, quinoline, resin (residue from the steam distillation of the bases), and residues (mother liquors, *etc.*, of undefined composition). Kjeldahl nitrogen estimations and mass-spectrometric analysis of the ^{15}N content of the nitrogen led to the following results: In contrast to the conventional opinion, only about 2 % of the quinoline contains nitrogen originating from the nitrobenzene; this percentage rises slowly as the overall conversion increases, but the content of ^{15}N from $C_6H_5{}^{15}NO_2$ is always higher in the aniline in the reaction mixture than in the quinoline; hence the low incorporation that does take place very probably proceeds *via* the aniline. Over 90 % of the nitrobenzene nitrogen recurs in the nitrobenzene and resinous fractions; after complete reaction, it is primarily in the resins, mainly in functional groups with N–N or N–O bonds. It follows that unlabelled nitrobenzene can be used to prepare [^{15}N]-quinolines from [^{15}N]-aniline. / Tetrahedron *20*, 2773 (1964) / –Bi. [Rd 267/476 IE]

Connections between the structures and long-wave infrared spectra of aliphatic amides have been demonstrated by *J. E. Katon, W. R. Feairheller*, and *J. V. Pustinger* for 78 compounds of this class in the region between 700 and 250 cm^{-1}. Here all amides have 2–4 absorption bands between the limits 700–550, 520–430, and 390–305 cm^{-1}. The exact positions of the peaks give information on finer structural details, *e.g.* the amount of branching and the approximate length of the aliphatic chain. The regions of characteristic absorption were tabulated for primary, secondary, and tertiary amides with diverse aliphatic substituents. Assignments of the bands to the following modes of vibration of the molecular skeleton were considered: The band near 600 cm^{-1} is due to deformation of the N–C=O group; the band at 500 cm^{-1} is probably due to a C–C=O deformation, for this band is absent in formamides; the origin of the band near 350 cm^{-1} is still unclear, but it is assumed to arise from a non-planar deformation vibration of the amide group. / Analytic. Chem. *36*, 2126 (1964 / –Hz. [Rd 234/442 IE]

The synthesis of polyamides containing phosphorus by interfacial polycondensation is described by *V. V. Korshak, S. V. Vinogradov*, and *U. Ban-Yuan*'. The reaction is carried out in 0.05 N solution in chloroform with vigorous stirring (6000 r.p.m.). Reaction of bis-(*p*-chlorocarbonylphenyl)methylphosphine *(1)* with 2,2-bis(*p*-hydroxyphenyl)propane *(2)* and hexamethylene diamine, for example in proportions of 2:1:1,



(1) *(2)*

yields a polyamide (η_r = 0.43 in tricresol, softening point ca. 160 °C) with a nitrogen content almost the same as that of the monomer mixture. The solubility of the polyamides in dioxane/CCl_4 depends on the ratio of monomers in the starting mixture and decreases with increasing hexamethylenediamine concentration. Since the yield of polymer in interfacial polycondensation depends on the surface area, the yields increase as the stirring becomes faster. At the same time, more hexamethylenediamine is incorporated, for it is apparently more reactive than *(2)*. / Polymer Sci. USSR *5*, 18 (1964) / – Hl. [Rd 269/478 IE]

The mechanism of the iodination of aromatic compounds with iodine/peroxyacetic acid in acetic acid [1] has been elucidated by *Y. Ogata* and *K. Nakajimi* by studying the effect of the acidity, the temperature, the solvent, and the nature of the peroxyacid on the yield of aryl iodide [see Equations (a) to (d)]. The overall rate of iodination is independent of the pH and of the concentration of the aromatic compound; instead, it is determined by the rate of the (pH-independent) reaction of the iodine with the peroxyacetic acid. However, since addition of sulfuric acid increases the yield of iodo compound (*e.g.* for benzene from 60.9 to 77.3 % iodobenzene with a molar ratio $H_2SO_4:I_2$ of 1.23:1.00, reaction for 160 min at 70 °C), it is concluded that a protonation of the iodinating reagent occurs. On the other hand, the yield of iodobenzene falls to 1.3 % if the peroxyacetic acid/acetic acid is replaced by peroxybenzoic acid/chloroform (270 min at 60 °C; here the weak iodinating agent is possibly I_2O, but the main product is HIO_3). When acetic acid is added in a molar ratio $CH_3COOH:I_2$ of 11:1, up to 5 % iodobenzene is formed. The importance of the peroxyacetic acid is due to the formation from it of acetyl hypoiodite; the species which then conducts an electrophilic attack on the aromatic compound is probably protonated acetyl hypoiodite $(CH_3COOHI)^{\oplus}$.

$$I_2 + CH_3CO_3H + H_2O \xrightarrow{\text{slow}} 2\,HOI + CH_3CO_2H \quad (a)$$

$$HOI + CH_3CO_2H + H^{\oplus} \underset{}{\overset{\text{fast}}{\rightleftharpoons}} (CH_3CO_2HI)^{\oplus} + H_2O \quad (b)$$

$$(CH_3CO_2HI)^{\oplus} + ArH \xrightarrow{\text{fast}} ArI + CH_3CO_2H + H^{\oplus} \quad (c)$$

$$HOI + 2\,CH_3CO_3H \longrightarrow HIO_3 + 2\,CH_3CO_2H \quad (d)$$

ArH can be benzene, toluene, *m*-xylene, cumene, anisole, naphthalene, chloro- or bromonaphthalene, or benzoic acid; the yields lie between 35 and 84.6 % ArI within 90–330 min at 50–90 °C. / Tetrahedron *20*, 2751 (1964) / –Bi. [Rd 277/486 IE]

[1] *Y. Ogata* and *K. Nakajima*, Tetrahedron *20*, 43 (1964); cf. Angew. Chem. *76*, 507 (1964).

An improved apparatus for continuous electrophoresis without a support has been developed by *K. Hannig*. In contrast to previous equipment, the electrophoresis cell (48×48 cm^2; 0.5 mm layer thickness) is mounted vertically and has a uniform flow of buffer normal to the electric field, achieved by introducing the buffer through six inlets at the upper edge and removing it from fifty leads at the lower edge. The solution to be separated can be fed in continuously to the buffer stream close to the upper edge at one of several points. Previously, the problem of non-uniform cooling prevented vertical arrangement of the electrophoresis cell, for the slightest temperature gradients caused disturbances of the laminar flow of buffer owing to convection currents. This difficulty has been overcome by covering the rear wall of the cell uniformly with Peltier batteries. About 2500 v at about 160 mA is used. – The apparatus can separate protein mixtures continuously even when the molecules in the mixture differ by only one charge unit. Because of the vertical arrangement, the range of application of the instrument could be extended even to particles which in horizontal cells sediment out on the lower plate and upset the separation. Clean separations of cellular constituents (*e.g.* chloroplasts, mitochondria, cell nuclei, and nuclear fragments from spinach leaves) and even of intact cells (*e.g.* human and rabbit erythrocytes or Walker ascites tumor cells and leucocytes) were achieved with the new instrument. The fractions exhibited excellent homogeneity in the electron miscroscope. Even virus mutants can be separated. / Hoppe-Seylers Z. physiol. Chem. *338*, 211, 278 (1964) / –Hö. [Rd 266/475 IE]

BOOK REVIEWS

Ionenaustausch-Chromatographie (Ion-Exchange Chromatography). By *K. Dorfner*. Akademie-Verlag, Berlin 1963. 1st edit., X + 236 pp., 149 illustrs., 14 tables, linen DM 32.50 (about $ 8.25).

The author, a former coworker of *B. Sansoni* in Marburg (Germany), has recorded his knowledge and experience in the field of ion exchangers in two books; in the present volume he presents a review of ion-exchange chromatography, starting from elementary fundamentals that can be understood by all. It is simultaneously the second volume in the series "Ionenaustauscher in Einzeldarstellungen" (Monographs on Ion Exchangers) edited by *Griessbach*. The book has two main divisions: methods of ion-exchange chromatography (fundamentals of chromatography, ion-exchange chromatography, types of ion exchangers, apparatus), and their applications in inorganic and organic chemistry (including natural products). The ordering principles applied are the groups of the periodic system of the elements and the compound classes in organic chemistry.

The text is augmented by 149 figures and 14 tables, and 946 literature references are given, covering publications up to about 1960. Within the aims of the book, all the essentials are well dealt with. The subject matter is well arranged, and the style of the writing is fluent, so that the book well fulfils its purpose of providing an introduction to the subject and serving as a source of information.

E. Blasius [NB 377/235 IE]

Die Nucleinsäuren (Nucleic Acids). By *E. Harbers* in collaboration with *G. E. Domagk* and *Werner Müller*. Eine einführende Darstellung ihrer Biochemie und Funktionen (An Introductory Description of their Biochemistry and Functions). Georg Thieme Verlag, Stuttgart 1964. 1st edit., XII + 303 pp., 155 figs., 20 tables, linen DM 68.– (about $ 17.25).

This monograph on nucleic acids does not merely bring a discussion of the fundamental facts in this field; the breadth and depth of the data given are sufficient to satisfy even high demands – in their didactic nature as well. The book is intended for all scientists with an interest in biology and to medical researchers occupied with biochemical problems.

The chemistry of nucleic acids and their constituents is given an exemplary historical and theoretical treatment by *W. Müller*, together with many practical tips for laboratory work. The biosynthesis of purines, pyrimidines, pentoses, and nucleotides is described by *G. E. Domagk*. There follow chapters on the metabolism of DNA and RNA, the transfer of genetic information from cell to cell, the induction of mutations, nuclei acids in tumor cells, interference of drugs in nucleic acid metabolism, and the effects of radiation on nucleic acids.

The newcomer to this field will welcome the appendix, which records some classical methods for metabolic studies and for preparative, analytical, and physico-chemical experimentation with nucleic acids. An unusually large list of sources of information and, in contrast, a very meagre subject index close the book, which is highly recommendable in view of its copious content. It is to be hoped that a more reasonable price will make a second edition available to a broader readership.

H. Matthaei [NB 383/241 IE]

Essays on Coordination Chemistry. Dedicated to Gerold Schwarzenbach on his 60th Birthday, 15 March, 1964. Edited by *W. Schneider*, *G. Anderegg*, and *R. Gut*. Experientia Supplementum IX, Birkhäuser Verlag, Basel-Stuttgart 1964. 1st Edit., 305 pp., numerous figures and tables, linen, DM 48.– (about $ 12.00).

Gerold Schwarzenbach is one of the most prominent scientists and responsible for significant advances in the modern development of complex chemistry. It is therefore only fitting that the scientific world should mark the special occasion of his sixtieth birthday, and all with an interest in coordination chemistry will certainly appreciate the fact that this was done in the form of an anthology of essays written by outstanding workers in this field.

Most of the 23 articles dedicated to *Schwarzenbach* are directly related in some way to his own work. This can be said in particular of the first contribution by *W. Schneider*, which is an appraisal of *Schwarzenbach*'s research in the field of organic chemistry, if the compounds investigated are considered. Actually, the problems studied were more of a physical-chemical nature, as for example the protogenic properties of organic acids in dependence upon the nature of the substituents. A list of papers published by *Schwarzenbach* up to 1963 is appended to this article.

The main credit due to *Schwarzenbach* is for his work on the chemistry of complexes in aqueous solutions. One of the most important results of this work is complexometry, which is now known to every chemist as an invaluable analytical tool. It is therefore not unwarranted that seven essays deal with the coordination chemistry of aqueous solutions, *e. g. L. G. Sillen*'s article (Thoughts during a Walk in Lappland), the value of which lies in its intimate personal note. Naturally *J. Bjerrum* is not missing among the authors. His essay deals with the behavior of $Hg^{2\oplus}$ towards ethylene diamine in contrast to that of $Ag^{\oplus}$ and frequently touches closely upon *Schwarzenbach*'s own work. The solid state also comes under discussion: *W. Feitknecht* describes the composition and structure of the hydroxide salts of bivalent metals formed during complex-chemical reactions.

Other articles in the book are important for the theoretical treatment of questions in coordination chemistry (problems

concerning the nature of the bonding, and stability problems, particularly in connection with coordination). These include, for example "Die Bedeutung quantenmechanischer Modelle für die Chemie" (the importance of quantum-mechanical models in chemistry) by *H. Hartmann*, "Inorganic Chromophores" by *C. K. Jörgensen*, "The Stabilisation, Stereochemistry, and Reactivity of Five-coordinated Compounds" by *R. S. Nyholm* and *M. L. Tobe*, and the "Structure and Bonding in Transition Metal Complexes of Some Unsaturated Ligands" by *R. Masen* and *G. Wilkensen*.

O. Schmitz-DuMont [NB 333/191 IE]

Chemotaxonomie der Pflanzen (Chemical Taxonomy of Plants). By *R. Hegnauer*. Vol. 3. Dicotyledoneae. Part 1: Acanthaceae-Cyrillaceae. Chemical Series, Vol. 18. Birkhäuser Verlag, Basel-Stuttgart 1964. 1st edit., 744 pp., 14 figs., 17 tables, clothbound DM 123.– (about $ 31.50).

When conservative standards are applied, dicotyledons are divided into about 270 families; 79 of these are discussed in the present volume [1]. The book therefore deals with some 3500 genera comprising about 45000 species. These include some very large families or genera that are important in other connections, including the Compositae, the Apocynaceae, Cruciferae, *etc.* Chemists interested in plant products will therefore want to inspect this volume with careful attention.

The organization of the material within each family discussed corresponds to that used in earlier volumes: first come a short botanical description and the systematic classification, then a summary of important morphological and chemical characteristics, the latter frequently being subdivided according to substance classes, and finally literature references and concluding remarks which contain the essence of the taxonomic features of the plants. Mostly the main chemical constituents of the plants are critically appraised here whenever they appear very frequently in a certain family and are highly typical for it in contrast to other families. In this way, sometimes clear-cut decisions can be made in favor of one or another known system of plants. The dangers of taxonomic classifications based on single substances are emphasized. There are of course many examples of individual chemical compounds that occur sporadically in plants which are definitely not interrelated, *e.g.* lysergic acid derivatives in certain species of Convulvulaceae or Ascomycetes. The reader again observes that extremely widespread and thoroughly investigated materials such as the carotenoids contribute but little to the solution of taxonomic problems.

In contrast to the volumes that have already appeared, on account of the immense amount of material dealt with, the literature and individual compounds have not been comprehensively reviewed. Nonetheless, a great deal of otherwise difficultly accessible literature has been evaluated. The organic chemist will be surprised to find that the formulae shown have again been drawn with complete disregard of the stereochemistry of the compounds concerned. The author indicates many deficiencies in phytochemical research and may thus provide incentives for new research work.

Misprints and factual errors are few; the quality of the paper, print and binding are as usual excellent.

C. H. Eugster [NB 409/266 IE]

The Monosaccharides. By *J. Staněk*, *M. Černy*, *J. Kocourek*, and *J. Pacák*. Academic Press, New York-London, and Publishing House of the Czechoslovakian Academy of Sciences, Prague, 1963. 1st edit., 1006 pp., 40 figs., 64 tables, linen $ 32.–.

An English translation is now available of the book "Monosacharidy" by *J. Staněk* et al. The appearance of this translation is to be welcomed, for now this monograph on a well defined section of carbohydrate chemistry is available to a much larger public. The English edition is not merely a simple translation of the first Czechoslovakian edition; the contents have been considerably reshuffled and extended, producing a great improvement in the book. Moreover, work published up until about 1962 has now also been included.

In the monograph, the most diverse derivatives of this class of substances are described, and their manifold reactions are discussed in detail, often exhaustively. The specialist in this field will therefore gladly take first recourse to this work for rapid orientation. The book is also aimed at satisfying the demands of other chemists associated in part with carbohydrate chemistry in close connection with their own investigations, *e.g.* biochemists and industrial chemists, for here they find a well arranged wealth of information. Numerous tables interspersed between the text give rapid information on the derivatives of the monosaccharides prepared to date. The list of references given has been compiled with especial care. Each chapter contains references to large review articles to facilitate the search for particular details or for original publications. The literature from relatively obscure journals has also been almost completely scanned, and even the specialist may find many a reference he has previously overlooked.

The book contains a short but fully satisfactory chapter for superficial information on the biochemical syntheses and conversions of sugars in biological systems. Further details on this rapidly advancing subject can be found in scientific journals in any case. However, a more extensive treatment of modern investigations into stereochemical topics and reaction mechanisms would have been preferable. Aspects such as conformational analysis, the mechanisms of substitution reactions and the associated questions of stereochemistry and neighboring-group participation, and applications of NMR spectroscopy are at the focus of attention in the carbohydrate field at present and will be studied more intensely in future. These suggestions might be considered for future editions.

The present volume is thus an important source of information for a large circle of users and deserves a place in every chemical library. A second volume on "The Oligosaccharides" has already been announced which ought to provide a supplement to the present book.

H. Paulsen [NB 370/228 IE]

The Proteins. Composition, Structure, and Function. Vol. I. Edited by *H. Neurath*. Academic Press, NewYork-London 1963. 2nd edit., XIII + 665 pp., numerous illustrs. and tables, linen $ 22.–.

The following topics are dealt with in six chapters: 1. "Amino-Acid Analysis of Peptides and Proteins" (*A. Light* and *E. L. Smith*) with an appendix on "Amino-Acid Analysis of Certain Proteins" by *G. R. Tristram* and *R. H. Smith*; 2. "Synthesis and Function of Peptides of Biological Interest" (*K. Hofmann* and *P. G. Katsoyannis*); 3. "Chemical Aspects of Protein Synthesis" (*J. S. Fruton*); 4. "Concepts and Experimental Approaches in the Determination of the Primary Structure of Proteins" (*R. E. Canfield* and *C. B. Anfinson*); 5. "Intramolecular Bonds in Proteins, I. The Role of Sulfur in Proteins" (*R. Cecil*); 6. "II. Non-covalent Bonds" (*H. A. Scheraga*).

The survey shows that the subjects dealt with are arranged less systematically than in the first edition, being aimed more directly at individual acute problems. The subtitle of the book reveals the reason for this selection, namely the coordination of chemical structure and biological function, as is prominently apparent, particularly in the second chapter. Following a discussion of the modern methods of peptide synthesis, their application to the preparation of hypophyseal hormone, angiotensin, bradykinin, and kallidin peptides is described, and the structure-function relationships are illuminated, particularly for the oxytocin-vasopressin group and for the melanophore-stimulating systems. The first chapter is also highly instructive, but a little more emphasis

[1] For reviews of Vols. 1 and 2 see Angew. Chem. *76*, 312 (1964); Angew. Chem. internat. Edit. *3*, 452 (1964).

on chromatography and its auxiliary methods might have been desirable. In the third chapter, a compromise had to be made, for it was impossible to give a detailed treatment of the biochemistry of nucleic acids alongside the discourse on protein biosynthesis, despite the equal importance of both fields. The solution found in the book can be considered ideal; however, since the manuscript was completed in June 1962, a few of the latest important results are missing, because of the rapid current developments in this field.

It is obvious from the fourth chapter that its authors are well familiar with the experimental side of their work; despite the brevity of their essay (61 pp.), it leaves little room for improvement. The same cannot be said without reservation for Chapter five: the discussion of the function of groups containing sulfur in proteins receives too little attention (7 pp. compared with 73 pp. devoted to analytical methods and chemical reactions). Chapter six furnishes a comprehensive review of the statistical thermodynamic theories of non-covalent interactions, with particular emphasis on hydrophobic bonds, and the part played by such phenomena in denaturation, ionization, proteolysis, and association. The reader can derive enormous value from the subject matter in this chapter, but will have to apply almost as much effort in order to work through it. Simplified, easily understandable summaries to each section would be a great help here.

Although the contributions in this first volume of the second edition of the book are of such great value, and although its authors are certainly excellent authorities in their fields, it does not appear to make the first edition completely redundant. It might have been better to publish supplementary volumes instead of a completely new edition. As far as can be judged, the selection of topics for inclusion in the new edition already marks a step in this direction.

F. Turba [NB 360/218 IE]

Introduction to Infrared and Raman Spectroscopy. By *N. B. Colthup, L. H. Daly,* and *S. E. Wiberley.* Academic Press, New York-London 1964. 1st edit., XII + 511 pp., numerous figs. and tables, linen $ 12.–.

Up to the present, it has always been difficult to recommend a single book for conveying an introduction to vibration spectroscopy, because in all the well-known monographs on this topic, either a theory of vibration spectroscopy is developed, or the stress is placed upon experimental or applied technical aspects, or only infrared group frequencies are listed and discussed. In the present introduction, an attempt is made to present all these aspects in a single book, and it must be said, with good success. An introductory chapter is devoted to an elementary treatment of the theory of rotation and vibration spectra, and despite its highly condensed form, all the important concepts are done justice. In the second chapter, the structural elements or infrared and Raman spectrographs and experimental questions are discussed. In a chapter on the classification of molecules, the symmetry properties of molecules are explained, and the group theory is presented up to the point required for comprehension of the classification of normal vibrations. Besides character tables for the point groups, many examples are given of molecules investigated. In the next nine chapters, group frequencies are summarized and discussed in detail. Following a very lucid explanation of the alteration of group frequencies caused by interactions with other vibrations, the characteristic frequencies are given, arranged according to groups. The literature on this material is evaluated up to 1961, sometimes until 1963. In a further chapter, the group frequencies are again given, this time arranged according to spectral regions and together with correlation charts. In addition, the absorption spectra of 624 molecules are given, mostly with indication of the characteristic group frequencies; this greatly facilitates introductions to the analytical applications of vibration spectroscopy. In the final two chapters, a theoretical vibrational analysis and a calculation of the thermodynamic functions with chloroform as an example are given, An extensive author and subject index greatly simplifies the use of the volume.

The book can be recommended to all chemists occupied with any problems in infrared or Raman spectroscopy and to students with interests in this field. It ought to prove an excellent introduction even for those who wish to conduct specialized spectroscopic investigations.

W. Liptay [NB 350/208 IE]

Les Réactions Chimiques dans les Solvants et les Sels Fondus (Chemical Reactions in Solvents and Molten Salts). By *G. Charlot* and *B. Trémillon.* Gauthier-Villars, Paris 1963. 1st Edit., VII + 602 pp., 114 figures, 157 tables, linen, NF 94.– (about $ 20.00).

The rapid advances of inorganic chemistry over the past decades has led to the initiation of new journals and new monograph series devoted to this subject: Journal of Inorganic Chemistry (U.S.A.), Journal of Inorganic and Nuclear Chemistry (U.S.A.), Journal of the Less-Common Metals (England); *A. Cotton*: Progress in Inorganic Chemistry; *H.J.Emeleus* and *A. G. Sharpe*: Advances in Inorganic Chemistry and Radiochemistry. Following the initiative of *A. Chrétien* of the Sorbonne, a journal "Revue de Chimie Minerale" (Reviews of Inorganic Chemistry) and a monograph series "Monographies de Chimie minerale" (Monographs in Inorganic Chemistry), both published by Gauthier-Villars, have been founded in France. This book on the chemistry in non-aqueous solvents and in molten salts forms the first volume of the new monograph series, which promises further volumes on polyanions and polycations, solubility diagrams, contact catalysis, and non-stoichiometric compounds.

In the introduction to the present volume, *A Chrétien* gives a brief review of the development of inorganic chemistry within recent times and points out the directives followed in planning future volumes of the series: only fields which have recently undergone widespread investigations will be dealt with, and particular stress will be laid upon broad literature coverage; on the other hand a critical and lucid picture of the subject under discussion is to be given, so that not only mere literature compilations will result. The present volume adheres rigorously to these general principles. In the first five chapters (158 pp.) general reviews are given of acid-base reactions in weakly and strongly dissociating solvents, of complexes (here including undissociated species such as $CdCl^{\oplus}$ and $CdCl_2$), of redox reactions, and of solubility phenomena. The next ten chapters (420 pp.) deal with individual solvents and contain abundant literature references. Nine of these chapters are devoted to low-melting – mainly organic – solvents, and only the last chapter, which is particularly long, deals with molten inorganic salts. Here a theoretical introduction is given.

The book gives a good survey of the field and will be particularly useful as a work of reference.

W. Klemm [NB 334/192 IE]

Ion Exchange Separations in Analytical Chemistry. By *C. Samuelson.* Almquist & Wiksell, Stockholm-Göteborg-Uppsala, and John Wiley & Sons, New York-London 1963. 2nd edit., 474 pp., numerous illustrs., linen Sw. Kr. 65.– (about $ 12.50).

It is more than ten years since the first well known review of the analytical applications of ion exchangers appeared in its first edition; its title has been altered a little in this second edition. A new edition had become essential in view of the ever increasing number of publications on this subject and because of the enhanced importance of its methods in practice. Although the author himself can look back on many years of experience in this field, he now applies himself to this task with counseling cooperation from a number of experts on the subject, and with highly successful results.

The literature has been completely cited until about 1960/61; Russian and Japanese publications are notably well covered. The subject matter is divided into three main sections, as in the first edition: fundamentals, practical aspects, and applications. Mainly ion exchange resins are dealt with. In the discussion of their applications, in contrast to the treatment in the first edition, the author has now restricted his discourse to inorganic chemistry. This chapter makes up about half of the book and describes the determination of the total salt concentration, removal of interfering ions of opposing charge, inorganic colloids and highly polymeric electrolytes, isolation of trace components, separations of metals, chromatographic separation of anions, and inorganic qualitative analysis.

Since in many of the separations described, recourse must still be taken to original publications, the reviewer thinks it would be better in future editions to introduce tabulated surveys for individual elements or groups of elements. This would leave more room for standard practical procedures, some of which might still have to be developed.

Nonetheless, the nature of the presentation in the text, figures, and tables reveals that the author has full command of the topic of his book. The work can therefore be recommended to all who are occupied in any way with the analytical applications of ion exchangers.

E. Blasius [NB 378/236 IE]

Kinetics of Precipitation. By *A. E. Nielsen.* International Series of Monographs on Analytical Chemistry. Chief editors: *R. Belcher* and *L. Gordon.* Vol. 18. Pergamon Press, Oxford-London-Edinburgh-NewYork-Paris-Frankfurt 1964. 1st edit., X + 153 pp., numerous illustrs., several tables, linen £2.0.0 (about $ 5.50).

This monograph deals with the kinetics of crystal growth in the situation where numerous crystallization nuclei are formed simultaneously, as in most analytical and technical crystallizations. The author has succeeded in covering the whole of this complex field very comprehensively in 12 well arranged chapters. This he achieves by neglecting to give a detailed discourse on the confusingly large variety of experimental reports on this topic and by placing the theoretical aspects in the forefront instead. Experimental results appear only when compared with the results of theory or when used for making premises. The relationships between the formulae are developed lucidly and the most important quantities are often expressed explicitly in various forms. Aspects considered in detail include work of nucleation, frequency of nucleation, diffusion-controlled growth, nucleation-controlled growth, and growth influenced by dislocations, combination of growth mechanisms, homogeneous and heterogeneous nucleation, Ostwald ripening, growth forms, and adsorption. The reviewer considers the last two chapters to be rather weak. Here the relation between equilibrium form and growth form is not quite clear, and that between surface energy and nucleation energy is unfortunately not described correctly. Nevertheless, this condensed and clear presentation of the subject will be of great value to all associated with the kinetics of crystal growth.

H. Heyer [NB 351/209 IE]

Advances in Organic Chemistry. Methods and Results. Edited by *R. A. Raphael, E. C. Taylor,* and *H. Wynberg.* Vol. 4. Interscience Publishers, a Division of John Wiley & Sons, New York-London 1963. 1st edit., VII + 361 pp., numerous tables, linen £5.10.0 (about $ 15.25).

Here *J. Szmuszkovicz* gives the most comprehensive survey to date (113 pp., 282 references) on aminoalkenes and aminodienes with the exception of their *N*-, α-, and β-acyl derivatives. Aspects dealt with include the preparation, physical properties, alkylation, acylation, halogenation, arylation, and reactions with azides, diazonium salts, and sulfonyl chlorides, of this class of compounds. Six practical procedures are appended. The section on "basicity" is misleading, for it centers on the erroneous idea that 1-aminoalkenes are more strongly basic than aminoalkanes. In their well presented review of "Synthetic Methods in the Carotenoid and Vitamin A Fields" (109 pp., 335 refs.), *O. Isler* and *P. Schudel* first describe chain-extension methods and syntheses of symmetrical C_8 to C_{30} intermediates, then the synthesis of carotinoids according to the scheme $C_x + C_y + C_x \rightarrow C_{40}$, dehydration reactions, rearrangements, and oxidations and reductions on the carotinoid skeleton. A table lists information on total syntheses of C_{40} all-*trans*-carotinoids. In the final article, "Coupling of Acetylenic Compounds", *G. Eglinton* and *W. McCrae* review methods for linking two acetylenic compounds to give 1,3-diynes. In addition to the classical symmetrical coupling of acetylenes in the presence of copper salts, much attention is given to the unsymmetrical coupling of one acetylene unit with a bromoacetylene in the presence of Cu_2Cl_2, a technique discovered in 1957. The terse and well arranged presentation is supplemented by extensive tables, 232 references (unfortunately not in alphabetical order), and descriptions of practical preparations.

The literature has been reviewed up to 1961. Addenda indicate the rapid developments in these fields, but also the length of time that has elapsed between submission of the manuscripts and the appearance of the book. This is another successful volume of highest quality and appearance in this admirable series. *G. Opitz* [NB 375/233 IE]

The Ring Index. A List of Ring Systems Used in Organic Chemistry. A Publication of the Chemical Abstracts Service. American Chemical Society, Washington. Supplement I to the 2nd edit. (1957–1959): 1963, XV + 371 pp., linen $ 8.75. Supplement II (1960–1961): 1964, X + 515 pp., linen $ 10.–.

The Ring Index, which appeared in second edition in 1960, is now extended with two supplementary volumes, in which new ring systems described in the literature between January 1st, 1957 and December 31st, 1961 are recorded. As emphasized in the foreword, the two volumes make a claim to absolute completion, thanks to close cooperation with the indexing staff of the Chemical Abstracts Service, and thus not only give reliable information on the all-too-frequently intricate nomenclature, but also indicate whether a ring system is already known or not. Together with the basic volume, the work has thus now catalogued 11524 ring systems. It is therefore hardly necessary to point out its value. Supplement II contains the first index of rings with heteroelements (with the exception of rings having only N, O, and/or S in addition to carbon). It also contains the complete subject index for all three volumes, in which errata are also indicated.

Chemists have become accustomed to expect exceptionally high standards from the Chemical Abstracts Service, and the Ring Index completely fulfils these expectations.

H. Grünewald [NB 361/219 IE]

Techniques for the Use of Radioisotopes in Analysis. A Laboratory Manual. By *D. A. Lambie.* General and Industrial Chemistry Series. Edited by *H. M. Bunbury.* E. and F. N. Spon Ltd., London 1964. 1st edit. VI + 135 pp., numerous figs., linen £2.0.0 (about $ 5.50).

It is the aim of this book to acquaint its readers with the applications of radioactive materials in analytical chemistry and to give some indication of special practical procedures and measuring techniques. The author begins with descriptions of radiometric procedures. Here the accent lies on isotope dilution analysis, the use of radioactive reagents, and activation analysis, less attention being paid, for example, to Hevesy-Paneth analysis, which is so important in biochemistry, pharmacology, and agronomy.

By far the largest portion of the presentation is devoted to introductions to the methods and to the prerequisites for work with radioactive substances. It is emphasized that application of the methods given to solve problems in analytical chemistry demands no or only insignificant radiation precautions, and that thus radiometric work can be done in any well equipped laboratory without any great additional expenditure. It is commendable that data are given for the permissible concentrations and amounts of radioactive wastes that may be present in effluent in England.

It is to be hoped that the book will be read by many analysts, for they will certainly be thankful to the author for his fine presentation, which goes into all the essential points.

H. Götte [NB 363/221 IE]

Practical Optical Crystallography. By *N. H. Hartshorne* and *A. Stuart*. Edward Arnold Publishers Ltd., London 1964. 1st edit., VI + 326 pp., numerous illustrs., linen £2.0.0 (about $ 5.50).

The present volume offers a very comprehensive introduction to the application of crystal optics to the investigation of crystalline structures. Not only are experimental methods discussed, but the fundamentals of geometrical optics and crystallography are also dealt with. However, the treatment in some parts assumes dimensions that are no longer in keeping with the prime purpose of the book. For example, allocation of 30 pages to crystal morphology tends to overemphasize this topic. The same may be said of the presentation of structural theory, which is also rather subjective in nature. On the other hand, a section is lacking which goes into more detail on the relation between crystal optics and crystalline structure. The book does not place high demands on the background of its reader and should therefore serve students well as an introduction to the subject. All the important methods for examining crystals with the polarization microscope are presented, but U-table methods are omitted.

The book contains some elementary errors. For example, on pp. 37 and 98 it is stated that crystals with mirror planes cannot be optically active, but every textbook of crystal physics quotes m, mm 2, and $\bar{4}2$ m as crystal classes in this category which may possess optical activity. Recent publications on the treatment of the Becke line are overlooked; this phenomenon is now known to be an effect of diffraction optics rather than of geometric optics.

Apart from these flaws, the new book offers a most useful opportunity for becoming acquainted with the fundamentals of geometrical crystal optics. The theoretical fundamentals should be improved in a later edition.

H. Jagodzinski [NB 347/205 IE]

Surface Properties of Silicate Glasses. By *G. Korányi*. Akadémiai Kiadó, publisher for the Hungarian Academy of Sciences, Budapest 1963. 1st edit., 104 pp., 39 figs., linen DM 15.20 (about $ 3.90).

Almost simultaneously with *L. Holland*'s book on "The Properties of Glass Surfaces", this short monograph by the Hungarian author on the same topic has appeared. It can be appreciated just how much literature is available today on the physical and chemical properties of glass surfaces from the fact that apart from the numerous articles reviewed by both authors, there are many publications which are dealt with in only one or the other of the two books. In *Koranyi*'s work, these are mainly numerous contributions from the eastern hemisphere and about 200 patents, which indicate his preferential consideration of technological aspects. The presentation is terse, despite the abundance of the literature reviewed, but often the personal opinions and experiences of the author shine through. The content is divided up as follows. 1. Morphology of glass surfaces (as a result of mechanical or chemical processing); 2. surface hardness; 3. sorption properties compared with liquid, dissolved, and gaseous materials – coating of glass surfaces for technical improvement; 4. wetting properties and adhesion; 5. and 6. surface conductivity and interactions with electrons and ions; 7. dealkalization and leaching.

The book provides a good survey of the complete field for the practical worker and is also a useful vade-mecum for the specialist.

H. Schröder [NB 348/206 IE]

Spectrometric Identification of Organic Compounds. By *R. M. Silverstein* and *G. C. Bassler*. John Wiley & Sons, Inc., New York-London 1963. 1st edit., 177 pp., linen $ 8.60.

Mass spectrometry, proton magnetic resonance spectroscopy, and infrared and ultraviolet spectroscopy are invaluable aids in organic chemistry nowadays. Every chemistry student becomes acquainted with the fundamentals of these methods during his studies, but this is generally not enough. More exercises in the practical applications of these methods to chemical problems should be included in study courses than has hitherto been the case. A relatively easy way in which an important step in this direction can be taken is revealed in this book by *Silverstein* and *Bassler*, which provides an excellent guide to the interpretation of the spectra of organic compounds.

The book contains only the basic essentials of the theory and of the instrumental techniques of mass spectrometry, and infrared, ultraviolet, and proton magnetic resonance spectroscopy. However, adequately detailed data on the relationships between the spectra and molecular structure are given for each method, and the main stress is laid upon empirical facts and the information that is of use for practical application.

In the second part of the book, twenty examples are taken to illustrate with a detailed discussion how the mass, PMR, infrared, and ultraviolet spectra of various types of organic substances (containing the elements C, H, O, N, S, and halogens, with molecular weights of up to 250) can be used without elemental analysis and without any other chemical information to derive the structural formulae of the compounds in question. Naturally one cannot expect to obtain such definitive structural knowledge from the spectra of all compounds, but the examples demonstrate impressively just how much information can be derived from exhaustive interpretation of spectra alone – especially mass spectra. For ten further substances, only the spectra are given; their appraisal is left to the reader, who can however check his conclusions by consulting Beilstein's handbook, for references for the pertinent compounds are given. The last ten examples are given without such references. Anyone who works through these 40 examples with care, even if he does not perhaps find all the correct answers, will have learned something of great importance, namely, routine in dealing with spectra, and this, together with the information given in the first part of the book, will aid him immensely in the solution of other problems.

There are of course more complete, more systematic, and, as far as details are concerned, even more competent books on each of the methods dealt with here, even on their practical application in organic chemistry. However, the present volume is outstanding in that it is a book for learning and for practice which teaches with method and in a minimum of space how to combine all four techniques. This approach seems to be of great importance at a time when the trend towards specialization has brought about the situation where an expert on mass spectrometry, for instance, cannot be an authority on proton magnetic resonance. Only the mutual support of the individual methods increases their efficiency to the extent that affords the greatest value to the organic chemist interested in structural problems.

The Silverstein-Bassler monograph can be highly recommended to any student interested in these topics and above all, to lecturers and demonstrators for use in practical classes and seminars.

H. A. Staab [NB 408/268 IE]

Subject Index

for the conference report "Meeting of South-West German Chemistry Lecturers" on p. 697 of this issue.
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The Formula of Benzene

A Short History of the Problem

BY PROF. DR. H. HARTMANN

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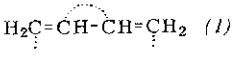
In 1865, while he was Professor at Ghent, *August Kekulé* published two papers dealing with aromatic compounds [1]. In the second of these, the now familiar hexagonal symbol made its first appearance, although the lines indicating double bonds were omitted. These were first incorporated in a third paper [2] on aromatic compounds published in 1872.

In the earlier paper in the Annalen, *Kekulé* referred to the benzene molecule as a "closed chain" or a "symmetrical ring". His proof was based on the observation of isomerism. It is remarkable that the absence of the "extra" isomers, which would be expected if the double bonds were fixed, was not found to be disturbing. Although *Kekulé* emphasized that his benzene theory was based on the "atomicity of the elements", like a true theorist he regarded the concept of "atomicity" simply as a heuristic tool, and when the use of this tool had led him to the theory of the six-membered ring, he set about trying to find experimental proof of this theory. Pedantic objections arising only from the original hypothesis were brushed aside. The question of the extra isomers to be expected if the double bonds were fixed is discussed in detail only in the second paper in the Annalen (1872). The first paper in the Annalen dealt mainly with the problem of the equivalence of the six hydrogen atoms. *Kekulé* also showed himself to be a true theorist in another particular. Unlike his contemporaries, as well as too many of those who followed, he recognized a more comprehensive system into which chemical phenomena can be classified. He wrote: "Although we still lack a truly mechanical concept in chemistry, it nevertheless seems to me that a mechanical approach must and can, in our present state of knowledge, at least be sought." *Kekulé*'s benzene formula has since proved to be one of the most valuable contributions to organic chemistry. In one respect, however, it was and still is unsatisfactory: the relatively saturated, specifically aromatic character of benzene could not be explained in terms of *Kekulé*'s scheme.

[1] *A. Kekulé*, Bull. Soc. chim. *1*, 98 (1865); Ann. Chem. Pharmac. *137*, 129 (1865).

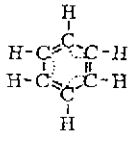
[2] *A. Kekulé*, Ann. Chem. Pharmac. *162*, 77 (1872).

In order to explain the usual, but by no means universal, 1,4 mode of addition to butadiene, *J. Thiele* [3] developed the idea of residual or partial valences, which, under suitable environmental conditions, can be saturated in the same way as normal valences. Residual valences are pictured as arising when the second bond of a double bond does not exhaust the combining power of the atoms involved. According to *Thiele*, butadiene should be formulated as *(1)*. The application of the idea of



(1)

partial valences to the benzene molecule leads us to the formulation *(2)*. Thus *Thiele*'s benzene formula eliminates, or at least covers up, the most glaring deficiency



(2)

of *Kekulé*'s formulation.

With the advent of quantum mechanics, all the requirements for the application of *Kekulé*'s "mechanical approach" in chemistry were satisfied. *Heitler* and *London* [4] showed in 1927, for the example of the hydrogen molecule, that the puzzling phenomenon of covalence can be explained in mechanical terms. Since then "quantum chemistry" has developed in two forms. The object of absolute quantum chemistry is the physical treatment of real molecules. It is only in the simplest cases, however, which are today of little interest to chemists, that this treatment yields results which are at all reliable, since even the simplest atomic and molecular systems are so complicated that approximations have to be made in the calculations. A fundamentally different procedure is used in the quantum chemistry of models [5]. Models are invented to represent the molecules of a class of substances, and the models are then subjected to the quan-

[3] *J. Thiele*, Liebigs Ann. Chem. *306*, 87 (1899).

[4] *W. Heitler* and *F. London*, Z. Physik *44*, 455 (1927).

[5] *H. Hartmann*, S.-Ber. wiss. Ges. Univers. Frankfurt/Main *2*, 5 (1963).

tum-theoretical treatment. Since the models themselves do not occur in nature, they cannot be discovered, but invented models can be more or less useful.

E. Hückel's great contribution to the problem was that he found an eminently suitable model for benzene and related substances. *Hückel* divided the electron system of the molecule in question into so-called σ electrons and π electrons. In his quantum-theoretical treatment [6], he made use of two approximation methods known at that time. One method that proved particularly useful had been developed by *F. Hund* [7], and represents molecular orbitals (MO) by linear combinations of atomic orbitals (LCAO method). In the "second approximation method" used by *Hückel*, the interaction of the π-electrons with one another is represented by an equivalent field. Thus this theory, which is now known as the HMO theory after *Hückel*, has the particularly simple form of a "one-electron theory"; this means that it assumes the existence of molecular orbitals which are occupied (Aufbau principle) by the π electrons (in accordance with the Pauli principle).

The HMO theory comprises a topological part and an energy part. The word "topological" here means that this part of the theory is concerned only with concepts relating to environmental situations of the C atoms in the molecule. The energies ε_i assigned to the molecular orbitals (MO) denoted by the subscript i can be calculated from the so-called Hückel numbers ρ_i of the orbitals by means of the equation:

$$\varepsilon_i = f(\rho_i) \qquad (a)$$

using a function f which is characteristic of all π-electron systems. The Hückel numbers are the roots of the algebraic equation:

$$| t_{jk} + \rho \cdot \delta_{jk} | = 0 \qquad (b)$$

The left-hand side is a determinant in which the number of rows and columns is equal to the number of C atoms with π-electrons in the molecule. Suppose that these atoms are arbitrarily but permanently denoted by the numbers j and k.

Here $\delta_{jk} = 1$ when $j = k$; otherwise $\delta_{jk} = 0$. Furthermore, $t_{jk} = 0$ when $j = k$; $t_{jk} = 1$ when the j-th atom and the k-th atom are neighbors; when the j-th atom and the k-th atom are further apart, $t_{jk} = 0$.

Equation (b) for benzene becomes:

$$\begin{vmatrix} \rho & 1 & 0 & 0 & 0 & 1 \\ 1 & \rho & 1 & 0 & 0 & 1 \\ 0 & 1 & \rho & 1 & 0 & 0 \\ 0 & 0 & 1 & \rho & 1 & 0 \\ 0 & 0 & 0 & 1 & \rho & 1 \\ 1 & 0 & 0 & 0 & 1 & \rho \end{vmatrix} = 0$$

or after expansion of the determinant:

$$\rho^6 - 6\rho^4 + 9\rho^2 - 4 = 0 \qquad (c)$$

This equation has the roots

$$\rho_1 = 2 \qquad \rho_4 = -1$$
$$\rho_2 = 1 \qquad \rho_5 = -1 \qquad (d)$$
$$\rho_3 = 1 \qquad \rho_6 = -2$$

Thus according to Equation (a), orbitals 2 and 3 have equal energies, as do orbitals 4 and 5.

The characteristic function f was given by *Hückel* as:

$$\varepsilon = \alpha - \rho\beta \qquad (e)$$

where α and β are parameters having the dimensions of energies. Since $\beta > 0$, orbitals for which ρ is positive have low energies and *vice versa*. The graph of the Hückel characteristic function is a straight line with a negative gradient (Fig. 1).

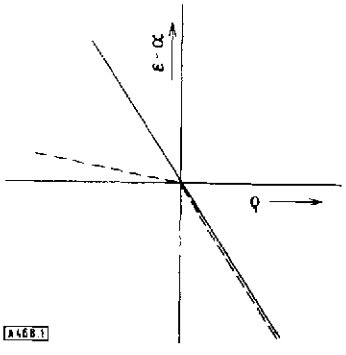


Fig. 1. Graph of the Hückel function $\varepsilon = \alpha - \rho\beta$. Full line: calculated. Broken curve: probable course on the basis of theoretical considerations [8].

The energy diagram of the molecular orbitals as found from Equations (c) and (d) is shown in Figure 2a. The distribution of the six π-electrons over the molecular orbitals in the ground state is also shown. Comparison of the diagram with the analogous diagram for *e.g.* the neon atom (Fig. 2b) reveals that the benzene molecule, like rare-gas atoms, has a "closed electron shell". This is therefore connected with the fact that the "breaking open" of the π-electron system to enable an addition reaction requires a high energy, and so provides an easy explanation of the aromatic character of benzene.

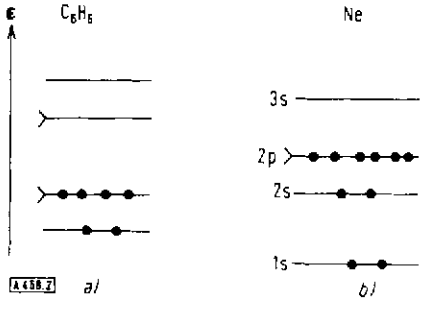


Fig. 2. Energies (ε) of the molecular orbitals (a) in benzene and (b) in the neon atom (diagrammatic).
The dots represent the electron distribution in the ground state.

Since the Hückel theory is made up of a topological part and an energy part, and since the important, *i.e.* qualitative, results of the theory are determined almost exclusively by the topological Hückel numbers ρ_i, the

[6] *E. Hückel*, Z. Physik *60*, 423 (1930); *70*, 204 (1931); *72*, 310 (1931); *76*, 628 (1932).

[7] *F. Hund*, Z. Physik *51*, 759 (1928); *63*, 719 (1929).

[8] *H. Hartmann*, Z. Naturforsch. *15a*, 993 (1960); *E. Ruch*, *ibid.* *16a*, 808 (1961); *H. Hartmann*, Adv. chem. Physics *5*, 1 (1963).

energy part of the theory, *i.e.* the characteristic function f, can be changed without essentially altering the results. Theoretical considerations suggest that f should follow the course shown by the broken curve in Figure 1 [8]. It is possible in this way to describe other observations, such as the Scheibe phenomenon [9], in terms of *Hückel*'s one-electron theory of the π-electron system.

The development of the benzene theory from *Kekulé* to *Hückel* is an inspiring chapter of chemical history. It is characterized by an intimate combination of experimental chemical ingenuity and a mechanical approach.

[9] *i.e.* the observation that the difference of the ionization potential and the first excitation energy is the same for many aromatic hydrocarbons.

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1,2-Dehydrobenzene [*]

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The historical development of the methods to generate dehydrobenzene is outlined. Dehydrobenzene readily adds nucleophilic as well as electrophilic partners. Diels-Alder addition to dienes is moreover a valuable synthetic principle. The intermediacy of dehydrobenzene has been proved for polar additions by labeling with ^{14}C or with a substituent. The same conclusion has been reached in Diels-Alder additions by competition experiments. The considerable selectivity displayed by dehydrobenzene in both types of reaction is not caused by solvation, since recently the existence of dehydrobenzene in the gas phase has been established, where it reacts similarly as in solution.

I. Introduction

In the first volume of his textbook "Organische Chemie" [1], published in 1861, *August Kekulé* wrote: "Apart from the laws of constant and multiple proportions..., chemistry as it stands has established no laws with certainty. We have no precise knowledge regarding the cause of the difference among the elements, the nature of the force that gives rise to chemical compounds, the laws that govern chemical metamorphoses, *etc*... Thus we cannot yet speak in chemistry of a real *theory*. All so-called theoretical considerations are simply considerations of *probability* and *convenience*. Deduced from a large number of facts, and found to apply to others, they must be regarded for the present as expressions approaching fact, but not as established fact."

This conveys the impression that chemistry 100 years ago was like a building site on which were piled roughhewn stones, which the as yet absent architect was to fit together. *Kekulé* was the master builder who, with the structural theory which he expounded in the same book, laid down the objective of "seeking a point of view which fits the largest number of facts with a minimum of difficulty, which represents the chemical processes as simply and as completely as possible, and which, while perhaps not explaining these processes, at least gives a reasonably clear picture of them."

The structural theory first molded by *Kekulé* from the principle of economy of thought, and which a few years later encompassed the structure of benzene, contributed decisively to the rapid development of organic chemistry. Of equal importance in inorganic chemistry is *Alfred Werner*'s theory of coordination compounds, which brought together a bewildering profusion of experimental observations and placed them on a common and at that time bold conceptual basis. Both concepts have condensed from the original speculative stage to well-knit theories, which although subsequently refined and extended, could not be refuted, and which, as we see today, have together helped to open up the common field of organic and inorganic chemistry.

It is not my intention to trace the effects of the benzene structure conceived by *Kekulé* in 1865 on the development of the chemistry of aromatic compounds. We shall consider only one branch of this tree of development, relating to a derivative of benzene, formally obtained by removal of two *ortho* hydrogen atoms from the aromatic ring, and which I accordingly call dehydrobenzene. The justification for speaking about this compound here at the Kekulé Celebration is that the six-membered aromatic ring remains intact in the new type of compound; moreover, this intermediate which, unlike benzene, cannot be isolated, has in the past few decades given fresh impetus to aromatic chemistry and to the investigation of short-lived intermediates which can be detected only by indirect evidence.

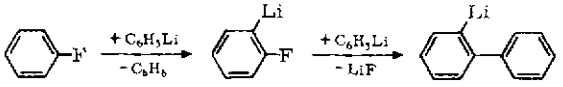
[*] From a lecture at the Kekulé Celebration in Bonn on September 15th, 1965.

[1] *A. Kekulé*: Organische Chemie. Verlag Friedrich Enke, Erlangen 1861, p. 95.

II. History of the Discovery of Dehydrobenzene

A C_6H_4 species as an intermediate in certain aromatic reactions has repeatedly been suggested [2], but the idea was neither substantiated nor pursued further. The first attempt to classify a large body of experimental facts relating to organometallic reactions by the postulated intermediate formation of dehydrobenzene was made at Freiburg [3] in 1940.

The surprisingly fast formation of biphenyl from phenyllithium and fluorobenzene, compared to the reactions with the other three halogenobenzenes, was explained by assuming that, owing to the strong inductive effect of the fluorine substituent, the *ortho* hydrogen is particularly readily displaced by the lithium atom, and the *o*-fluorolithiobenzene *(1)* reacts with the phenyl-lithium still present.



(1) *(2)*

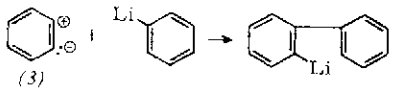
The expected *o*-lithiobiphenyl *(2)* was detected as 9,9-diphenylfluorene by reaction with benzophenone to form the corresponding carbinol, followed by ring closure. Since it was shown that biphenyl does not form a lithium compound under the conditions of the reaction, the rapid formation of biphenyl from fluorobenzene and phenyl-lithium was apparently explained.

It was still puzzling, however, why the fluorine attached to the aromatic nucleus becomes so reactive after the replacement of an *ortho* proton by a lithium cation. The key to the problem was provided by our further discovery [4] that olefinic halides such as ω-chlorostyrene are readily converted into acetylene derivatives by organolithium compounds. This process was interpreted as resulting from the introduction of metal into the β-position, followed by the elimination of lithium halide:

$$C_6H_5\text{-}CH{=}CH\text{-}Cl + 2\ C_6H_5Li \rightarrow C_6H_5\text{-}C{\equiv}C\text{-}Li + 2\ C_6H_6 + LiCl$$

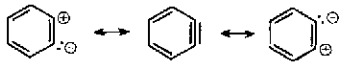
In applying the substitution-elimination mechanism to aromatic halides, it was postulated [5] that the formation of a halogenobenzene anion leads to the elimination of the fluoride ion, and that the intermediate dehydrobenzene *(3)*, in its dipolar form, combines with the nucleophilic phenyl-lithium to form the observed *o*-lithiobiphenyl *(2)*.

This explanation agreed with the fact that it was not possible to detect *o*-lithiohalogenobenzene at that time, *e.g.* as its adduct with benzophenone [*].



(3) *(2)*

The resonance of dehydrobenzene (which favors the elimination of metal halide, owing to the associated decrease in energy) should, according to this interpretation, lead to equivalence of the dehydrogenated ring atoms, so that nucleophilic addition should lead to the formation of isomers. However, we found no experimental support for this conclusion [6]. Although we did find clear indications of the existence of the



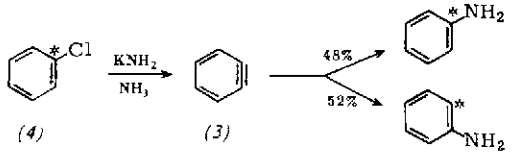
(3)

short-lived, electrophilic dehydrobenzene, which were supplemented by the results of reactions between halogenobenzenes and phenyl-lithium in the presence of tertiary amines (to be discussed later), we had no proof.

III. Evidence of the Occurrence of Short-Lived Dehydroaromatic Compounds

a) Dehydrobenzene in Solution

The first convincing arguments for the occurrence of dehydrobenzene arose from work carried out by *Roberts* and co-workers in Pasadena [7], who independently demonstrated the equalization effect in 1953. In the reaction of [1-^{14}C]-chlorobenzene *(4)* with potassium amide in liquid ammonia, they obtained both of the expected labelled anilines in approximately 50 % yields.



(4) *(3)*

The name "aryne" proposed by *Roberts et al.* for their postulated intermediate seems unfortunate, since this term specifies the presence of a normal C–C triple bond [cyclohexadienyne *(3)*], against which, however, on the basis of *Kekulé*'s benzene structure, one could with equal justification propose a triply cumulated system of double bonds [cyclohexatetraene *(5)*].

(3) *(5)*

[2] Cf. *W. E. Bachmann* and *H. T. Clarke*, J. Amer. chem. Soc. *49*, 2089 (1927); *A. A. Morton*, *J. B. Davidson*, and *B. L. Hakan*, J. Amer. chem. Soc. *64*, 2242 (1942); *R. Stoermer* and *B. Kahlert*, Ber. dtsch. chem. Ges. *35*, 1633 (1902); *A. Lüttringhaus* and *G. v. Sääf*, Liebigs Ann. Chem. *542*, 250 (1939).

[3] *G. Wittig*, *G. Pieper*, and *G. Fuhrmann*, Ber. dtsch. chem. Ges. *73*, 1193 (1940).

[4] *G. Wittig* and *H. Witt*, Ber. dtsch. chem. Ges. *74*, 1480 (1941); *G. Wittig* and *G. Harborth*, *ibid.* *77*, 306, 316 (1944).

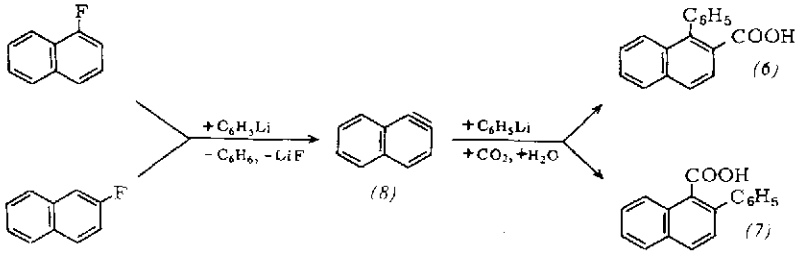
[5] *G. Wittig*, Naturwissenschaften *30*, 696 (1942).

[*] *H. Gilman* and *R. D. Gorsich* [32] later succeeded in intercepting intermediates of this kind at low temperatures.

[6] *G. Wittig* and *G. Fuhrmann*, Ber. dtsch. chem. Ges. *73*, 1197 (1940); *R. Huisgen* and *H. Rist*, Liebigs Ann. Chem. *594*, 143 (1955).

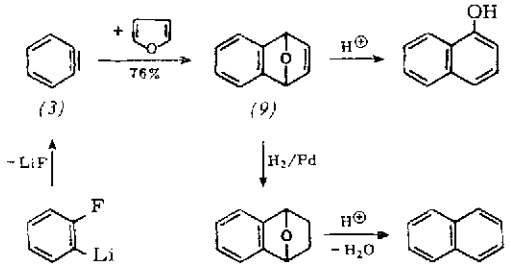
[7] *J. D. Roberts*, *H. E. Simmons*, *L. A. Carlsmith*, and *C. W. Vaughan*, J. Amer. chem. Soc. *75*, 3290 (1953); *J. D. Roberts*, *D. A. Semenow*, *H. E. Simmons*, and *L. A. Carlsmith*, *ibid.* *78*, 601 (1956).

In 1954, *Huisgen* and *Rist* [8] in Tübingen reported an investigation in which they had treated 1- and 2-fluoronaphthalenes with phenyl-lithium; after carboxylating the reaction mixture, they obtained 1-phenyl-2-naphthoic acid *(6)* together with the isomeric 2-phenyl-1-naphthoic acid *(7)*.

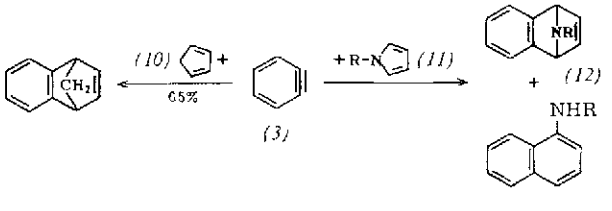


This discovery supplemented *Roberts*' results, since it shows that this reaction also proceeds *via* a short-lived intermediate, namely 1,2-dehydronaphthalene *(8)*.

Wittig and *Pohmer* [9] argued on an entirely different basis, contending that dehydrobenzene should react as a dienophile. They treated *o*-bromofluorobenzene with lithium amalgam in furan, which as an ether should promote organometallic reactions, and as a diene should intercept the dehydrobenzene formed *in situ* by a Diels-Alder reaction. The product isolated was the endoxide *(9)*, the structure of which was confirmed *inter alia* by acid-catalysed isomerization to α-naphthol, hydrogenation and subsequent dehydration to naphthalene.



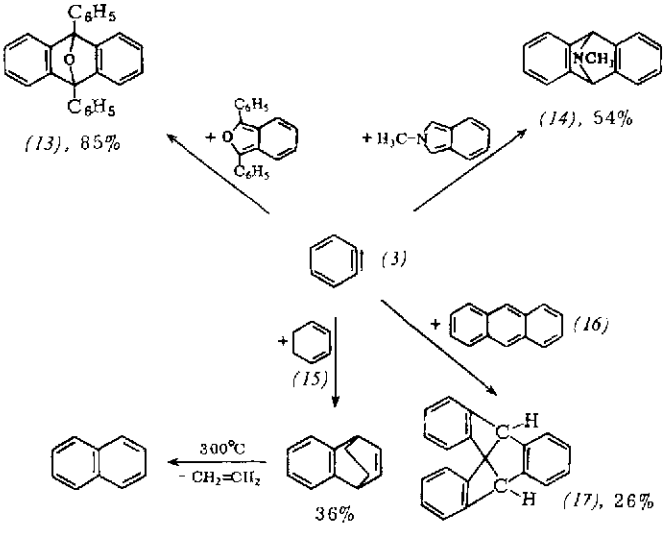
Similar diene additions to dehydrobenzene have also been observed in the presence of pyrrole derivatives *(11)* [10] and cyclopentadiene *(10)* [11].



During the reaction, the unstable endamine derivatives *(12)* are largely converted into the isomeric naphthylamines and to carbazoles.

Dehydrobenzene, generally produced from *o*-bromofluorobenzene and magnesium in boiling tetrahydrofuran, has been used in the synthesis of new heterocyclic systems, such as *(13)* and *(14)* [12]:

In analogy with the Diels-Alder reaction of dehydrobenzene with cyclohexadiene *(15)* [13], anthracene *(16)* has been converted in the same way into triptycene *(17)* [14].



A variant of the formation of dehydrobenzene from fluorobenzene and phenyl-lithium has proved advantageous in this case. The concentration of the phenyl-lithium is buffered to a very low value by the reversible formation of the ate complex with pentaphenylantimony, so that the addition of phenyl-lithium to dehydrobenzene no longer competes with

$$\mathrm{Li\,[Sb(C_6H_5)_6]} \rightleftharpoons (\mathrm{C_6H_5})_5\mathrm{Sb} + \mathrm{C_6H_5Li}$$

the addition of anthracene, and triptycene is formed in 26 % yield [15].

Cycloadditions of this type were later used as a test for the occurrence of short-lived dehydroaromatics in the course of reactions. New routes to dehydrobenzene not involving organometallic compounds were thus found. A significant example is the thermolysis of benzenediazonium *o*-carboxylate *(18)* investigated by

[8] *R. Huisgen* and *H. Rist*, Naturwissenschaften *41*, 358 (1954); Liebigs Ann. Chem. *594*, 137 (1955).

[9] *G. Wittig* and *L. Pohmer*, Angew. Chem. *67*, 348 (1955); Chem. Ber. *89*, 1334 (1956).

[10] *G. Wittig* and *W. Behnisch*, Chem. Ber. *91*, 2358 (1958); *G. Wittig* and *B. Reichel*, *ibid. 96*, 2851 (1963).

[11] *G. Wittig* and *E. Knauss*, Chem. Ber. *91*, 895 (1958).

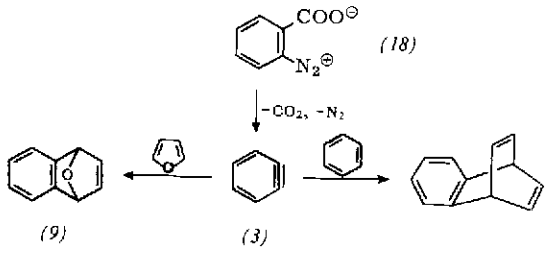
[12] *G. Wittig*, *W. Stilz*, and *E. Knauss*, Angew. Chem. *70*, 166 (1958); *G. Wittig*, *E. Knauss*, and *K. Niethammer*, Liebigs Ann. Chem. *630*, 10 (1960).

[13] *E. Knauss*, Dissertation, Universität Tübingen, 1957; cf. *G. Wittig* and *H. Dürr*, Liebigs Ann. Chem. *672*, 55 (1964).

[14] *G. Wittig* and *R. Ludwig*, Angew. Chem. *68*, 40 (1956); Organic Syntheses. Wiley, New York 1959, Vol. 39, p. 75.

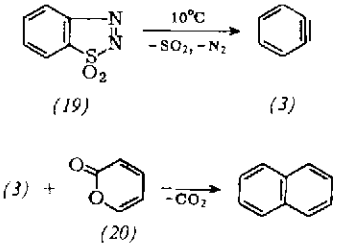
[15] *G. Wittig* and *E. Benz*, Tetrahedron *10*, 37 (1960).

Stiles and *Miller* [16], which in boiling furan leads to the endoxide *(9)*. The high dienophilic activity of dehydrobenzene, which is even capable of adding on benzene [17], is manifested in this reaction.



(18) *(9)* *(3)*

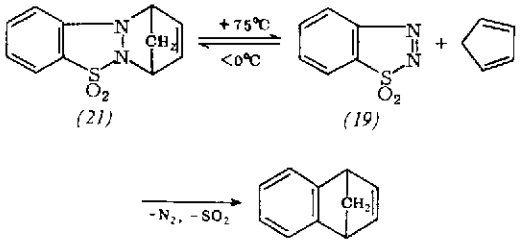
A related procedure is that developed by *Wittig* and *Hoffmann* [18] for the generation of dehydrobenzene from benzothiadiazole dioxide, which exists as the heterocyclic system *(19)*, and not as a betaine. Dehydrobenzene reacts with the lactone *(20)* to form naphthalene with the elimination of CO_2.



(19) *(3)* *(20)*

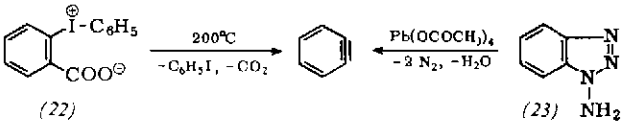
With the aid of the compound *(19)* and its derivatives, which already decompose at room temperature, it is possible to study the behavior of dehydroaromatics under mild conditions, as will be discussed later.

At temperatures below 0 °C, *(19)* reacts with cyclopentadiene to form the adduct *(21)*, which can be isolated, and which dissociates into its components at 75 °C by a retrodiene reaction. The resulting dehydrobenzene is captured by the cyclopentadiene as 1,4-dihydro-1,4-methanonaphthalene.



(21) *(19)*

Temperatures up to 200 °C are required for the formation of dehydrobenzene from the iodonium compound *(22)* [19], whereas room temperature suffices in the oxidation of *N*-aminobenzotriazole *(23)* with lead tetraacetate in benzene [20,21]. The addition of 1,2,3,4-tetraphenyl-1,3-cyclopentadienone to dehydrobenzene leads to the elimination of CO and formation of 1,2,3,4-tetraphenylnaphthalene.

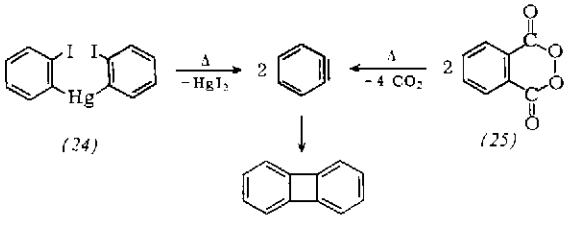


(22) *(23)*

Huisgen and *Knorr* [22] also used cycloadditions to prove the intermediate formation of dehydrobenzene. These authors treated dehydrobenzene, formed from *o*-bromofluorobenzene and magnesium in tetrahydrofuran, simultaneously with furan and cyclohexadiene, and found the competition constant of the simultaneous Diels-Alder additions to be $K \approx 20$. Since this agreed closely with the competition constants obtained for the liberation of dehydrobenzene from benzenediazonium *o*-carboxylate *(18)* and from benzothiadiazole dioxide under comparable conditions, it follows that the same intermediate, *i.e.* dehydrobenzene, reacts in all the above examples.

b) Dehydrobenzene in the Gaseous State

Experiments carried out by *Wittig* and *Ebel* [23], in which biphenylene was formed by the decomposition of bis-*o*-iodophenylmercury *(24)* or of phthaloyl peroxide *(25)* under reduced pressure of argon at 600 °C, show that dehydrobenzene without a solvation sheath, *i.e.* in the gaseous state, also exists for short periods.



(24) *(25)*

When furan was passed in behind the decomposition zone, α-naphthol resulted from the further reaction of the initially formed 1,4-dihydro-1,4-oxidonaphthalene *(9)*. *Ebel* and *Hoffmann* [24] determined a maximum lifetime of 20 msec for dehydrobenzene under these conditions.

By a combination of flash photolysis and mass spectrometry, *Berry et al.* [25] found that the decomposition of benzenediazonium *o*-carboxylate *(18)* yields only dehydrobenzene (m/e = 76), N_2 (28), and CO_2 (44). The peak at m/e = 76 reaches a maximum when the ultraviolet spectrum contains a broad absorption at 2430 Å, which is assigned to dehydrobenzene. This gives way to the spectrum of biphenylene, which is observed in the mass spectrum at m/e = 152.

[16] *M. Stiles* and *R. G. Miller*, J. Amer. chem. Soc. *82*, 3802 (1960).

[17] *R. G. Miller* and *M. Stiles*, J. Amer. chem. Soc. *85*, 1798 (1963).

[18] *G. Wittig* and *R. W. Hoffmann*, Chem. Ber. *95*, 2718 (1962).

[19] *E. LeGoff*, J. Amer. chem. Soc. *84*, 3786 (1962); *F. M. Beringer* and *S. J. Huang*, J. org. Chemistry *29*, 445 (1964).

[20] *C. D. Campbell* and *C. W. Rees*, Proc. chem. Soc. (London) *1964*, 296. The mechanism of the process is similar to that of the preparation of cycloalkynes by the photolysis of tosylaminotriazole anions, as described by *F. G. Wiley*, Angew. Chem. *76*, 144 (1964); Angew. Chem. internat. Edit. *2*, 138 (1964).

[21] For the detection by cycloaddition of dehydrobenzene produced in other ways, see *J. I. G. Cadogan* and *P. G. Hibbert*, Proc. chem. Soc. *1964*, 338; *G. Cainelli*, *G. Zubiani*, and *S. Morrocchi*, Chim. e Ind. *46*, 1489 (1964); *R. F. C. Brown* and *R. K. Solly*, Chem. and Ind. 1965, 181.

[22] *R. Huisgen* and *R. Knorr*, Tetrahedron Letters *1963*, 1017.

[23] *G. Wittig* and *H. F. Ebel*, Liebigs Ann. Chem. *650*, 20 (1961); cf. also *H. Günther*, Chem. Ber. *96*, 1801 (1963); *I. P. Fisher* and *E. P. Lossing*, J. Amer. chem. Soc. *85*, 1018 (1963).

[24] *H. F. Ebel* and *R. W. Hoffmann*, Liebigs Ann. Chem. *673*, 1 (1964).

[25] *R. S. Berry*, *G. N. Spokes*, and *M. Stiles*, J. Amer. chem. Soc. *84*, 3670 (1962); *R. S. Berry*, *J. Clardy*, and *M. E. Schafer*, *ibid.* *86*, 2738 (1964).

IV. Structural Problems

Whereas the structure of the C_6H_4 fragments produced from 1,3- and 1,4-benzenediazonium carboxylates is not yet known [26], all the evidence available indicates

(3b) *(3a)* *(3c)*

that the bonding in 1,2-dehydrobenzene is probably described by the resonance *(3b)* ↔ *(3a)* ↔ *(3c)* [27].

With retention of the aromatic 6 π-electron system, the sp^2 orbitals freed by removal of two *ortho* substituents, which are coplanar with the benzene ring, will overlap as indicated in *(3a)*. The energy gained facilitates the elimination of metal halide from *o*-lithiohalogenobenzene to form dehydrobenzene. Owing to the ring strain in dehydrobenzene, however, the overlap can only be slight in comparison with the overlap in acyclic acetylenes, explaining the enhanced dienophile reactivity of the dehydro bond.

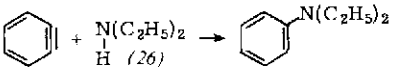
The relative weakness of the dehydro bond, however, also explains its susceptibility to attack by nucleophiles such as phenyl-lithium, which intercepts dehydrobenzene as *o*-lithiobiphenyl, as described earlier. The polarizability of the dehydro bond makes possible a rearrangement to the dipolar limiting form *(3a)* or *(3b)* in the transition state by approaching reactants [28].

V. Dehydroaromatic Compounds as Electrophiles and Nucleophiles

The pronounced electrophilic character of dehydroaromatic compounds has been confirmed in numerous investigations, of which some examples will now be given.

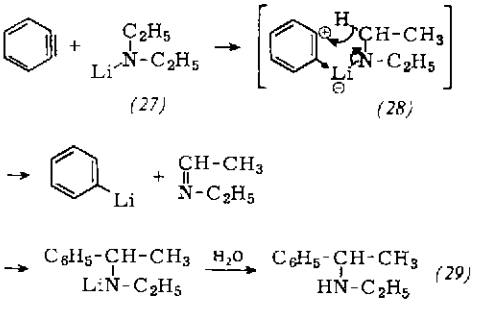
Lithium piperidide or phenyl-lithium add smoothly to dehydrobenzene to form *N*-phenylpiperidine or biphenyl, as was found by *Huisgen et al.* [29]. These authors concluded from the competitive addition of *e.g.* lithium piperidide and phenyl-lithium that the selective intermediate for which these nucleophiles are competing is short-lived "benz-yne."

The complexity of these reactions can be seen *inter alia* from work carried out by *Wittig*, *Schmidt*, and *Renner* [30], who found that the reactions of fluorobenzene with lithium diethylamide and with diethylamine *(26)* give widely varying yields of diethylaniline and α-phenyldiethylamine, depending on the molar ratio of the reactants. It was shown that the free amine probably takes part in the formation of diethylaniline, while



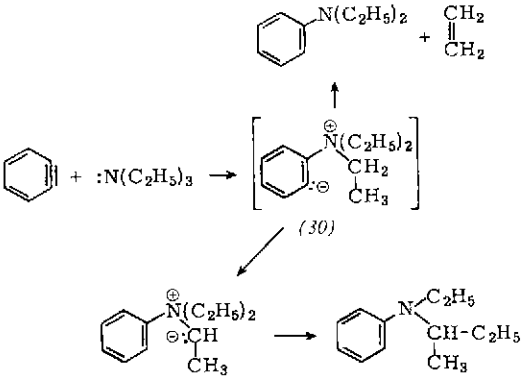
(26)

lithium diethylamide *(27)* probably reacts *via* the ate complex *(28)* by a redox reaction to form ethylidin ethylamine and phenyl-lithium, which then react further to form the isomeric α-phenyldiethylamine *(29)*.



(27) *(28)* *(29)*

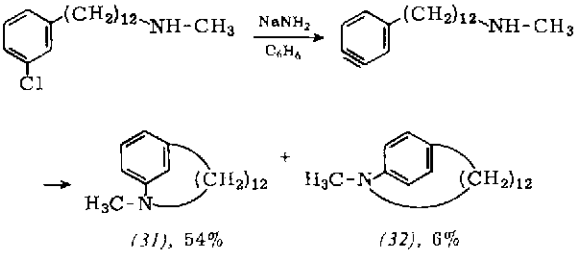
Dehydrobenzene liberated from fluorobenzene and phenyl-lithium also suffers nucleophilic attack by tertiary amines, as shown below for triethylamine [31].



(30)

The betaine intermediate *(30)* is discharged to form diethylaniline and ethylene, and undergoes a Stevens rearrangement to *N*-ethyl-*N*-(1-methylprop-1-yl)aniline.

The nucleophilic reactivity of nitrogen bases towards dehydroaromatic compounds makes possible preparations based on intramolecular ring closure. For example, cyclic amines with large rings, such as *(31)* and *(32)*, have been synthesized in this way [29].



(31), 54% *(32)*, 6%

[26] *R. S. Berry, J. Clardy*, and *M. E. Schafer*, Tetrahedron Letters *1965*, 1001, 1011.

[27] Cf. *R. Huisgen* and *J. Sauer*, Angew. Chem. *72*, 107 (1960).

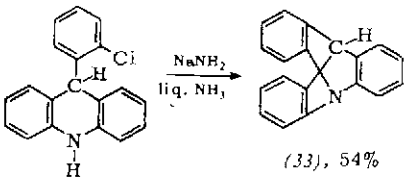
[28] It would be of interest in this connection to study the reactivity of the dehydro bonds in the unstrained bisdehydroannulene; cf. *F. Sondheimer, Y. Gaoni, L. M. Jackman, N. A. Bailey*, and *R. Masoni*, J. Amer. chem. Soc. *84*, 274 (1962); *86*, 521 (1964).

[29] Reviews: *R. Huisgen* and *J. Sauer*, Angew. Chem. *72*, 91 (1960); *R. Huisgen*: Theoretical Organic Chemistry. Butterworths, London 1959, p. 158 *et seq.*; *R. Huisgen* in *H. Zeiss*: Organometallic Chemistry. Reinhold, New York 1960, p. 78.

[30] *G. Wittig, H.J. Schmidt*, and *H. Renner*, Chem. Ber. *95*, 2377 (1962).

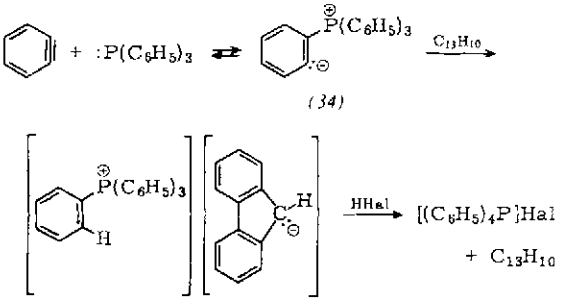
[31] *G. Wittig* and *E. Benz*, Chem. Ber. *92*, 1999 (1959).

The theoretically interesting, strongly basic azatriptycene *(33)* has also been made available by the same method of ring closure [32].



(33), 54%

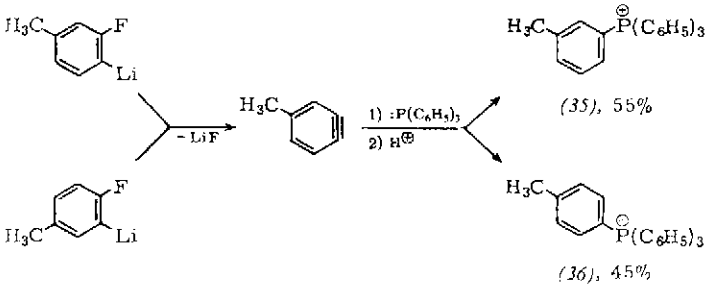
A clear case of a nucleophilic addition to dehydrobenzene is the reaction with triphenylphosphine. The *o*-lithiofluorobenzene prepared by *Gilman* and *Gorsich* [33] reacts with triphenylphosphine in the presence of fluorene ($C_{13}H_{10}$) only above −70 °C, where the elimination of metal halide begins [34].



(34)

The resulting tetraphenylphosphonium halide, which was isolated in good yield, is formed from the betaine adduct *(34)* with the aid of the proton-donating fluorene, the anion of which colors the solution deep red.

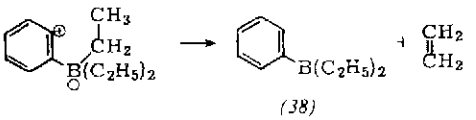
It can be shown that the first step of this quaternization of aromatic phosphines, which is generally applicable under mild conditions, does not involve the direct nucleophilic displacement of the fluoride ion by the tertiary phosphine, since the reaction of fluorotoluene under the same conditions always yields the same mixture of isomeric triphenyltoluylphosphonium salts *(35)* and *(36)*, irrespective of the position of the methyl group in the aromatic ring.



(35), 55%

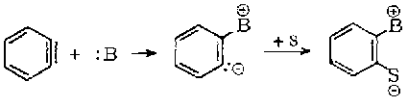
(36), 45%

In the presence of triphenylboron, the phosphonium betaine *(34)* which is initially formed from triphenylphosphine and dehydrobenzene is stabilized by formation of the isolable betaine *(37)*; this is a further indication that the reaction proceeds *via* dehydrobenzene [31]. That the latter can also act as a nucleophile is shown by its behavior towards triethylboron, which is converted into diethylphenylboron *(38)* [31].

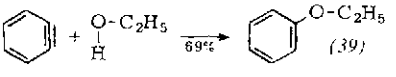


(38)

The fact that reactions of dehydrobenzene with triphenylphosphine yield the phosphonium betaine *(34)* as the initial product confirms the high polarizability of the dehydro bond in the vicinity of nucleophilic reagents. However, the addition of diethylamine to dehydrobenzene shows that the process (shown below) leading by a further step to the end product does not always prevail, but that additions which circumvent charged intermediates are also possible. Synchronous



additions of this type have been observed, *e.g.* in the decomposition of benzothiadiazole dioxide *(19)* in ethanol, which leads to good yields of phenetole *(39)* [18].



(39)

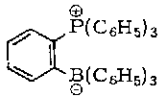
From the postulate that the sp^2 orbitals of the dehydro bond spread out in the plane of the benzene nucleus (*i.e.* perpendicular to the 6 π-electron system), it follows that the direction of addition to unsymmetrically substituted dehydroaromatics is largely determined by the inductive effect of the remaining substituent [35].

This is confirmed by the addition of ethanol to 3,4-dehydrotoluene (which is formed from 5- and 6-methylbenzenethiadiazole dioxides), which again gives the same mixture of *m*- and *p*-methylphenetoles (62 % and 38 % respectively), irrespective of the starting material used.

Conversely, owing to the different electron-density distribution, the addition of ethanol to 3,4-dehydronitrobenzene yields a mixture of nitrophenetoles in which the *p*-isomer predominates (75 %) [36] [*].

Hoffmann investigated this synchronous addition of ethanol on a wider basis [37], and concluded that the relationship between the isomer ratio and the inductive effect of the substituent can be expressed by a Hammett relationship (involving σ').

Only a little phenetole is formed if benzothiadiazole dioxide is decomposed in ethanol containing lithium



(37)

[32] *G. Wittig* and *G. Steinhoff*, Liebigs Ann. Chem. *676*, 21 (1964).

[33] *H. Gilman* and *R. D. Gorsich*, J. Amer. chem. Soc. *77*, 3919 (1955); *78*, 2217 (1956).

[34] *G. Wittig* and *H. Matzura*, Angew. Chem. *76*, 187 (1964); Angew. Chem. internat. Edit. *3*, 231 (1964); *H. Matzura*, Dissertation, Universität Heidelberg, 1964.

[35] *J. D. Roberts*, *C. W. Vaughan*, *L. A. Carlsmith*, and *D. A. Semenov*, J. Amer. chem. Soc. *78*, 611 (1956).

[36] *G. E. Vargas-Núñez*, Dissertation, Universität Heidelberg, 1963; *G. Wittig*, Pure appl. Chem. *7*, 173 (1963).

[*] *G. Wittig* and *H. F. Bertorello* obtained the same isomer ratio of 75% *p*- and 25% *m*-ethoxydiphenyl sulfone from the addition of ethanol to 3,4-dehydrodiphenyl sulfone.

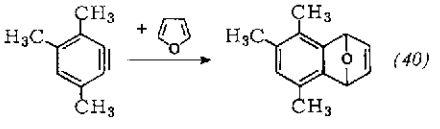
[37] *R. W. Hoffmann*, *G. E. Vargas-Núñez*, *G. Guhn*, and *W. Sieber*, Chem. Ber., in press.

halide. In this case the two-step addition evidently predominates, since the main product is halogenobenzene, the yield of this product increasing with the nucleophilic strength of the halide ion. This is shown particularly impressively by the formation of dehydrobenzene in ethanol containing equimolar quantities of chloride, bromide, and iodide ions, as can be seen from Table 1 [38].

Table 1. Decomposition of 5 mmole of benzothiadiazole dioxide *(19)* in ethanol in the presence of foreign substances.

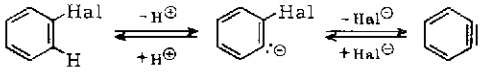
Foreign substance	Product	Yield [%]	Competition constant
50 mmole LiCl	Chlorobenzene	0.7	1
50 mmole LiBr	Bromobenzene	5.4	8
50 mmole LiI	Iodobenzene	46	65
850 mmole C_2H_5OH	Phenetole	0.4	—

The results show the surprisingly high selectivity of dehydrobenzene, from which it can he concluded to have an appreciable life-time. A relatively long life of dehydroaromatic compounds may also be responsible for the reaction of *o*-bromofluoropseudocumene with butyl-lithium in furan to give an 81 % yield of the endoxide *(40)*, whereas only 76 % of the unsubstituted



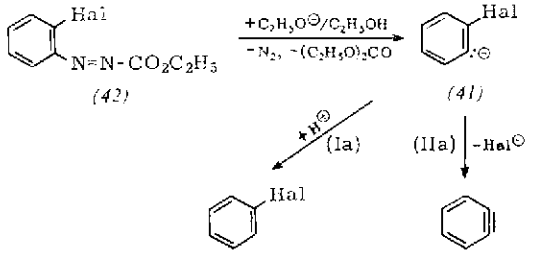
(40)

endoxide is obtained from *o*-bromofluorobenzene [39]. Furthermore, the fact that halide ions add to dehydrobenzene to form halogenobenzene shows that the elimination of lithium halide from *o*-lithiohalogenobenzene must be described by two [7, 29] reversible steps:



I *(41)* I'

Hoffmann [40] showed that the intermediate *(41)* between the halogenobenzene and dehydrobenzene can be reached directly by the base-catalysed fragmentation of ethyl 2-halogenobenzeneazocarboxylate *(42)*.



(42) *(41)*

[38] *G. Wittig* and *R. W. Hoffmann*, Chem. Ber. *95*, 2729 (1962).

[39] *G. Wittig* and *H. Härle*, Liebigs Ann. Chem. *623*, 17 (1959).

[40] *R. W. Hoffmann*, Chem. Ber. *98*, 222 (1965); cf. also the pyrolysis of metal salts of 2-halogenobenzoic acid: *G. Köbrich*, Chem. Ber. *92*, 2985 (1959); *96*, 2544 (1963); Liebigs Ann. Chem. *664*, 88 (1963).

From the constants of the competing protonation (Ia) and dehalogenation (IIa) of the 2-halogenophenyl anion *(41)*, and the relative rates of addition of halides to dehydrobenzene, *Hoffmann* was able to estimate the relative equilibrium constants for the reactions (II). The equilibrium favors dehydrobenzene most in the case of the bromide [40, 41].

VI. The Industrial Importance of Research on Dehydrobenzene and Closing Remarks

The influence of research on dehydrobenzene on chemical technology is of interest here, inasmuch as dehydroaromatic compounds also play a part in industrial processes. Thus in the alkaline hydrolysis of chlorobenzene to phenol, *Lüttringhaus* and *Ambros* [42] found by-products such as *o*- and *p*-hydroxybiphenyl, which are also formed by the action of phenylsodium on diphenyl ether [43]. In studies carried out by *Bottini* and *Roberts* [44] on the alkaline hydrolysis of [1-^{14}C]-chlorobenzene, the distribution of the hydroxyl groups in the products showed that the reaction proceeds *via* the short-lived intermediate dehydrobenzene.

The same conclusion is indicated *inter alia* by the predominance of resorcinol in the products of the alkali fusion of *m*- and *p*-halogenobenzenesulfonates [45]. *Kekulé*, who discovered this method of preparing phenols in 1864 [46], even then expressed doubt regarding the retention of structure during this operation.

The answer to the question of whether through consistent application of *Kekulé*'s structural theory, dehydrobenzene might have been discovered earlier, is probably negative, since although the vocabulary of the new language was there, the grammar had not yet developed to a sufficient degree. On this point, I shall close with *Kekulé*'s words on the 25th anniversary of the benzene theory [47]: "We all stand on the shoulders of our predecessors; is it surprising, therefore, that we have a wider view than they?"

Received: May 13th, 1965 [A 457/239 IE]
German version: Angew. Chem. *77*, 752 (1965)
Translated by Express Translation Service, London

[41] Cf. the 3-phenylsulfonylhalogenobenzenes which, according to *H. E. Zieger* and *G. Wittig*, J. org. Chemistry *27*, 3270 (1962) and *K. Grohmann*, Dissertation, Universität Heidelberg, 1965, rapidly become metallated, and are then converted into dehydroaromatic compounds in rate-determining metal halide eliminations.

[42] *A. Lüttringhaus* and *D. Ambros*, Chem. Ber. *89*, 463 (1956).

[43] *A. Lüttringhaus* and *K. Schubert*, Naturwissenschaften 42, 17 (1955); *A. Lüttringhaus* and *H. Schuster*, Angew. Chem. *70*, 438 (1958).

[44] *A. T. Bottini* and *J. D. Roberts*, J. Amer. chem. Soc. *79*, 1458 (1957).

[45] *H. Limpricht*, Ber. dtsch. chem. Ges. *7*, 1349 (1874).

[46] *A. Kekulé*, C. R. hebd. Séances Acad. Sci. *64*, 753 (1864); Z. Chem. *1867*, 300.

[47] *R. Anschütz*: August Kekulé. Verlag Chemie, Berlin 1929, Vol. I, p. 624.

Valence-Bond Isomers of Aromatic Systems

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The prefix $\varkappa^n$ is proposed for the classification of valence-bond isomers of aromatic systems, where n is the change in the number of rings or in the number of π-bonds on isomerization. Representatives of the $\varkappa^1$-series are Dewar benzene and 9,10-dihydronaphthalene. Benzvalene and prismane belong to the $\varkappa^2$ and $\varkappa^3$ series, respectively. Various derivatives of such valence-bond isomers have recently become known.

I. Introduction

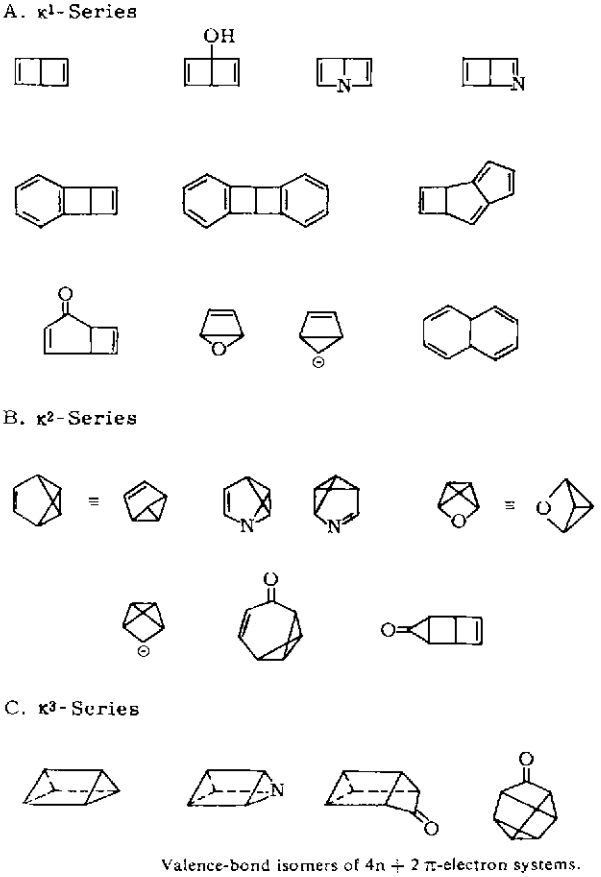
Approximately one hundred years ago, when the structural theory of organic chemistry was in its infancy, the founding fathers were concerned especially with benzene and its derivatives. During the nineteenth century, various non-Kekulé representations *(1)*–*(5)*

(1) *(2)* *(3)* *(4)* *(5)*

originated, most of which have little significance in terms of modern theory of aromatic compounds and remain only as epitaphs in present-day descriptions. However, the so-called "Dewar benzene" structure *(1)* (named after *Sir James Dewar*, who recorded it as a less desirable alternative to the Kekulé proposal [1]) has lived on as a minor contributor to the resonance hybrid emerging from the valence bond description of the benzene ring [2]. In addition, it has long been recognized that structures *(1)* and *(2)* have physical meaning as non-planar forms, and should be capable of independent existence as "valence-bond isomers" of benzene. Despite this obvious but sound theoretical basis, for many years organic chemists did not seriously consider the capture of such isomers, but by and large suspected that they would be too unstable for normal laboratory handling. Only recently have valence-bond isomers of traditional aromatic molecules been synthesized, identified, and shown to be substances of reasonable stability.

II. Classification and Nomenclature

Many types of valence bond isomers of aromatic $(4n + 2)$ π-electron systems can be imagined, and the number of individual possibilities is limitless; thus a system of classification is desirable. Of the several possible means for systematizing structures, some are ambiguous or arbitrary. For example, since π-electrons are implicit in aromatic structures, definition of valence-bond isomers thereof by reference to the number of such electrons in the non-aromatic isomer (*e.g.* "Dewar benzene" would be in the 4n π-electron group) could be considered. However, many aromatic systems incorporate, as an integral part of the aromatic bonding, electron pairs on heteroatoms which in the non-aromatic partner would be non-bonding (*e.g.* "Dewar furan"); thus, in the same "series" the number of π-electrons can vary (*i.e.* "Dewar benzene" has 4 π-electrons; "Dewar furan" has 2 π-electrons). Clearly, the common denominator for the valence-bond isomer types is the difference in the number of rings, π-electrons, or formal single bonds. We suggest the prefix $\varkappa^n$ (n = change in the number of rings, or in the number of π-bonds) [3]



Valence-bond isomers of 4n + 2 π-electron systems.

[1] (a) *C. K. Ingold*, J. chem. Soc. (London) *121*, 1133 (1922); (b) *W. Baker*, Chemistry in Britain *1*, 191 (1965).

[2] *G. Wheland*: Advanced Organic Chemistry. Wiley, New York 1960, pp. 117–118.

[3] Gr. κύκλος = ring or circle.

as a means for classifying members of valence-bond isomer systems according to their order. Examples are given below [4].

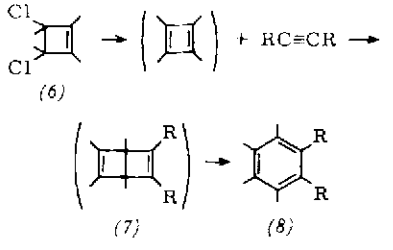
Aromatic members are obviously $\varkappa^{-n}$ valence bond isomers of their non-aromatic counterparts. Here we shall consider mainly the $\varkappa^1$ category, since (with one exception) [5] members of the $\varkappa^2$ and $\varkappa^3$ group have so far not been isolated.

III. $\varkappa^1$-Valence-Bond Isomers of 6 π-Electron Aromatic Systems

A. Bicyclo[2.2.0]hexa-2,5-dienes ("Dewar benzenes")

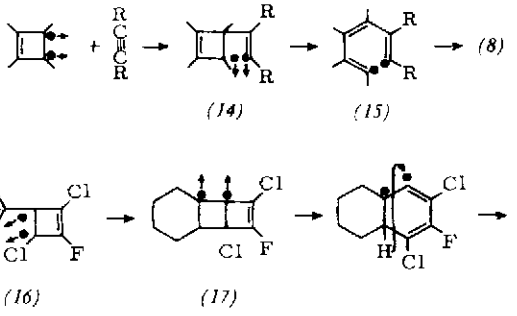
i. Dewar Benzenes as Intermediates

During the early 1960's there were invoked on occasion $\varkappa^1$-valence bond isomers of aromatic systems as unstable intermediates in certain unusual transformations. For example, 3,4-dichloro-1,2,3,4-tetramethylcyclobutene *(6)*, on treatment with metallic zinc in the presence of 2-butyne or diethyl acetylenedicarboxylate, affords the benzene derivative *(8)*, supposedly *via* the unstable non-planar Dewar benzene *(7)* [6].



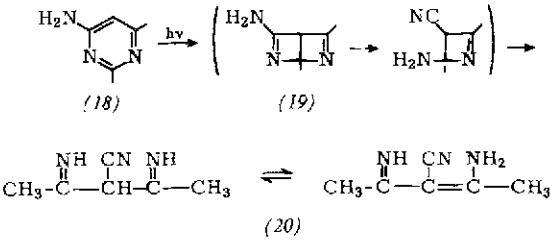
Similarly, triethylamine-induced elimination of hydrogen fluoride from the cyclohexenylcyclobutene *(9)* leads to formation of the tetralin derivative *(13)*, for which reaction the intermediates *(10)–(12)* were proposed [7].

In each of these cases, the "Dewar benzene" is assumed to be generated from a cyclobutadiene. The latter would presumably exist and react as a triplet in the ground state so that the ground state (singlet) "Dewar benzene" could not form directly. After reaction with the cyclobutadiene is initiated, time may be available for other processes to occur, *e.g. (14)* → *(15)*; *(16)* → *(17)*; and thus, for these changes, a Dewar benzene intermediate

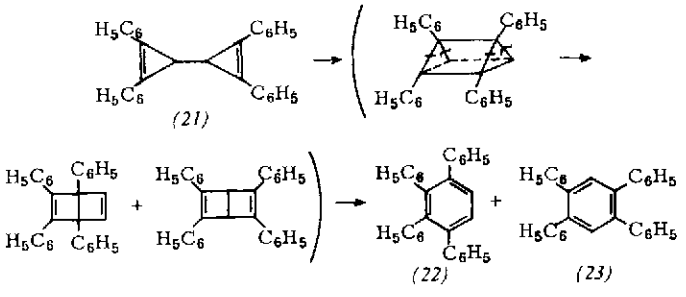


is not obligatory. Alternatively, a triplet state Dewar benzene may be involved, which, being of higher energy, may proceed ultimately to observed aromatic product without traversing the ground state Dewar benzene route.

In the heterocyclic series, the novel formation of 2-amino-3-cyano-pent-2-ene-4-imine *(20)* from 2,6-dimethyl-4-aminopyrimidine *(18)* may be initiated by photo-induced formation of a "Dewar pyrimidine" *(19)* [8].



Finally, *Breslow* [9] has suggested that the isomerization of the tetraphenylbicyclopropenyl *(21)* to the tetraphenylbenzenes *(22)* and *(23)* involves transient Dewar benzene intermediates, in addition to prismane.



In all these cases, the idea of a Dewar structure is interpretative or conjectural – neither was the Dewar-type molecule isolated, nor was additional evidence adduced for its intermediacy.

[4] Inclusion of a given example carries no implication as to lifetime or isolability.

[5] *H. G. Viehe, R. Merényi, J. F. M. Oth, J. R. Senders,* and *P. Valange,* Angew. Chem. *76*, 922 (1964); Angew. Chem. internat. Edit. *3*, 755 (1964); *H. G. Viehe,* Angew. Chem. *77*, 768 (1965); Angew. Chem. internat. Edit. *4*, 746 (1965).

[6] *C. E. Berkoff, R. C. Cookson, J. Hudec,* and *R. O. Williams,* Proc. chem. Soc. (London) *1961*, 312.

[7] *C. M. Sharts* and *J. D. Roberts,* J. Amer. chem. Soc. *83*, 871 (1961).

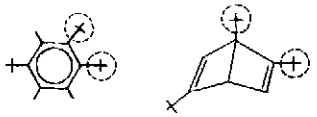
[8] *K. L. Wierzchowski, D. Shugar,* and *A. R. Katritzky,* J. Amer. chem. Soc. *85*, 827 (1963).

[9] *R. Breslow* in *P. de Mayo*: Molecular Rearrangements, Part I. Interscience, New York-London 1963, pp. 243–245.

2. Synthesis and Properties of Bicyclo[2.2.0]hexa-2,5-dienes

In 1960, at which time the synthesis of a "Dewar benzene" was being seriously considered in the author's laboratory, it was not possible to predict the stability of a member of this unknown class. Efforts therefore were made to secure one of the more stable representatives imaginable; concurrently, one promising route to the parent bicyclo[2.2.0]hexa-2,5-diene was initiated.

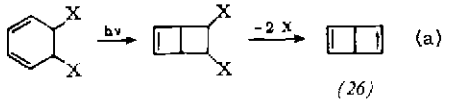
Preparation of a stable Dewar benzene was achieved by irradiation of 1,2,4-tri-t-butylbenzene *(24)*. In selecting this case for study we reasoned that the high degree of steric interference between the bulky 1,2-t-butyl groups would have a stabilizing effect on the non-planar Dewar form *(25)*, in which the two large substituents are farther separated in space relative to the



(24) *(25)*

benzenoid isomer. Ultraviolet radiation proved to be a suitable energy source for the required type of change. The product, 1,2,5-tri-t-butylbicyclo[2.2.0]hexa-2,5-diene *(25)*, structural assignment to which depends on spectral and other considerations, was found to be stable at room temperature and to be converted (incompletely) to starting 1,2,4-tri-t-butyl benzene on being heated to 200 °C for 15 minutes. These results [10], reported in 1962, established for the first time the existence of a non-planar Dewar benzene, and taken together with the synthesis of the parent compound, opened up a new and viable field of research.

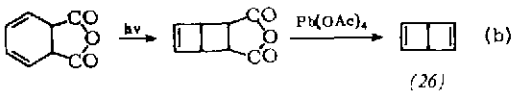
By 1963, several years of persistent effort in our laboratory were rewarded with the preparation and identification of the second known Dewar benzene, the parent compound, C_6H_6 *(26)* [11]. The synthesis route selected for this goal is expressed in general terms as (a) below.



(a)

(26)

Among the factors which were considered to be of prime importance, two should be mentioned here. First, because of over-all geometrical as well as stereoelectronic (see below) considerations, existence of a preformed cyclobutene moiety in the last intermediate was regarded as highly desirable, in that this structural feature would offer some insurance against formation of ordinary benzene in the last step. Second, this final step should be carried out under the mildest possible conditions with respect to temperature, pH, and nature of the reagent. The reaction we used is shown as (b) below.

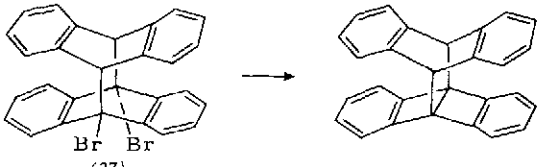


(b)

(26)

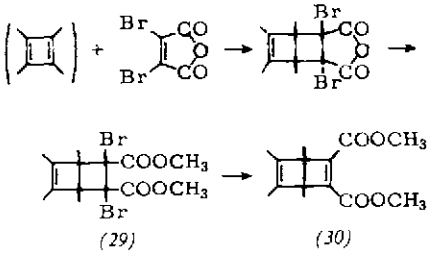
Parent Dewar benzene *(26)* can be chromatographed in the vapor phase and can he stored for several months in pyridine solution below 0 °C. At room temperature in pyridine, its half-life is about two days; at 90 °C, conversion to benzene is very rapid and complete. The bicyclohexadiene exhibits two NMR signals, one at 3.45 τ (triplet) and the other at 6.16 τ (quintuplet) (pyridine solution, 60 Mc/sec), in the ratio of 2:1. Diimine reduction [11a] gives bicyclo[2.2.0]hexane.

In the following year, four additional Dewar benzenes were reported from other laboratories. *Applequist* and *Searle* [12] described the dehalogenation of the anthracene dimer *(27)*, the product of which was assigned structure *(28)*. This anthracene derivative should be regarded



(27) *(28)*

as a "formal" non-planar Dewar benzene, in that the intrinsic properties of the distinguishing moiety are obscured by 1) incorporation of the unsaturated edges in *bona fide* benzene rings, and 2) the geometrical impossibility of its conversion to a normal benzene derivative. *Criegee* and *Zanker* [13], using a modification of reaction (a), reported that zinc-copper dehalogenation of the ester *(29)* derived from the tetramethylcyclobutadiene/dibromomaleic anhydride adduct leads to tetramethyl-"Dewar phthalic acid" dimethyl ester *(30)*,



(29) *(30)*

a stable solid (m.p. 32–33 °C) which quantitatively generates dimethyl tetramethylphthalate at 130 °C. The presumed stability of this Dewar benzene under the conditions used by *Cookson* et al. [6] in their attempted route to the same product implies that the substance was not involved in their system. *Arnett* and *Bollinger* described in the latter part of 1964 [14] an interesting variant (see Section 3 below) of the original 1,2,4-tri-t-butylbenzene irradiation, namely the photo-induced

[10] *E. E. van Tamelen* and *S. P. Pappas*, J. Amer. chem. Soc. *84*, 3789 (1962).

[11] *E. E. van Tamelen* and *S. P. Pappas*, Abstract, 18th National Organic Symposium, Columbus, Ohio (U.S.A.), June 1963; J. Amer. chem. Soc. *85*, 3297 (1963).

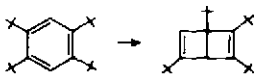
[11a] For a review, cf. *S. Hünig, H. R. Müller*, and *W. Thier*, Angew. Chem. *77*, 368 (1965); Angew. Chem. internat. Edit. *4*, 271 (1965).

[12] *D. E. Applequist* and *R. Searle*, J. Amer. chem. Soc. *86*, 1389 (1964).

[13] *R. Criegee* and *F. Zanker*, Angew. Chem. *76*, 716 (1964); Angew. Chem. internat. Edit. *3*, 695 (1964).

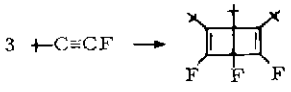
[14] *E. M. Arnett* and *J. M. Bollinger*, Tetrahedron Letters *1964*, 3803.

conversion of 1,2,4,5-tetra-t-butylbenzene *(31)* to Dewar-1,2,3,5-tetra-t-butylbenzene *(32)*. Finally, *Viehe*



(31) *(32)*

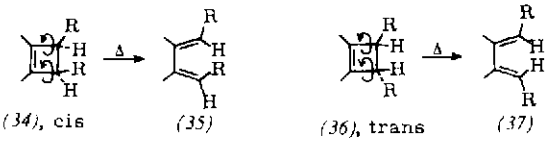
and co-workers recently reported the startling trimerization of t-butylfluoroacetylene, in which process a Dewar benzene *(33)* and a $\varkappa^2$-isomer ("benzvalene") are formed in addition to the true benzenoid trimer [5].



(33)

The "Dewar pyridine" reported [15a] to be formed by photolysis of 2-amino-5-chloropyridine has been shown [15b] to be a normal dimer.

Because the preparation and isolation of non-planar Dewar benzenes has met with surprise [16] and even skepticism [17], it may be in order to comment briefly on various factors relating to the system's stability. Two thermodynamic factors, namely the strain of Dewar benzene and the resonance stability of normal benzene, reinforce each other and make for a considerable difference in ground state energies between the two structures. Morphologically, the difference between benzene and the bicyclohexadiene is so small that entropy factors should not present any great barrier to isomerization. If no other factor were at play, the energy path to normal benzene would be largely downhill. What property, then, is responsible for the stability of Dewar benzene? The answer must be given in terms of bond rehybridization, including the stereoelectronic factors at work in the thermally induced ring opening of a cyclobutene to a 1,3-diene [20–22]. In the absence of unusual restraints, *cis* and *trans*-3,4-disubstituted cyclobutenes, on being heated, exhibit clean stereochemical behavior [18,19], each giving rise to one diene geometrical isomer: *(34)* → *(35)*; *(36)* → *(37)*.



(34), cis *(35)* *(36)*, trans *(37)*

[15a] *E. C. Taylor, W. W. Paudler*, and *I. Kuntz, Jr.*, J. Amer. chem. Soc. *83*, 2967 (1961).

[15b] *E. C. Taylor, R. O. Kan*, and *W. W. Paudler*, ibid. *83*, 4484 (1961).

[16] *D. Seebach*, Angew. Chem. *77*, 119 (1965); Angew. Chem. internat. Edit. *4*, 124 (1965).

[17] Personal communications.

[18] *E. Vogel*, Liebigs Ann. Chem. *615*, 14 (1958).

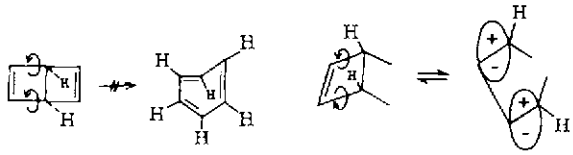
[19] *R. Criegee* and *K. Noll*, Liebigs Ann. Chem. *627*, 1 (1959).

[20] *L. J. Oosterhoff*, as quoted in *E. Havinga* and *J. L. M. A. Schlatmann*, Tetrahedron *16*, 151 (1961).

[21] *R. B. Woodward* and *R. Hoffmann*, J. Amer. chem. Soc. *87*, 395 (1965).

[22] *H. C. Longuet-Higgins* and *E. W. Abrahamson*, J. Amer. chem. Soc. *87*, 2045 (1965).

In the case of *cis*-bicyclo[2.2.0]hexa-2,5-diene *(38)*, this preferred (conrotative) mode of stereoisomerization cannot operate, since an extraordinarily strained *cis,cis*,

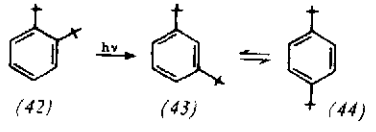


(38) *(39)* *(40)* *(41)*

trans-cyclohexa-1,3,5-diene *(39)* would result. In the stereoelectronically less preferred (disrotative) course of ring opening, molecular orbital symmetry [*(40)* → *(41)*] [20–22] preference defers to stability of the 6 π-electron product, but the transition state energy is raised and Dewar benzene enjoys comparative stabilization.

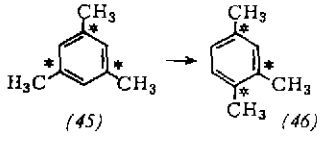
3. Excited Valence-Bond Isomers of Benzenes

After identifying tri-t-butyl Dewar benzene, we examined the ultraviolet irradiation of the simpler *o*-di-t-butyl benzene *(42)* [23]. In that case, no Dewar benzene product could be isolated. Instead, *m*- and *p*-di-t-butylbenzene *(43)* and *(44)* were formed, and it was readily



(42) *(43)* *(44)*

established that there existed a photochemical equilibrium between these two isomers, with a component ratio of 58 *p*: 42 *m* [24]. In 1964, *Wilzbach* and *Kaplan* [25] described photo-induced isomerizations among *o-m-p* isomers in even simpler alkyl systems. In neither laboratory were "cross-alkylations" detected; thus, isomerization by way of migrating free alkyl radicals was considered less likely than some type of annular isomerization [23]. The latter possibility was confirmed recently [26] with the demonstration that during the



(45) *(46)*

isomerization of [1,3,5-$^{14}C_3$]mesitylene *(45)* to 1,2,4-trimethylbenzene *(46)*, methyl substituents remained attached to labelled ring carbons. These results can be taken to indicate isomerization through a prismane *(47)*, a benzvalene *(48)*, or a set of equivalent equilibrating Dewar benzenes *(49a)–(49c)*, any of which

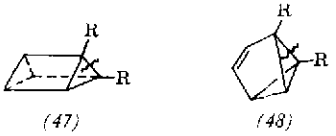
[23] *K. Kirk*, Ph. D. Thesis, University of Wisconsin, 1963.

[24] After learning about our prior results (personal communication), *A. W. Burgstahler* and *P.-L. Chien* published independently their confirmatory observations: J. Amer. chem. Soc. *86*, 2940 (1964).

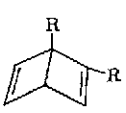
[25] *K. E. Wilzbach* and *L. Kaplan*, J. Amer. chem. Soc. *86*, 2307 (1964).

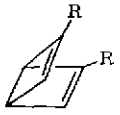
[26] *L. Kaplan, K. E. Wilzbach, W. G. Brown*, and *S. S. Yang*, J. Amer. chem. Soc. *87*, 675 (1965).

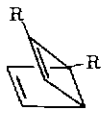
valence-bond isomer types could permit the series of bond-making and -breaking processes required for overall alkyl isomerization. In view of the apparent


(47)

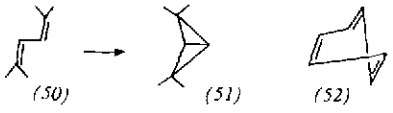
(48)


(49a)


(49b)


(49c)

dependence of photo-induced 1,3-diene → bicyclobutane isomerizations on the ground state conformation of starting material *(50)* [27,28], photochemical formation of a benzvalene *(48)* seems less likely – the


(50) (51) (52)

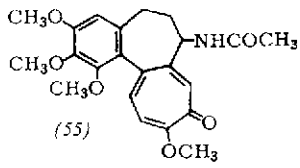
required ground state conformation *(52)*, a severely racked "benzene" ring, would be unavailable. *o*-Di-t-butylbenzenes are probably not planar, *(53)*, but warped, *(54)* [29], and thereby suffer from lessened π-orbital overlap. Conditions are proper, therefore, for easy conversion to an excited state "aromatic" having the same

(53) (54)

geometry as *(54)*, which intermediate can then readily rehybridize, with attendant minor geometrical changes, to a Dewar benzene system, presumably either in an excited electronic state or merely vibrationally excited. Ultimately, there is released ground state Dewar benzene. The latter cannot – as shown above – undergo the stereoelectronically preferred thermal conrotatory [21] isomerization to parent aromatic, and cannot absorb to any great measure the ultraviolet radiation used for its production; therefore it survives. Clearly, ring closure of an excited Dewar benzene to a prismane remains a possibility deserving consideration.

B. Other π^1-Valence-Bond Isomers of 6 π-Electron System

In 1955, on the basis of extensive chemical studies, *Forbes* [30] proposed the correct structure *(56)* for the monomeric lumicolchicines, obtained years earlier by illumination of the natural product *(55)*. This structural assignment was amply confirmed by subsequent investigators [31,32], who determined the stereochemistry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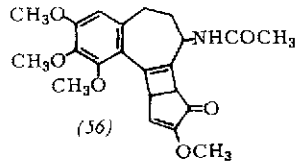
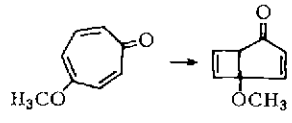
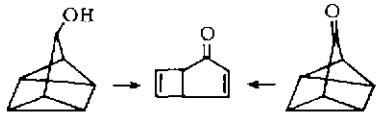
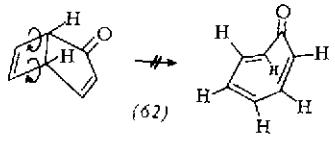

(56)

as well. Photochemistry of simpler tropone derivatives has also been pursued, including, for example, isomerization of γ-tropolone methyl ether *(57)* to the bicyclic ketone *(58)* [33]. In 1965, the parent bicycloheptadienone *(60)* was reported, which arises either from *(59)* under Oppenauer oxidation conditions, or from *(61)* by the action of alumina [34]. All of these substances – valence-bond isomers of the $(4n + 2)$ π-electron

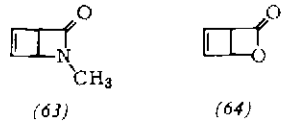

(57) (58)


(59) (60) (61)

aromatic type, tropone – are remarkably stable, temperatures in the vicinity of 350 °C being used for conversion to the monocyclic parent. As in previous cases discussed herein, their stability is explicable by inhibition *(62)* of the normally stereoelectronically preferred conrotatory conversion to *trans-cis*-1,3-diene.


(62)

In a similar situation, *N*-methylpyridone and α-pyrone, when irradiated in solvent by ultraviolet light, form the relatively stable valence isomers *(63)* and *(64)* [35].


(63) (64)

[27] *R. Srinivasan*, J. Amer. chem. Soc. *85*, 4045 (1963).

[28] *W. G. Dauben* and *F. G. Willey*, Tetrahedron Letters *1962*, 893.

[29] *C. Hoogzand* and *W. Hübel*, Tetrahedron Letters *1961*, 637.

[30] *E. J. Forbes*, J. chem. Soc. (London) *1955*, 3864.

[31] *P. D. Gardner*, *R. L. Brandon*, and *G. R. Haynes*, J. Amer. chem. Soc. *79*, 6334 (1957).

[32] *O. L. Chapman*, *H. G. Smith*, and *R. W. King*, J. Amer. chem. Soc. *85*, 803 (1963).

[33] *O. L. Chapman* and *D. J. Pasto*, J. Amer. chem. Soc. *80*, 6685 (1958); *82*, 3642 (1960).

[34] *P. R. Story* and *S. R. Fahrenholtz*, J. Amer. chem. Soc. *87*, 1623 (1965).

[35] *E. J. Corey* and *J. Streith*, J. Amer. chem. Soc. *86*, 950 (1964).

IV. χ^1-Valence-Bond Isomers of 10 π-Electron Aromatic Systems

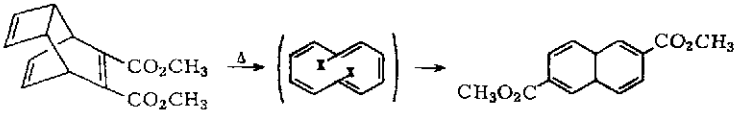
A. 9,10-Dihydronaphthalenes

1. Early Observations

In 1956 *Prelog* referred to the structural relation between two substances unknown at that time, cyclodecapentaene *(65)* and 9,10-dihydronaphthalene *(66)* [36,37]. Some-

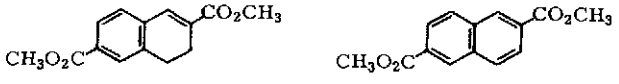
(65) *(66)*

what later, *Nenitzescu* et al. [38] claimed the isolation of the dicarbomethoxy-9,10-dihydronaphthalene *(69)*,



(67) *(68)*, X = CO_2CH_3 *(69)*

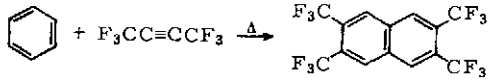
presumed to arise *via* the isomeric cyclodecapentaene *(68)* during the pyrolysis of the cyclooctatetraene-dimethyl acetylenedicarboxylate adduct *(67)*. Later investigations [39,40] revealed, however, that the substance isolated by *Nenitzescu* et al. was actually dimethyl 3,4-dihydronaphthalene-2,6-dicarboxylate *(70)*. Whether this material or a companion product, dimethyl naph-



(70) *(71)*

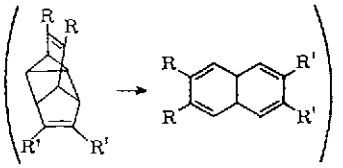
thalene-2,6-dicarboxylate *(71)*, is formed through a route involving a 9,10-dihydronaphthalene or a cyclodecapentaene, remains unanswered.

In order to explain the formation of 2,3,6,7-tetrakis(trifluoromethyl)naphthalene *(72)* by interaction of hexafluorobut-2-yne and benzene, *Krespan*, *McKusick*, and *Cairns* [41] suggested a mechanism featuring ring-opening of a hexafluorobutyne-bis(trifluoromethyl)-



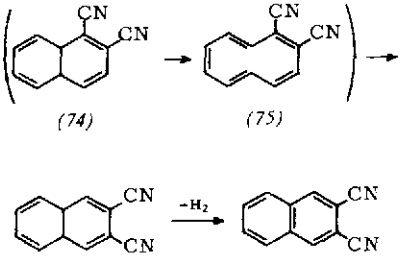
(72)

barrelene adduct *(73)*, R=R'=CF_3) to a 9,10-dihydronaphthalene (both unisolated) followed by dehydrogenation to the observed product. *Zimmermann* and *Grunewald* [42] subsequently reported that barrelene and



(73)

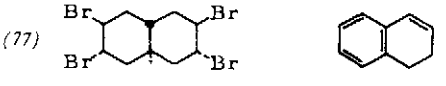
either dimethyl acetylenedicarboxylate or dicyanoacetylene at lower temperatures yield a well-defined adduct *(73)*, R=H; R'= $-COOCH_3$ or $-CN$, which on further pyrolysis gives rise to 1,2-dicyano- or 1,2-dicarbomethoxynaphthalene. These results suggested a "reverse Diels-Alder" reaction of *(73)* to give a 9,10-dihydronaphthalene, an unisolated progenitor of the observed product. The fact that a small amount of 2,3-dicyanonaphthalene results from these rearrangements is in keeping with the conversion of *(74)* to cyclodecapentaene *(75)*, followed by valence-bond isomerization to 2,3-dicyano-9,10-dihydronaphthalene *(76)*.



(74) *(75)*

(76)

Mention may also be made here of early attempts [43] in the author's laboratory to dehydrohalogenate the tetrabromo-*trans* decalin *(77)* to *trans*-9,10-dihydronaphthalene, which elimination, however, led to the



(77)

known 1,2-dihydronaphthalene. In this process, as in those referred to earlier in this section, no 9,10-dihydronaphthalene was isolated; no supporting evidence for its role in this, and in the other overall changes, is available.

2. Synthesis and Properties of 9,10-Dihydronaphthalenes

In addition to the *Nenitzescu* dihydronaphthalene, another substance assigned to the 9,10-dihydronaphthalene category was reinvestigated a few years ago. During the 1930's, *Diels* and *Alder* published several papers [44] on the 1:2 adducts, usually a pair of "labile"

[36] *V. Prelog*, Perspectives in Organic Chemistry, edited by *A. Todd*. Interscience, New York 1956, p. 127.

[37] Consideration should be given two hypothetical cyclodecapentaenes: The all-*cis* and the *cis-cis-trans-cis-trans* isomers.

[38] *C. D. Nenitzescu, M. Avram*, and *E. Marica*, Chem. Ber. *90*, 1857 (1957).

[39] *R. Cookson, J. Hudec*, and *M. Marsden*, Chem. and Ind. *1961*, 21.

[40] *B. C.T. Pappas*, Ph. D. Thesis, University of Wisconsin, 1963.

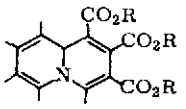
[41] *C. G. Krespan, B. C. McKusick*, and *T. L. Cairns*, J. Amer. chem. Soc. *82*, 1515 (1960); *83*, 3428 (1961).

[42] *H. E. Zimmerman* and *G. L. Grunewald*, J. Amer. chem. Soc. *86*, 1434 (1964).

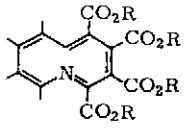
[43] *H. Winicov*, Ph. D. Thesis, University of Wisconsin, 1960.

[44] *O. Diels* and *K. Alder*, Liebigs Ann. Chem. *498*, 16 (1932); *505*, 103 (1933); *510*, 87 (1934).

and "stable" isomers, secured when a pyridine is treated with acetylenedicarboxylic ester. Although the zwitterionic structure originally proposed for the former type is unacceptable, the constitution *(78)* preferred by *Diels* and *Alder* for the "stable" system is a reasonable



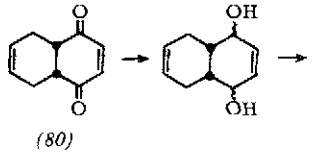
(78)



(79)

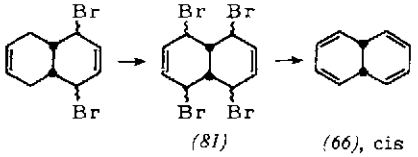
construction. The possibility that either of the adducts is the planar azacyclodecapentaene *(79)*, a valence-bond isomer of *(78)*, was considered early by us and induced further structural investigations. Detailed spectral -- especially NMR -- analysis of various members of the "labile" class revealed that the representation *(78)* in fact expresses the nature of this type whereas the "stable" isomers possess another structure, arising from *(78)* by proton shift [45]. As far as can be determined, the "labile" pyridine-acetylenedicarboxylic ester adducts are the first authenticated 9,10-dihydro(aza)-naphthalene derivatives. The finding that the quinolizine *(78)* molecule apparently is energetically preferred to the 10 π-electron valence-bond isomer *(79)* was significant, all the more so because it foreshadowed the results of experiments with the parent 9,10-dihydronaphthalene system.

In 1963 we synthesized and identified 9,10-dihydronaphthalene [46]. Starting from the available quinone-butadiene adduct *(80)* the route involved the inter-



(80)

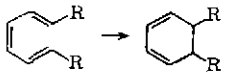
(c)



(81) *(66)*, cis

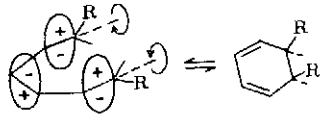
mediates shown in sequence (c). Lithium-amalgam dehalogenation of the tetrabromide *(81)* led to a hydrocarbon, which chemical and spectral studies showed to be the *cis*-9,10-dihydronaphthalene *(66)*. Neither heat nor light converted this bicyclic hydrocarbon to the monocyclic valence-bond isomer *(65)*. In the range 150–200 °C, only naphthalene was formed; ultraviolet irradiation produced unknown material which exhibited only end absorption in that region of the spectrum.

The tendency of 1,6-disubstituted 1,3,5-trienes *(82)* to thermally induced, stereospecific ring closures to 1,2-disubstituted cyclohexa-3,5-dienes *(83)* has been established [47] and rationalized in terms of favorable



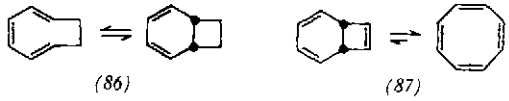
(82) *(83)*

symmetry properties of the highest occupied molecular orbital of the triene system *(84)*; the reverse reaction



(84) *(85)*

is considered to be subject to similar control [21, 22]. These generalizations are in keeping with the readily induced equilibration between the partners in the classical Cope valence isomerization *(86)* [48], and the more recently observed rapid conversion of triene *(87)* to cyclooctatetraene [49].



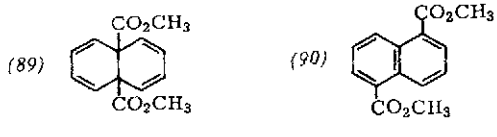
(86) *(87)*

Of importance in this discussion is 1) the stereoelectronically preferred conversion of triene of geometry *(84)* to *cis*- rather than *trans*-1,2-disubstituted-3,5-cyclohexadiene *(85)*, and 2) the geometrical course of the reverse process. Thus the *cis*-, but not the *trans*-, 9,10-dihydronaphthalene should afford all-*cis* or di-*trans* cyclodecapentaene, if similar considerations apply, and the activation energy for conversion of the less stable to the more stable isomer should be relatively low in the *cis* series. It is reasonable to conclude, then, that maintenance of the *cis*-9,10-dihydronaphthalene structure reflects the lower thermodynamic stability of cyclodecapentaene. It appears thus that the unsubstituted 10 π-electron system is indeed severely destabilized by 1,6-

(88)

hydrogen interactions *(88)*, as suggested by *Mislow* [50] and remains still unknown.

More recently *Vogel* [51] described the diester *(89)* and its behavior when it is heated. At 90 °C a mixture of



(89) *(90)*

[45] *E. E. van Tamelen, P. E. Aldrich, P. Bender*, and *G. Miller*, Proc. chem. Soc. *1959*, 309. See also *R. M. Acheson* and *G. A. Taylor*, ibid. *1959*, 186.

[46] *E. E. van Tamelen* and *B. Pappas*, J. Amer. chem. Soc. *85*, 3296 (1963).

[47] For review and discussion, see [20].

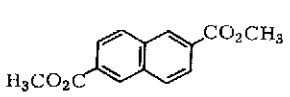
[48] *A. C. Cope, A. C. Haven, F. L. Rampand*, and *E. R. Trumbull*, J. Amer. chem. Soc. *74*, 4867 (1952).

[49] *E. Vogel, H. Kiefer*, and *W. R. Roth*, Angew. Chem. *76*, 432 (1964); Angew. Chem. internat. Edit. *3*, 442 (1964).

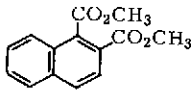
[50] *K. Mislow*, J. chem. Physics *20*, 1489 (1952).

[51] *E. Vogel, W. Meckel*, and *W. Grimme*, Angew. Chem. *76*, 786 (1964); Angew. Chem. internat. Edit. *3*, 643 (1964).

isomeric 9,10-dihydronaphthalenedicarboxylic esters results; at 150 °C, dehydrogenation occurs, and naphthalenedicarboxylic esters *(90)*, *(91)*, and *(92)* are formed. It seems likely that the 1,5- and 2,6-diesters arise



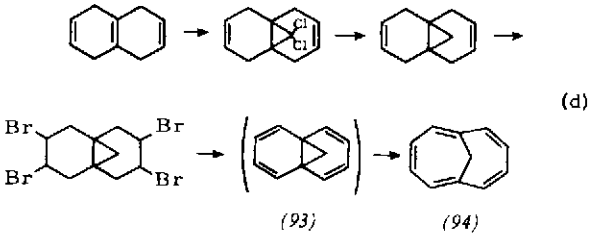
(91)



(92)

by isomerization, *via* the transient cyclodecapentaene, of starting material to 1,5- and 2,6-dihydronaphthalene diesters, followed by aromatization [52]. Thus, insofar as *simple* monocyclic cyclodecapentaenes are concerned, certain facts suggest their momentary appearance as intermediates during various reaction sequences; however, they seem to be unstable relative to the valence isomeric 9,10-dihydronaphthalene.

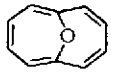
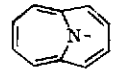
This situation changes when certain steric constraints are imposed on the 10-membered ring. *Vogel* and *Roth* [53] showed that the cyclodecapentaene nucleus is stabilized if a methylene group is used to bridge the 1,6-carbons in the ring, thereby removing the "overlapping" 1,6-hydrogens. The synthesis of 1,6-methanocyclodecapentaene *(94)* involves the series of reactions (d), and proceeds to final product by way of the 9,10-dihydro-



(d)

(93) *(94)*

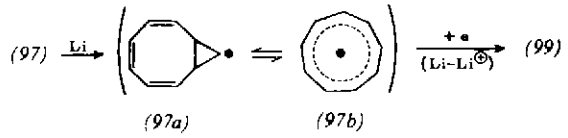
naphthalene intermediate *(93)*. By similar means, the systems bridged with oxygen *(95)* and nitrogen *(96)* were later secured [54, 55]. Chemical and spectral

(95)  *(96)* 

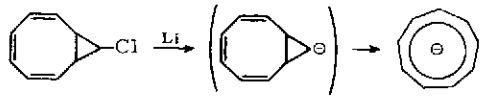
properties of the methylene-bridged molecule suggest that it indeed possesses aromatic character [56].

B. The Bicyclo[6.1.0]nonatrienyl and Cyclononatetraenyl Anions

In their preparation of the aromatic cyclononatetraenyl anion *(99)*, both *Katz* and *Garratt* [57] as well as *LaLancette* and *Benson* [58] developed a pathway from the bicyclo[6.1.0]nonatriene system.



(97a) *(97b)*

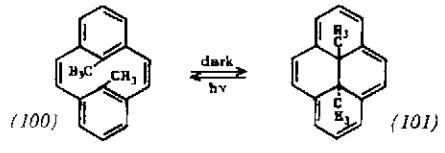


(97) *(98)* *(99)*

Lithium metal was used to abstract halogen from the cyclopropyl chloride *(97)*; assuming a 2-electron exchange without valence isomerization, this process leads to the bicyclo[6.1.0]-nonatrienyl anion *(98)*, a valence-bond isomer of the more stable 10 π-electron configuration [59].

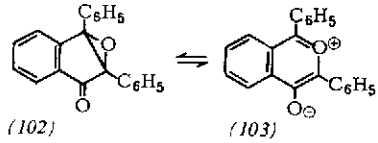
V. Miscellaneous

Several additional, intriguing valence isomerizations involving aromatic rings have appeared in the literature of the 1960's. *Heilbronner*, *Boekelheide*, and co-workers [60] have described the interconversion of metacyclo-



(100) *(101)*

phane *(100)* and dimethyl dihydropyrene *(101)*. In an earlier study, *Ullman* and *Milks* [61] demonstrated the equilibrium between benzopyrylium oxide *(103)* and



(102) *(103)*

indenone oxide *(102)*, the former constituent being responsible for the thermochromic properties of the system.

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German version: Angew. Chem. 77, 759 (1965)

[52] The novel formation of 1,2-diester *(92)* may involve isomerization of *(89)* – by one of several alternative pathways – to diester *(73)*, known to be a progenitor of naphthalene-1,2-dicarboxylic ester at the temperature involved [42].

[53] *E. Vogel* and *H. D. Roth*, Angew. Chem. *76*, 145 (1964); Angew. Chem. internat. Edit. *3*, 228 (1964).

[54] *E. Vogel*, *M. Biskup*, *W. Pretzer*, and *W. A. Böll*, Angew. Chem. *76*, 785; Angew. Chem. internat. Edit. *3*, 642 (1964).

[55] *F. Sondheimer* and *A. Shani*, J. Amer. chem. Soc. *86*, 3168 (1964).

[56] *E. Vogel* and *W. A. Böll*, Angew. Chem. *76*, 784 (1964), Angew. Chem. internat. Edit. *3*, 642 (1964).

[57] *T. J. Katz* and *P. J. Garratt*, J. Amer. chem. Soc. *85*, 2852 (1963).

[58] *E. A. LaLancette* and *R. E. Benson*, J. Amer. chem. Soc. *85*, 2853 (1963).

[59] Alternatively, a pathway involving valence-bond isomerization of a radical [*(97a)* → *(97b)*] can be visualized.

[60] *H.-R. Blattmann*, *D. Meuche*, *E. Heilbronner*, *R. J. Molyneux*, and *V. Boekelheide*, J. Amer. chem. Soc. *87*, 130 (1965).

[61] *E. F. Ullmann* and *J. E. Milks*, J. Amer. chem. Soc. *84*, 1315 (1962).

Valence-Bond Isomers of Substituted Benzenes [*]

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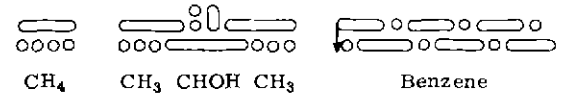
Dewar benzene, Ladenburg benzene (prismane), and a combination of these bond systems (benzvalene) have variously been discussed as planar limiting structures of benzene, although they have no physical reality. If, however, we regard these systems as non-planar structures (as did their originators), they become chemical individuals, derivatives of which have recently been isolated. In addition to being a valence-bond isomer of benzene, benzvalene is also the first member of a still largely hypothetical series of molecules (the valenes), in which the skeleton atoms can change places with their neighbors to produce the valence-bond isomers. The best-known representative of this class is bullvalene.

Introduction

Kekulé at first wrote the formula of benzene in the now unfamiliar notation that he used for paraffin chains *(1)* [1]. This first formulation *(2)* [2] was intended to be illustrative, but not structural or, as *Kekulé* expressed it, constitutional. Soon afterwards he used the now well-known formula *(3)*. Only a few years later he was confronted with the counterproposals *(4)–(7)* of his contemporaries, which were in part also regarded as structural.



CH_4 Methane — CH_3 CHOH CH_3 Isopropanol — Benzene

(1), "Paraffin chains" — *(2)*, Kekulé 1864/65

(3) — *(4)* *(5)* — *(6)*

Kekulé [2,3] 1865/66 — Claus [4] 1867 — Dewar [5] 1867

(7) — *(8)*

Ladenburg [6] 1869 — Hückel 1937 [7]

[*] Based on the opening lecture at the Kekulé Centenary Exhibition in Ghent (Belgium) on November 25, 1964. Cf. Meded. vlaamse chem. Vereen. *26*, 193 (1964); Chem. Engng. News *42*, No. 49, 38 (1964).

[1] *A. Kekulé*, Liebigs Ann. Chem. *104*, 129 (1857); see also *H. A. Staab*, Angew. Chem. *70*, 37 (1958).

[2] *A. Kekulé*, Bull. Soc. Chim. France *3*, 98 (1865) [Jan. 27th, 1865]. For historical notes see: *J. Gillis*, Meded. Vlaamse, Chem. Vereen. *26*, 189 (1964).

[3] *A. Kekulé*, Bull. Acad. roy. Belgique (2) *19*, 551 (1865) [May 11th, 1865]; Liebigs Ann. Chem. *137*, 129 (1866).

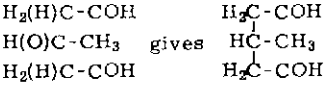
[4] *A. Claus*: Theoretische Betrachtungen und deren Anwendung zur Systematik der organischen Chemie. Freiburg 1867, p. 207; cf. [8].

[5] *J. Dewar*, Proc. Roy. Soc. Edinburgh *1866/1867*, 84.

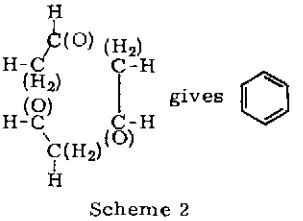
[6] *A. Ladenburg*, Ber. dtsch. chem. Ges. *2*, 140 (1869); *5*, 322 (1872).

In 1872 *Kekulé* examined these proposals [8]. He ruled out formulae *(4)* and *(6)* on the grounds of the equivalence of the six H atoms. The "saturated" structures *(5)* and *(7)* could not, in his opinion, be reconciled with the ability of benzene to add on bromine. The possibility of a combination of systems *(6)* and *(7)* to give a formula *(8)* was mentioned, but was thought to be unlikely for reasons of symmetry.

When *Ladenburg* insisted on his prismatic formula [6], offering as his argument the formation of benzene by non-planar condensation of acetylene, *Kekulé* replied that planar trimerization of acetylene could equally be imagined Nevertheless, he tried to reach a decision by experiment. By analogy with the known condensation of acetone to mesitylene (trimethylbenzene), he tried to prepare benzene by the stepwise condensation of acetaldehyde. He reasoned that if this reaction gave branched-chain intermediates (Scheme 1), then *Ladenburg*'s prismatic structure would be more likely than the planar triene structure, which could only be formed in accordance with Scheme 2 [9a].



Scheme 1



Scheme 2

[7] *E. Hückel* has discussed this system as a planar form: Z. Elektrochem. *45*, 752, 760 (1937). In 1964 we isolated a derivative of tricyclohexane which we named benzvalene [25]. *E. E. van Tamelen* and *S. P. Pappas* [14] discussed a similar structure for a product of photo-isomerization of 1,2,4-t-butylbenzene, which however has a Dewar structure. Cf. also [34] and *E. E. van Tamelen*, Angew. Chem. *77*, 759 (1965); Angew. Chem. internat. Edit. *4*, 738 (1965).

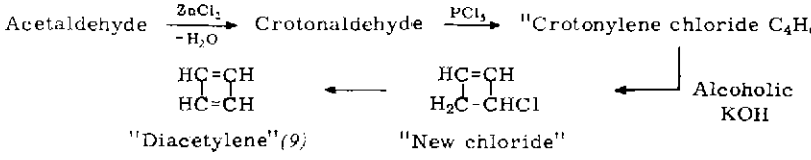
[8] *A. Kekulé*, Liebigs Ann. Chem. *162*, 77 (1872).

[9] a) [8] p. 91; b) [8] p. 98.

The fact that *Kekulé* could not make much progress beyond the unstable crotonaldehyde, formed from two molecules of acetaldehyde, is not surprising. Moreover, since he then attacked the even now unsolved problem of cyclobutadiene [he called it "diacetylene" *(9)*], his experimental failure deserves at least our respectful historical interest [9b].

"Treatment of crotonaldehyde with phosphorus perchloride yields ... crotonylene chloride ... When crotonylene chloride is brought into contact with alcoholic caustic potash, potassium chloride ... precipitates. It seemed likely that hydrochloric acid had been eliminated to form the chloride C_4H_5Cl, and I even hoped to be able to obtain the much-sought diacetylene by the further removal of hydrochloric acid."

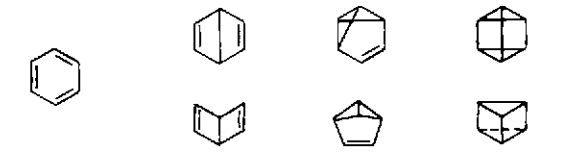
"Unfortunately, I have not yet succeeded in doing this. My experiments indicate very strongly that the reaction of at least part of the crotonaldehyde proceeds in this



direction, but although I used more than a pound of crotonaldehyde for these experiments, I have been unable to obtain either the chloride C_4H_5Cl or diacetylene in the pure form."

We now know from physical measurements that the benzene molecule has a planar symmetrical structure [10]. *Kekulé*'s cyclohexatriene formula is the notation most commonly used, although, as *Kekulé* himself recognized [8], it does not fully satisfy these conditions. According to current concepts, the benzene molecule cannot be completely described by a single Kekulé formula. The ground state can according to the "valence bond" treatment [11] be described to a first approximation by the linear combination of two cyclohextriene structures. A better approximation is obtained if three planar Dewar structures are introduced. In these mathematical discussions, the Ladenburg and benzvalene structures are neglected for the description of the benzene ground state [11]. It is important to remember, however, that the structures proposed by *Kekulé (3)*, *Dewar (6)*, and *Ladenburg (7)*, as well as benzvalene, are only conceived as planar systems without physical reality as isolable entities.

If, on the other hand, the valence-bond isomeric [12] formulae are regarded in the sense of their authors, *i.e.* as being non-planar, they become individual compounds, whose isomerism is due only to the different arrangements of their valences (Scheme 3).



Scheme 3. The valence isomers of benzene

Valence-Bond Isomers of Benzene

Owing to the resonance-stabilization of the planar "Kekulé benzene" and the steric strain in the three non-planar valence isomers of benzene, these should have relatively unfavorable energies and should isomerize more or less readily to the planar benzene. Up to three years ago, despite repeated experiment and discussion, no valence isomers of benzene had been isolated. In 1962, however, *Van Tamelen* used a particularly suitable benzene derivative, namely 1,2,4-tri-t-butylbenzene (which had been prepared by *Hoogzand* and *Hübel* [13]) for photo-isomerization to the Dewar benzene derivative [14]. A year later, the same author carried out an elegant synthesis of Dewar benzene itself, again *via* a bicyclohexene derivative of photochemical origin [15]. Finally, two further syntheses of Dewar structures have recently been achieved, one by *Criegee* et al. [16], apparently by the interception of a "cyclobutadiene" derivative, and the other by *Arnett* et al. [17] by the photoisomerization of 1,2,4,5-tetra-t-butylbenzene.

We entered the field of the valence isomers of benzene from an entirely different point. We had for some years been interested in heterosubstituted acetylenes [18], since owing to the electronic interactions of the triple bond and the heterosubstituents, the linear bond system *(10)* of these compounds is particularly suited to the study of substitution on unsaturated C atoms, without interference (as occurs in alkenes and aromatic com-

[10] *C. K. Ingold* 1936 (infrared and Raman spectra); *R. Wierl* 1913 (C–C distances by electron diffraction); *V. Schomaker* and *L. Pauling* 1939 (X-ray analysis); and further literature cited in *H. A. Staab*: Einführung in die Theoretische Organische Chemie. Verlag Chemie 1960, p. 80.

[11] *E. Hückel*, Z. Phys. *70*, 204 (1931), and [7]; quoted in *L. Pauling*, J. chem. Phys. *1*, 280 (1933), and *H. A. Staab*, [10] pp. 82 and 84.

[12] For the term "valence-bond isomerism", see: *E. Vogel*, Angew. Chem. *74*, 829 (1962); Angew. Chem. internat. Edit. *2*, 1 (1963).

[13] *C. Hoogzand* and *W. Hübel*, Tetrahedron Letters *1961*, 637.

[13a] *E. M. Arnett*, *M. Strom*, and *R. A. Friedel*, Tetrahedron Letters *1961*, 658.

[13b] *L. R. C. Barclay*, *C. E. Milligan*, and *N. D. Hall*, Canad. J. Chem. *40*, 1664 (1962); *A. W. Burgstahler* and *M. O. Abdel-Rahman*, J. Amer. chem. Soc. *85*, 173 (1963).

[14] *E. E. van Tamelen* and *S. P. Pappas*, J. Amer. chem. Soc. *84*, 3789 (1962).

[15] *E. E. van Tamelen* and *S. P. Pappas*, J. Amer. chem. Soc. *85*, 3297 (1963).

[16] *R. Criegee* and *F. Zanker*, Angew. Chem. *76*, 716 (1964); Angew. Chem. internat. Edit. *3*, 695 (1964).

[17] *E. M. Arnett* and *J. M. Bollinger*, Tetrahedron Letters *1964*, 3803.

[18] *H. G. Viehe*, Chem. Ber. *92*, 1270 (1959); Angew. Chem. *76*, 922 (1964); Angew. Chem. internat. Edit. *3*, 755 (1964).

pounds) by short-range effects among the substituents *(11)* [19].

(10) *(11)*

The same is true of additions, and particularly cycloadditions. In linear heterosubstituted acetylenes, the electronic influence of a single hetero-atom decides the direction and rate of the addition. A precise knowledge of this theoretically simple class of compounds is therefore desirable, even though their high reactivity causes considerable experimental difficulties.

Of the particularly interesting acetylenes containing elements of Groups V, VI, and VII as substituents, the alkyne ethers and thioethers are well known, mainly as a result of the work of *Arens* and his school [20]. Of the other two groups, *i.e.* the fluoroalkynes and ynamines, on the other hand, not even the parent compounds were known until recently. Since these compounds should be very reactive, their synthesis is of preparative as well as theoretical interest.

Monofluoroacetylene, which is now obtainable by several methods [21, 22], exhibits surprising chemical behavior [21]. The acidity of the hydrogen is low, but the fluorine atom can be readily substituted, whereas the chlorine atom in chloroacetylene is much more difficult to replace [21]. Thus fluoroalkynes appear to be the most suitable starting material for the anionic introduction of other substituents, particularly heteroatoms, into acetylenes [23].

After many unsuccessful attempts, the first alkylfluoroacetylene, namely tertbutylfluoroacetylene, was synthesized [24]. This compound can only be stored as a gas or in solution at low temperatures. Like monofluoroacetylene [21], it gives a characteristic infrared and NMR spectrum, and has also been characterized by its molecular weight (determined from vapor-density and mass-spectrometric measurements) and by analytical data on its oligomers.

Oligomerization of t-Butylfluoroacetylene

The surprising characteristic of t-butylfluoroacetylene is that it undergoes spontaneous exothermic oligomerization in the liquid phase to trimers and tetramers [25].

[19] *H. G. Viehe*, Chem. Ber. *93*, 1697 (1960); Chem. Ber. *97*, 602 (1964).

[20] Reviewed by *J. F. Arens*, Advances org. Chemistry *2*, 117 (1960).

[21] *H. G. Viehe* and *E. Franchimont*, Chem. Ber. *95*, 319 (1962).

[22] *W. J. Middleton* and *W. H. Sharkey*, J. Amer. chem. Soc. *81*, 803 (1959); *A. S. Jakubowicz, K. M. Smirnow*, and *S. S. Dubow*, Khim. Nauka i Promy. *4*, 551 (1959).

[23] For example, ynamine syntheses *via* fluoroalkyne intermediates: *H. G. Viehe*, Angew. Chem. *75*, 638 (1963); Angew. Chem. internat. Edit. *2*, 477 (1963); *H. G. Viehe* and *M. Reinstein*, Angew. Chem. *76*, 537 (1964); Angew. Chem. internat. Edit. *3*, 506 (1964).

[24] *H. G. Viehe, R. Merényi, J. F. M. Oth*, and *P. Valange*, Angew. Chem. *76*, 888 (1964); Angew. Chem. internat. Edit. *3*, 747 (1964).

Two of the three non-aromatic the valence-bond isomers of the substituted benzene can be isolated from the trimer fraction, which accounts for two-thirds of the entire reaction product, and which consists of roughly equal parts of the Dewar benzene derivative *(12)* and the compound we have named benzvalene *(13)*, together with 1–3 % of a product first formulated as a prismane on the basis of preliminary molecular-weight determinations [25]. X-ray data however showed eight t-butylfluoroacetylene molecules to be present in the unit cell, and redeterminations of the molecular weight when more material had been isolated showed that the compound is a tetramer of t-butylfluoroacetylene and not a prismane. An X-ray structure analysis of this product is in progress.

If this oligomerization is allowed to take place without cooling and in the absence of solvent, the Dewar benzene *(12)* in the product is replaced by the aromatization product 1,2,3-tri-t-butyltrifluorobenzene *(15)*, the structure of which is proved beyond doubt by its nuclear magnetic resonance spectrum and other data.

Thermal and catalytic trimerizations of acetylene are known since the time of *Berthelot*. All previous experience had indicated that monosubstituted acetylenes give benzene derivatives with substituents in the 1,2, and 4 or 1,3, and 5 positions, apparently *via* planar intermediates similar to the Kekulé structures [26]. Our trimerization product *(15)*, on the other hand, corresponds to a 1,2,3-trimerization which had not previously been observed, being similar to that imagined by *Ladenburg* and sought by *Kekulé* [8]. However, not only the 1,2,3-arrangement of the substituents, but also their volume, points to the participation of non-planar intermediates. The volume occupied by the t-butyl group makes even a planar trimerization to 1,2,4-tri-t-butylbenzene unlikely, and a 1,2,3-trimerization should only be possible in a non-planar structure.

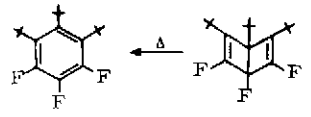
The readily crystallizable 1,2,3-tri-t-butyltrifluorobenzene *(15)* exhibits greater steric strain than any other benzene derivative known at that time. Its formation is all the more surprising in that even *o*-di-t-butylbenzenes had been thought to be sterically incapable of existing until products of this kind were prepared by *Hoogzand* and *Hübel* [13], *Arnett* [13a], and others [13b]. In the meantime, *Arnett* has also obtained a derivative of 1,2,3-tri-t-butylbenzene [17] in which, as in our compound, the steric strain is shown *inter alia* by the ease of thermal or photochemical elimination of a t-butyl group as isobutylene.

The main source of difficulty in the isolation of the non-aromatic valence isomers *(12)* and *(13)* is their limited stability. The thermal stability of these compounds increases from Dewar benzene *(12)* to benzvalene *(13)* [25]. This result was at first surprising. Later the author, together with *J. F. M. Oth* and *R. Merényi*, determined the activation energies of the isomerizations to the aromatic systems [*(12)* → *(15)* and

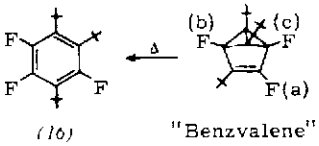
[25] *H. G. Viehe, R. Merényi, J. F. M. Oth, J. R. Senders*, and *P. Valange*, Angew. Chem. *76*, 922 (1964); Angew. Chem. internat. Edit. *3*, 755 (1964).

[26] *W. Hübel* and *C. Hoogzand*, Chem. Ber. *93*, 103 (1960).

(13) → *(16)*] [27]. The results agree approximately with those obtained by subtracting the strain energy and the resonance energy (allyl resonance stabilization) from the C–C single bond energy [28]. The decrease in



1,2,3-Tri-t-butyl-trifluorobenzene *(15)* — „Dewar benzene" *(12)*



(16) — "Benzvalene" *(13)*

instability of these compounds is not surprising, since the phenyl substituents should facilitate the rupture of a C–C bond in the prismane skeleton by resonance-stabilization of the resulting benzyl radical. The synthesis of prismanes containing aliphatic substituents, preferably those that exert a sterically stabilizing action, should be the next aim.

We know from interception reactions during the oligomerization of t-butylfluoroacetylene in styrene or acrylonitrile (without polymerization of these olefins!) that the oligomerization proceeds *via* two dimeric intermediates [27]. Thus in an eightfold excess of styrene or acrylonitrile, the reaction leads to compounds containing two moles of the acetylene and one mole of the olefinic component in yields of up to 80 %. The formation of tetramers in completely suppressed, and the remainder of the product consists of trimers. This part, too, contains the Dewar benzene derivative *(12)* and the benzvalene derivative *(13)* in roughly the same ratio as

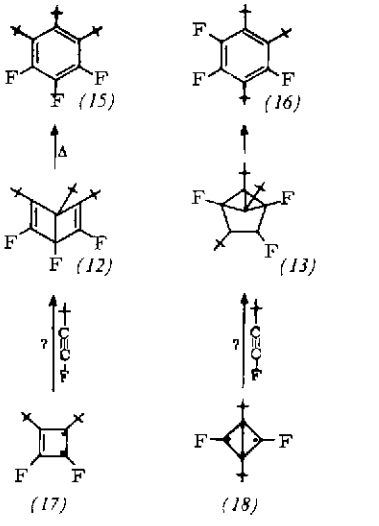
	Behavior on heating	IR C = C	UV	NMR: δ in ppm w.r.t. $Si(CH_3)_4$ or CCl_3F I = intensity
(12)	Rearrangement at 100 °C	5.96 μ	Terminal absorption	Protons: −1.2 (I = 2); −1.12 (I = 1) Fluorine: +103 (I = 2); +181 (I = 1)
(13)	B.p. 140 °C at 11 mm Hg (bath temp.)	5.98 μ	λ_{max} = 232; 300 mμ ε = 2500; 300	Protons: Doublet −1.22 (I = 1) Multiplet −1.16 (I = 2) Fluorine: 102 (I = 1); Doublet 182 (I = 1) Quadruplet 184 (I = 1)
(15)	M.p. 112–114 °C	6.28 μ	λ_{max} = 209; 228; 266; 319 mμ $\varepsilon \times 10^{-3}$ = 14; 7; 19; 1; 4; 1; 0; 79	Protons: Multiplet −1.45 (I = 2) Singlet −1.39 (I = 1) Fluorine: Doublet +127.7 (I = 2) Triplet +154.8 (I = 1)
(16)	M.p. 53–54 °C	6.22 μ	λ_{max} = 201; 238; 297 mμ $\varepsilon \times 10^{-3}$ = 25; 6.6; 1.5	Protons: An asymmetric multiplet centered at −1.45 Fluorine: Multiplet +102 (I = 1) Double multiplet +132 (I = 1) Double multiplet +135 (I = 1)

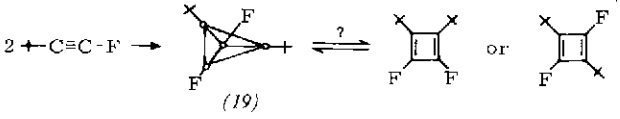
activation energy by resonance stabilization predominates, explaining why the activation energy for isomerization to the more stable aromatic system increases with the number of double bonds in the valence isomer.

For the same reason, bicyclobutane is more stable than cyclobutene, *i.e.* the activation energy of the isomerization to 1,3-butadiene is about 8 kcal/mole higher for bicyclobutane [29]. Cubane is another example of a thermally stable saturated system of condensed microcycles [30].

A different situation obtains for the energies of the valence isomers in the ground state than for the apparent thermal stabilities, which are determined by the activation energies. The resonance-stabilized aromatic system *(3)* has the lowest ground state energy, while prismane probably has the highest. Nothing can be said about the ground-state energies of Dewar benzene and benzvalene until thermochemical data are available.

Tetraphenylprismane and hexaphenylprismane have been postulated as extremely unstable intermediates [31]. The in the undisturbed trimerization of t-butylfluoroacetylene. The structure of the interception products is not known with certainty, but they are probably condensed bicyclobutane derivatives (similar to benzvalene).





Scheme 4. Possible course of the formation of the Dewar benzene and benzvalene derivatives *(12)* and *(13)* from t-butylfluoroacetylene.

[27] *J. F. M. Oth, R. Merényi,* and *H. G. Viehe,* unpublished work.

[28] *W. v. E. Doering* and *W. R. Roth,* Angew. Chem. *75,* 27 (1963); Angew. Chem. internat. Edit. *2,* 115 (1963).

[28a] Cf. also *W. N. Lipscomb,* Tetrahedron Letters *1959,* No. 18, p. 20.

[29] *H. M. Frey* and *I. D. R. Stevens,* Trans. Faraday Soc. *61,* 90 (1965).

[30] *P. E. Eaton* and *T. W. Cole,* J. Amer. chem. Soc. *86,* 3157 (1964).

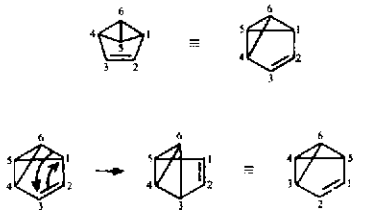
[31] *R. Breslow* and *P. Gal,* J. Amer. chem. Soc. *81,* 4747 (1959); *R. Breslow* in *P. de Mayo*: Molecular Rearrangements. Interscience, New York 1963, p. 243.

Thus the valence isomers of benzene lead us to those of cyclobutadiene [28a]. Our trimers *(12)* and *(13)* can be formally derived most easily from the biradical forms of cyclobutadiene and bicyclobutane *(17)* and *(18)* corresponding to the cyclobutadiene and tetrahedrane limiting formulae. A tetrahedrane structure with two t-butyl groups and two fluorine atoms seems energetically more favorable than the corresponding planar cyclobutadiene derivative with t-butyl groups in positions 1 and 2. Moreover, an intermediate tetrahedrane structure *(19)* would provide a simple explanation of the simultaneous "head-to-head" and "head-to-tail" trimerization, owing to the possibility of valence isomerization to form either the planar 1,2- or the 3-cyclobutadiene derivative, as shown in Scheme 4. These views are summarized in the hypothetical reaction Scheme 4. The alternatives of tetramer formation by the condensation of dimer and dimer or of trimer and monomer remain undecided.

The Formal Series of Valenes

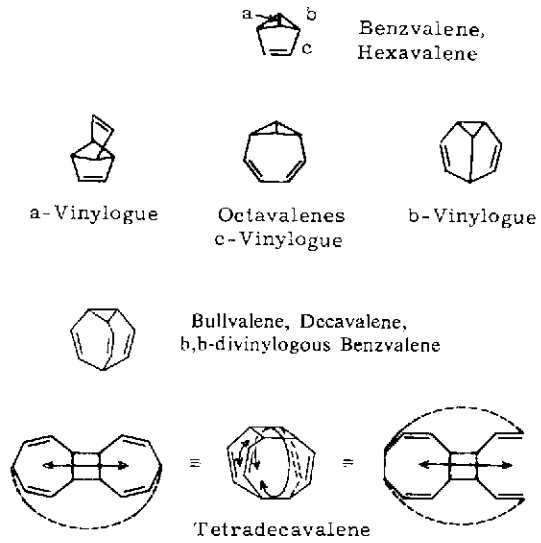
The name "benzvalene" for the compound *(13)* is intended to express two ideas. The first is that the compound is a valence isomer of benzene, and the second is that it is the first member of the hypothetical series of valenes.

If the atoms of benzvalene are numbered as in Scheme 5, the relative positions and linkages of the C atoms in the skeleton can be changed, without the formation of a new molecule, by a valence interchange between the double bond and the cyclopropane rings. If this valence isomerization occurs sufficiently often, the atoms numbered 1–6 in Scheme 5 must ultimately be statistically distributed over the entire molecule. *Doering* has developed similar concepts for bullvalene [28]. The vinylogues of benzvalene should also behave in a similar manner.



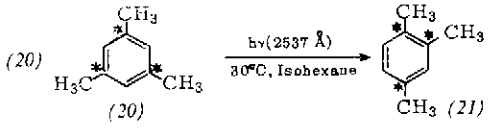
Scheme 5. Isomerization of benzvalene

Benzvalene contains three different types of single bonds, which are indicated by letters in Scheme 6. If these bonds are opened and two C atoms with a new double bond inserted, we obtain three vinylogous octavalenes. The insertion of another vinyl group into the octavalenes yields a series of decavalenes, one of which has recently become well known; this is bullvalene [28, 32], in which the steric and electronic conditions are optimal for valence isomerization. Among the higher vinylogous valenes, a special place is accorded to the hypothetical tetradecavalene. Just as valence isomerization takes place between two double bonds and one cyclopropane ring in bullvalene, so a cyclobutane ring in tetradecavalene would formally migrate in a closed band between the two cycloheptadiene rings, which are linked by three single bonds. Another valence isomerization transverse to this band, with disintegration of the four-membered ring and formation of a three-membered ring, would also be possible, but this would lead to a different molecule.



Scheme 6. Valenes

Evidence of the reality of these ideas has recently been found, at least for benzene. Thus when *o*-xylene is irradiated with ultraviolet light, the *meta* and *para* isomers are formed [33]. Similarly, 1,2,4-trimethylbenzene *(21)* is obtained from 1,2,3-trimethylbenzene *(20)*. For the latter reaction it was shown by labelling with ^{14}C that the methyl groups do not change their positions by separating from the benzene ring [34]. If, however, the bonds between the ring atoms and the methyl groups remain intact during the photoisomerization, then valence isomers of benzene must be involved in this rearrangement. A simple explanation is offered by a benzvalene structure, which is formally equivalent to an excited Dewar benzene structure. However, the question of why the isomers are unequally distributed in the photo-stationary equilibrium still remains unanswered so long as the effect of substituents on the isomerization is unknown. The C atoms in the unsubstituted benzene

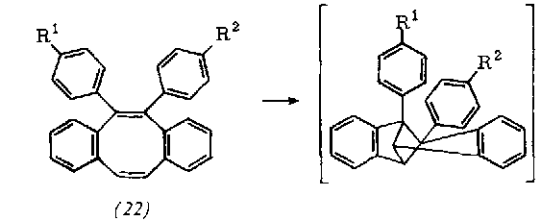


[32] *G. Schröder*, Angew. Chem. *75*, 722 (1963); Angew. Chem. internat. Edit. *2*, 481 (1963).

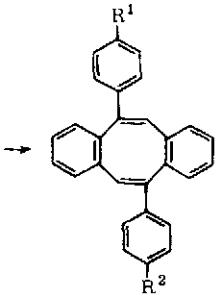
[33] *K. E. Wilzbach* and *L. Kaplan*, J. Amer. chem. Soc. *86*, 2307 (1964).

[34] *L. Kaplan, K. E. Wilzbach, W. G. Brown*, and *Shü Shu Yan*, J. Amer. chem. Soc. *87*, 675 (1965).

should also be statistically distributed under the conditions of the valence isomerization. A similar phenomenon would also explain the recently observed photo-isomerizations of t-butylbenzenes [17, 35]. There is also some evidence of similar valence isomerizations among the octavalenes [36]. Under relatively mild conditions,



(22)



a) $R^1 = R^2 = C_6H_5$
b) $R^1 = R^2 = p\text{-}CH_3\text{-}C_6H_4$
c) $R^1 = R^2 = p\text{-}Br\text{-}C_6H_4$
d) $R^1 = C_6H_5$; $R^2 = p\text{-}Br\text{-}C_6H_4$

for example, the cyclooctatetraene derivative *(22)* undergoes a valence isomerization which is formulated as proceeding *via* an *a*-vinylogous octavalene [36]. It is not yet known whether a similar explanation applies in the case of the Jacobsen rearrangement, which according to recent evidence proceeds by a free-radical mechanism [37]. The photo-isomerization of indazole to benzimidazole [38] also deserves attention in this connection.

[35] *A. W. Burgstahler* and *P. Chien*, J. Amer. chem. Soc. *86*, 2940, 528 (1964).

[36] *M. Stiles* and *C. Burkhardt*, J. Amer. chem. Soc. *86*, 3396 (1964).

[37] *F. Bohlmann* and *J. Riemann*, Chem. Ber. *97*, 1515 (1964).

[38] *H. Tiefenthaler*, *W. Dörschelen*, *H. Goth*, and *H. Schmid*, Tetrahedron Letters *1964*, 2999.

Summary

1. Whereas t-butylchloroacetylene is stable for long periods at 150 °C, t-butylfluoroacetylene undergoes an exothermic oligomerization even below 0 °C. Thus there is an analogy to the relationships between tetrafluoroethylene and tetrachloroethylene, and between vinylidene fluoride and vinylidene chloride.

2. The oligomerization of t-butylfluoroacetylene proceeds *via* dimers as shown by interception with styrene or acrylonitrile. The fact that no polymerization of the olefin occurs makes the formation of free-radical intermediates unlikely, even though they are used as limiting formulae to describe the reaction.

3. The dimers react to give products that can be formally explained by the assumption of intermediate biradical limiting structures based on cyclobutadiene and its valence-bond isomer, tetrahedrane.

4. The stability (expressed by the activation energy of the isomerization to the aromatic system) of the non-aromatic valence isomers increases as the number of double bonds decreases.

5. The vinylogous benzvalene may be regarded as the parent member of a hypothetical vinylogous series of valenes, if we define these as compounds whose valence isomerization leads to the mutual displacement of atoms of the skeleton. An example of these compounds is bullvalene, which, as a decavalene, is a member of the series.

The author is grateful to *A. Bothner-By*, *J. H. Block*, *E. H. Braye*, *S. Y. Delavarenne*, *R. H. Gillette*, *C. Hoogzand*, *A. Halleux*, *R. G. Merényi*, *P. L. Moentack*, *C. H. Moussebois*, *J. F. M. Oth*, *J. R. Senders*, *P. Valange*, *and R. B. Woodward for valuable discussions or practical assistance.*

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Molecules Undergoing Fast, Reversible Valence-Bond Isomerization [1]

(Molecules with Fluctuating Bonds)

BY PRIV.-DOZ. DR. G. SCHRÖDER

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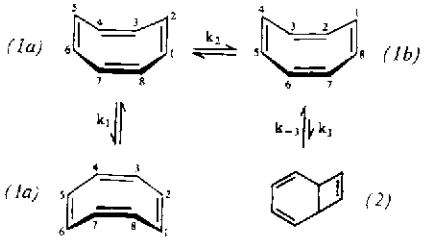
Compounds which undergo fast and reversible valence-bond isomerization (i.e. which have fluctuating cyclopropyl and/or double bonds) are taken to be those in which the average lifetime of the valence-bond isomers at 0 °C is of the order of 100 seconds at most, and for which the maximum activation energy of the bond migration is 20 kcal/mole. The fast, reversible bond shift can scarcely be detected by chemical means, but can be recognized by NMR spectroscopy, since the time for which a proton occupies a position with a given magnetic environment has a pronounced influence on the NMR spectrum. Some examples of molecules with fluctuating bonds are cyclooctatetraene and its derivatives, unsaturated seven-membered ring systems, homotropilidene, bridged homotropilidene systems, bullvalene, and substituted bullvalenes. The last class is particularly interesting, since here the carbon atoms are continually changing their relative positions and neighbors.

I. Introduction

In order to reconcile the equivalence of all six carbon-carbon bonds in benzene with his cyclohexatriene formula, *Kekulé* [2] assumed that "one carbon atom is doubly bonded to one of the adjacent carbon atoms for one unit of time, and to the other adjacent carbon atom for the next . . ." Thus according to the *Kekulé* picture, the bonds in benzene jump backwards and forwards, *i.e.* they oscillate or fluctuate. This attempted explanation is now known to be untenable. The actual structure of benzene is somewhere between two fictitious limiting cyclohexatriene structures; the π-electrons in benzene are delocalized. However, *Kekulé*'s basic postulate of the equivalence of all six carbon-carbon bonds in benzene is correct.

Kekulé's oscillation theory is currently attracting interest again, since it is capable of describing the behavior of molecules with fluctuating bonds. The bonding electrons in these molecules, however, unlike those in benzene, are localized, and depend on valence isomerization for their sudden shift. Valence isomerization is a reorganization of π, or of π and σ, electrons accompanied by changes in interatomic distances and bond angles but without migration of atoms or groups [3]. It is an intramolecular rearrangement which obeys first-order kinetics, is practically uncatalysable, is independent of solvent, and can be influenced only by temperature. It belongs to the class of "no-mechanism" reactions [4].

Of the many molecules that exhibit valence isomerization, we shall be concerned only with those in which the phenomenon is fast and reversible, *i.e.* in which the mean lifetime of the valence-bond isomers at 0 °C is of the order of 100 seconds or less and the activation energy ΔE^* of the isomerization is not greater than 20 kcal/mole. This arbitrary convention is based on the use of NMR spectroscopy as the means of detection. Molecules of this type may be said to have fluctuating bonds. This concept may be illustrated with cyclooctatetraene *(1)* as an example.



This compound can undergo three different isomerizations, the kinetic data for which are given in Table 1:

1. The ring inversion *(1a)* $\rightleftarrows$ *(1a)* (see Section III, 1) is due to rotation about the C–C single bonds. There is no reorganization of the bonding electrons. Consequently this is not a valence - bond isomerization.

2. The reaction *(1a)* $\rightleftarrows$ *(1b)* (see Section III, 1), on the other hand, is characterized by a reversible bond migration involving all four double bonds [5]. The molecular structure remains unchanged, but if we number the carbon atoms, the structures *(1a)* and *(1b)* are different. The two valence isomers have the same energy and the same lifetime $\Delta t_{(1a)}$ of about 1.4×10^{-2} sec at 0 °C. Thus according to our arbitrary condition, this is an example of a fast, reversible valence-bond isomerization.

3. As far as the type of reaction is concerned, there is fundamentally no difference between *(1a)* $\rightleftarrows$ *(1b)* and the dynamic

[1] Part VII. Part VI: *J. F. M. Oth, R. Merényi, J. Nielsen,* and *G. Schröder,* Chem. Ber., in press.

[2] *A. Kekulé,* Bull. Soc. chim. France *3,* 98 (1865); Liebigs Ann. Chem. *137,* 129 (1866); *H. A. Staab,* Angew. Chem. *70,* 37 (1958).

[3] *E. Vogel,* Angew. Chem. *74,* 829 (1962).

[4] *S. J. Rhoads* in *P. de Mayo,* Molecular Rearrangements. Wiley, New York/London 1963, p. 655.

[5] *F. A. L. Anet,* J. Amer. chem. Soc. *84,* 671 (1962).

equilibrium of cyclooctatetraene with bicyclo[4.2.0]octa-2,4,7-triene *(2)* [6,7]. This is again a reversible valence isomerization (equilibrium constant $K = [(1)]/[(2)] \approx 10^4$), but it is not fast, since the lifetimes of *(2)* and *(1)* (carbon atoms not distinguished) at 0 °C are more than 100 sec (see Table 1).

Table 1. Kinetic data for the isomerizations of cyclooctatetraene [5—7]. k = rate constant, $\Delta E^{\neq}$ = activation energy, Δt = lifetime.

Structure	Δt at 0 °C [sec]	Isomerization	k at 0 °C [sec^{-1}]	$\Delta E^{\neq}$ [kcal/mol]
(1) [a]	1.7×10^{9}	Ring inversion *(1a)* ⇄ *(1a)*	$k_1 \approx 10$ [b]	—
(1a) or *(1b)*	1.4×10^{-2}	Valence isomerization *(1a)* ⇄ *(1b)*	$k_2 = 70$	13.7
(2)	1.1×10^{3}	Valence isomerization *(1)* ⇄ *(2)*	$k_3 = 6\times10^{-10}$ $k_{-3} = 9.1\times10^{-4}$	27.2 18.7

[a] C atoms not distinguished.

[b] Estimated from measurements on substituted cyclooctatetraene *(15)* (see Section III,1).

II. Detection of Valence-Bond Isomerization

Molecules with fluctuating bonds can scarcely be recognized as such by chemical means. The simplest and best method of detection is NMR spectroscopy. The lifetime Δt of a structure, or in general, the time during which a position with a given magnetic environment is occupied by a proton, has a strong influence on the NMR spectrum.

In infrared and ultraviolet spectroscopy, the energy difference, $\Delta E = h\Delta\nu$, between the individual absorption bands is so large that, even for short-lived structures, the spectrum obtained reflects all the structures present. The chemical shifts in the NMR spectra, on the other hand, correspond to very small energy differences, the measurement of which requires an appreciable time. It follows that the lifetime Δt of a compound plays an important part in NMR spectroscopy. The product $\Delta t\cdot\Delta\nu$ determines the NMR spectra of dynamic systems, where $\Delta\nu$ (in c.p.s.) $= \nu_A - \nu_B$; ν_A and ν_B are the chemical shifts of the same proton in two valence isomers in the absence of exchange [8].

Molecules with fluctuating bonds have temperature-dependent spectra provided that 1. the rate constant for the valence isomerization is such that $10^{-3} < \Delta t\cdot\Delta\nu < 10$, *i.e.* $10^{-3} < k^{-1}\cdot\Delta\nu < 10$; and 2. the valence isomers in equilibrium with one another have identical structures (equilibrium constant $K = 1$), or if the structures are different, they are present in comparable concentrations (equilibrium constant $K < 20$).

The temperature-dependence of the NMR spectra of tricyclo[3,3,2,$0^{4,6}$]deca-2,7-diene (dihydrobullvalene) [9] is shown in Fig. 1. The valence isomers in this case are structurally identical. However, if the carbon (or hydrogen) atoms are distinguished from one another, the two coexisting structures become different.

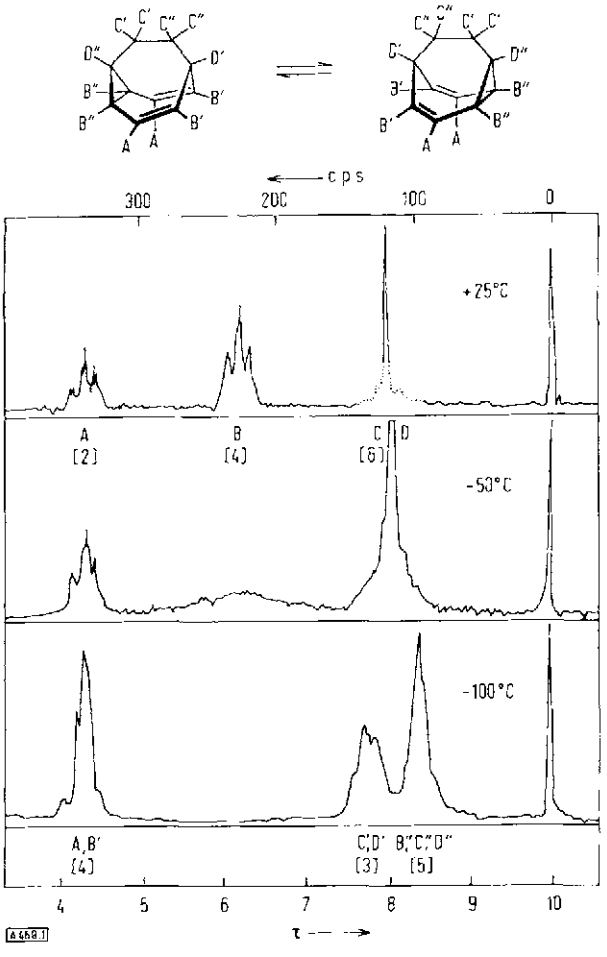


Fig. 1. NMR spectrum of dihydrobullvalene (tricyclo[3.3.2.0.4,6] deca-2,7-diene) [9,10]. Internal standard: tetramethylsilane.

A hydrogen atom B, for example, is attached to a cyclopropane group in one valence isomer, while in the other it is attached to an olefinic group. The average lifetime of the isomers at −100 °C is so long ($\Delta t\cdot\Delta\nu > 10$) that the NMR spectrum contains relatively sharp bands corresponding to the states of the protons. The spectrum can now be said to correspond to the structural formula.

As the average lifetime decreases with rising temperature ($10 > \Delta t\cdot\Delta\nu > 10^{-3}$), the bands for the protons B first become indistinct and then spread until they finally coalesce to form one wide band. Only one maximum is observed at −50 °C.

If the valence isomerization is accelerated by further heating ($\Delta t\cdot\Delta\nu < 10^{-3}$), the NMR spectrum again exhibits sharp bands. As a result of the fast and reversible valence isomerization, pairs of protons become identical and the chemical shifts and coupling constants now have average values. For example, at 25 °C the spectrum contains a band centered at about $\tau = 6.32$, corresponding to the four B protons.

At higher temperatures, therefore, the NMR spectrum reflects the dynamic situation (valence isomerization), while

[6] *R. Huisgen*, Lecture at the International Symposium on Reaction Mechanisms in Organic Chemistry, July 20th—25th, 1964 in Cork (Ireland). Cf. Angew. Chem. *76*, 928 (1964); *R. Huisgen* and *F. Mietzsch*, Angew. Chem. *76*, 36 (1964); Angew. Chem. internat. Edit. *3*, 83 (1964).

[7] *E. Vogel, H. Kiefer*, and *W. R. Roth*, Angew. Chem. *76*, 432 (1964); Angew. Chem. internat. Edit. *3*, 442 (1964).

[8] *H. S. Gutowsky* and *C. H. Holm*, J. chem. Physics *25*, 1228 (1956).

[9] *R. Merényi, J. F. M. Oth*, and *G. Schröder*, Chem. Ber. *97*, 3150 (1964).

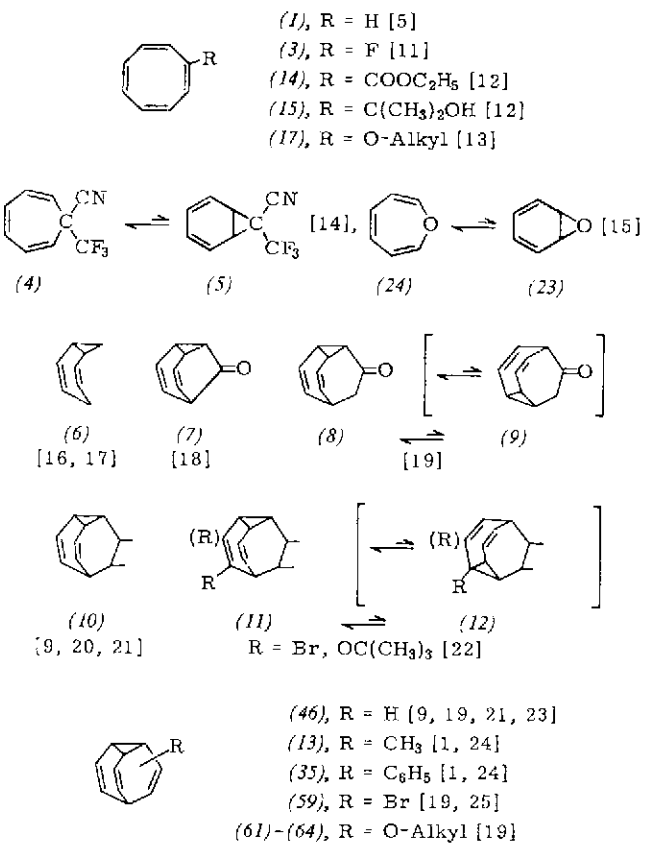
[10] The numbers in square brackets indicate the relative intensities of the signals. The sensitivity of the instrument was occasionally varied during the recording of a spectrum.

at lower temperatures it reflects the static situation, *i.e.* the structure of the compound.

The kinetic data for the valence isomerization can be deduced from the form of the NMR signal at various temperatures [8] (for examples, see Table 3).

III. Known Molecules with Fluctuating Bonds

Several molecules with fluctuating bonds have recently become known. These include cyclooctatetraene *(1)* and some of its derivatives, such as *(3)*, *(14)*, *(15)*, and *(17)*, a number of unsaturated seven-membered ring systems such as *(4)* ⇄ *(5)*, *(23)* ⇄ *(24)*, bicyclo[5.1.0]octa-2,5-diene *(6)* (homotropilidene), bridged homotropilidene systems of the type *(7)*, *(8)* ⇄ *(9)*, *(10)*, *(11)* ⇄ *(12)*, and bullvalene *(46)* and some of its derivatives (see Scheme 1).

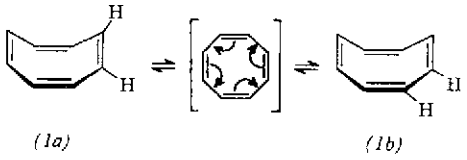


Scheme 1.

1. Cyclooctatetraene and Derivatives

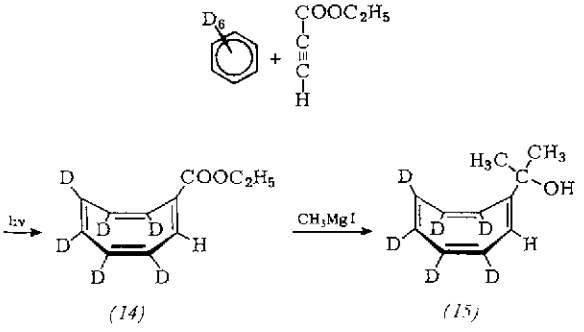
The fluctuation of the bonds in cyclooctatetraene was recently recognized by *Anet* [5] and *Roberts* [11] from the NMR spectra. The ^{13}C satellites in the proton resonance spectrum of this compound (resulting from a spin-spin coupling of the H atoms with the natural ^{13}C in the cyclooctatetraene) change with temperature. The rate constant k for the valence isomerization *(1a)* ⇄ *(1b)* was deduced from the temperature-dependence of the satellites. The free energy of activation is about 13.7 kcal/mole at −10 °C [5].

The valence isomerization very probably passes through a planar cyclooctatetraene in the transition state.

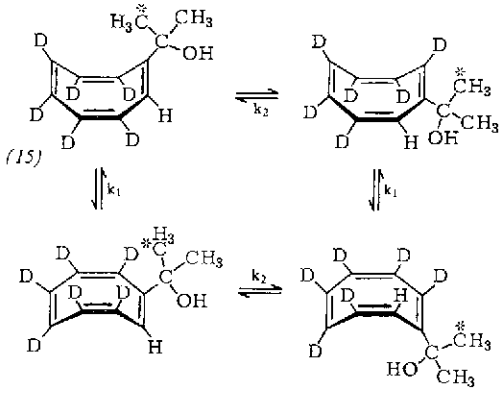


The bonds in the eight-membered ring also fluctuate in substituted cyclooctatetraenes. Thus the fluorine resonance signal of fluorocyclooctatetraene *(3)* undergoes a striking change between room temperature and −65 °C [11]. The free energy of activation for the valence-bond isomerization at −33 °C is about 12 kcal/mole [11].

Anet et al. [12] prepared the derivatives *(14)* and *(15)*.



The kinetic data k_2 for the bond migration in *(14)* and *(15)* and k_1 for the ring inversion in *(15)* were deduced from the temperature-dependence of the ^1H–NMR spectra with additional irradiation at the frequency of deuterium [*]. One of the two (non-equivalent) methyl groups in *(15)* is distinguished by an asterisk.



It can be seen from Table 2 that the bond migration in the ethyl cyclooctatetraene carboxylate *(14)* is faster than in the cyclooctatetraenyldimethylcarbinol *(15)*, and that the free energy of activation for the ring inversion in *(15)* is less than that for the bond migration.

[11] *J. D. Roberts*, Angew. Chem. *75*, 20 (1963); Angew. Chem. internat. Edit. *2*, 53 (1963); *D. E. Gwynn, G. M. Whitesides*, and *J. D. Roberts*, J. Amer. chem. Soc. *87*, 2862 (1965).

[12] *F. A. L. Anet, A. J. R. Bourn*, and *Y. S. Lin*, J. Amer. chem. Soc. *86*, 3576 (1964).

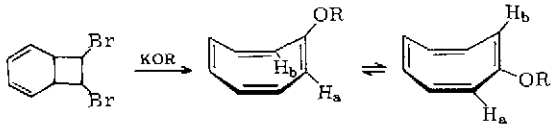
[*] Simpler spectra are obtained by this additional irradiation because the H/D coupling is eliminated.

The cyclooctatetraenyl alkyl ethers *(17)*, which are prepared by the action of potassium alkoxides on the dibromide *(16)*, also have temperature-dependent NMR spectra [13]. The resonance signal of the proton H_a in *(17a)* is clearly separated in the low-temperature spectrum from the signals of the other

Table 2. Kinetic data for the bond migration k_2 and the ring inversion k_1 in compounds *(14)* and *(15)*. ΔF^*, ΔH^*, ΔS^* = free energy, enthalpy, and entropy of activation, respectively.

Compound	Temp. [°C]	Reaction	k [sec^{-1}]	ΔF^* [kcal/mole]	ΔH^* [kcal/mole]	ΔS^* cal·mole^{-1}·deg^{-1}
(14)	40	k_2	126	15.3	12.8	−8.0
(15)	41	k_2	5.4	17.4	15.4	−6.3
	−2	k_2	0.1	17.1		
	−2	k_1	7.8	14.7		

protons attached to the eight-membered ring. At higher temperatures, the NMR method cannot distinguish between H_a and H_b. This result shows that the cyclooctatetraenyl alkyl ethers undergo a rapid and reversible valence-bond isomerization *(17a)* ⇄ *(17b)*.



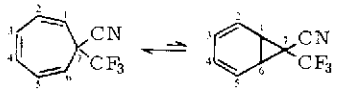
(16) *(17a)* *(17b)*

R = CH_3, C_2H_5, $C(CH_3)_3$

2. Unsaturated Seven-Membered Ring Systems

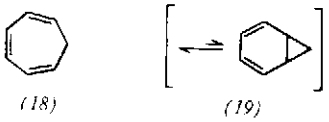
a) A Cycloheptatriene/Norcaradiene Derivative

Cycloheptatriene and norcaradiene were shown by *Ciganek* [14] to be related by a rapid and reversible valence isomerization in the case of a 7-cyano-7-trifluoromethyl derivative *(4)* ⇄ *(5)*.



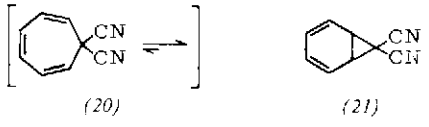
(4) 80% *(5)* 20%

The valence isomers *(4)* and *(5)* have different structures. Since the equilibrium constant is about 4, the valence-bond isomerization can be recognized by the temperature-dependence of the NMR spectrum. At room temperature the ^{1}H-NMR spectrum contains a complex multiplet between τ = 3.2 and 3.8 (protons on C-2, C-3, C-4, and C-5 and a doublet centered at about τ = 5.30 (protons on C-1) and C-6). This doublet widens as the temperature is lowered, and ultimately gives two new signals: a doublet at τ = 4.60 [protons on C-1 and C-6 in *(4)*] and a fairly broad singlet at τ = 7.01 [protons on C-1 and C-6 in *(5)*], the areas being in the ratio 4:1.



(18) *(19)*

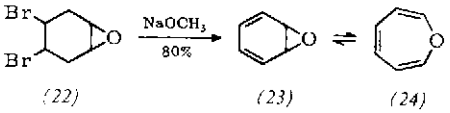
NMR measurements on cycloheptatriene *(18)* at various temperatures give no indication of the presence of norcaradiene *(19)* [26]. On the basis of *Ciganek*'s results, it may be assumed that a reversible valence isomerization occurs, but that cycloheptatriene is present to the extent of practically 100%. In the case of a 7,7-dicyano derivative, on the other hand, the equilibrium mixture consists almost entirely of the norcaradiene structure *(21)* [27].



(20) *(21)*

b) Oxepin/Benzene Oxide

Vogel, *Böll*, and *Günther* [15] found that the dehydrohalogenation of 1,2-epoxy-4,5-dibromocyclohexane *(22)* leads to a non-phenolic, orange product in good yield. The temperature-dependence of the NMR spectrum indicates a fast and reversible valence isomerization between oxepin *(24)* and benzene oxide *(23)*. The equilibrium constant appears to be affected by the temperature and (as ultraviolet absorption studies show) by the solvent [*].



(22) *(23)* *(24)*

[13] *G. Schröder*, *Th. Martini*, *J. F. M. Oth*, and *R. Merényi*, unpublished work.

[14] *E. Ciganek*, J. Amer. chem. Soc. *87*, 1149 (1965).

[15] *E. Vogel*, *W. A. Böll*, and *H. Günther*, Tetrahedron Letters *1965*, 609.

[16a] *W. v. E. Doering*, Zh. Vses. Khim. Obshchestva im D.I. Mendeleeva, *7*, 308 (1962).

[16b] *W. v. E. Doering* and *W. R. Roth*, Angew. Chem. *75*, 27 (1963); Angew. Chem. internat. Edit. *2*, 115 (1963).

[17] *W. v. E. Doering* and *W. R. Roth*, Tetrahedron *19*, 715 (1963).

[18] *W. v. E. Doering* and *B. Ferrier*, footnote in [16b, 17].

[19] *W. v. E. Doering* and *G. Klumpp*, unpublished work.

[20] *G. Schröder*, Chem. Ber. *97*, 3131 (1964).

[21] *G. Schröder*, Chem. Ber. *97*, 3140 (1964).

[22] *H. Röttele*, Diploma Thesis, Technische Hochschule Karlsruhe, 1965.

[23] *G. Schröder*, Angew. Chem. *75*, 722 (1963); Angew. Chem. internat. Edit. *2*, 481 (1963).

[24] *G. Schröder*, *R. Merényi*, and *J. F. M. Oth*, Tetrahedron Letters *1964*, 773.

[25] *G. Schröder*, Angew. Chem. *77*, 682 (1965); Angew. Chem. internat. Edit. *4*, 695 (1965).

[26] *F. A. L. Anet*, J. Amer. chem. Soc. *86*, 458 (1964); *F. R. Jensen* and *L. A. Smith*, ibid. *86*, 956 (1964).

[27] *E. Ciganek*, J. Amer. chem. Soc. *87*, 652 (1965).

[*] Note added in proof: The following kinetic data (at 0 °C) were determined from the half-widths of the α-proton signals (*H. Günther*, personal communication):

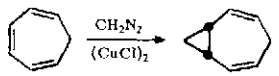
(23) $\underset{k_b}{\overset{k_a}{\rightleftharpoons}}$ *(24)*

k_a = 14.1 · 10^6 sec^{-1}; ΔE_a^* = 9.1 kcal/mole

k_b = 2.29 · 10^6 sec^{-1}; ΔE_b^* = 7.2 kcal/mole.

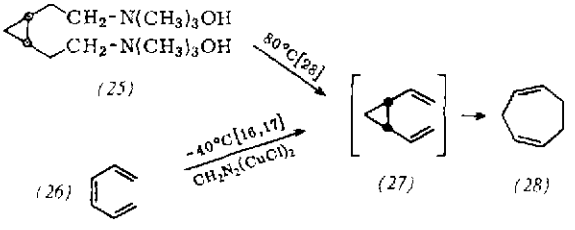
c) Homotropilidene (Bicyclo[5.1.0]octa-2,5-diene)

The reaction of cycloheptatriene *(18)* with diazomethane leads *inter alia* to bicyclo[5.1.0]octa-2,5-diene (homotropilidene *(6)* [16,17].



(18) *(6)*

Homotropilidene contains the *cis*-1,2-divinylcyclopropane grouping. Attempts at the preparation of *(27)* [16,17,28] resulted in the formation of 1,4-cycloheptadiene *(28)*, the valence-bond isomer of *(27)*.

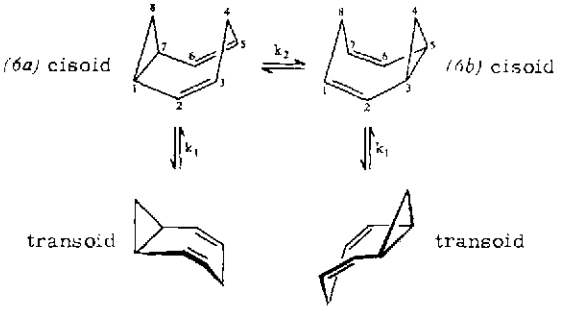


(25) *(26)* *(27)* *(28)*

The formation of *(28)* was explained by postulating the occurrence of *cis*-1,2-divinylcyclopropane *(27)* as an intermediate; this presumably undergoes a very fast Cope rearrangement. The valence-bond isomerization *(27)* → *(28)* is made possible by the reduction of the activation energy owing to the *cis* arrangement of the two vinyl groups on the three-membered ring. The geometry of the transition state is already largely present in the ground state [17,28]. The geometry of the *trans*-isomer, on the other hand, does not favor the rearrangement [3]; this isomer can therefore be isolated, and rearranges into *(28)* only at 190 °C.

The lifetime of the compound *(27)* at −40 °C is evidently still so short that the compound cannot be isolated [17]. If the two vinyl groups in *(27)* are linked by one methylene group, the resulting structure is homotropilidene *(6)*.

The structure of *(6)* is not changed by valence isomerization. If the carbon (or hydrogen) atoms are distinguished from one another, however, the two structures *(6a)* and *(6b)* existing in equilibrium are different.



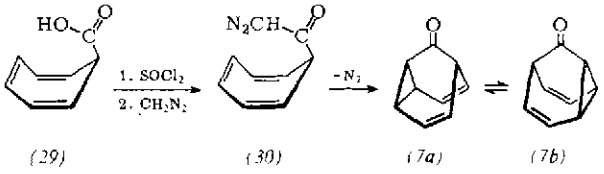
The temperature-dependence of the NMR spectrum of homotropilidene shows it to undergo fast and reversible valence-bond isomerization [29]. The dynamic equilibrium between the two valence-isomeric structures is superposed on an equilibrium between two conformational isomers *(cisoid* and *transoid)*. This makes it difficult to determine the kinetic data for the valence isomerization from the NMR spectra.

[28] *E. Vogel, K.-H. Ott*, and *K. Gajek*, Liebigs Ann. Chem. *644*, 172 (1961).

[29] *Doering* and *Roth* [16,17] coined the term "fluctuating structure" in a study of homotropilidene.

d) Bridged Homotropilidene Systems of the Type *(7)*

The reaction of the acid chloride of cycloheptatrien-7-carboxylic acid *(29)* with diazomethane yields a diazoketone *(30)*, which by elimination of nitrogen forms tricyclo[3.3.1.$0^{4,6}$]nona-2,7-dien-9-one *(7)* [18] [*].

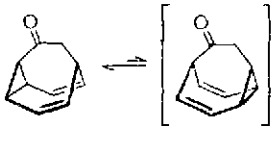


(29) *(30)* *(7a)* *(7b)*

The homotropilidene part of the tricyclic ketone *(7)* is fixed in the *cisoid* configuration by the carbonyl bridge. This compound undergoes a reversible and extremely fast valence-bond isomerization. The NMR spectrum of *(7)* shows little change as a result of cooling to −30 °C. The chemical shifts and coupling constants found for the pairs of identical protons resulting from the valence-bond isomerization *(7a)* ⇄ *(7b)* are average values. The spectrum comprises three groups of bands corresponding to three groups of equivalent protons. Only at about −90 °C does the average lifetime of the isomers becomes sufficiently long to give a spectrum corresponding to the structural formula. The kinetic data for *(7)* were determined by *Lambert* [30] from the NMR spectra. The activation energy ΔE^* of the reaction *(7a)* ⇄ *(7b)* is 8.2 kcal/mole (cf. Table 3).

e) Bridged Homotropilidene Systems of the Type *(8)*

Doering and *Klumpp* [19] synthesized the tricyclic ketone *(8)* by the Al_2O_3-catalysed ring expansion of *(7)* with diazomethane.



(8) *(9)*

Valence-bond isomerization should lead to the formation of the structurally different *(9)* from *(8)*. The NMR spectrum of *(8)* is independent of temperature [19], suggesting that the equilibrium is dominated by a single isomer. Conjugation between the carbonyl group and the three-membered ring evidently makes *(8)* by far the more stable of the two isomers.

f) Bridged Homotropilidene Systems of the Type *(10)*

Homotropilidene systems of the type *(8)* contain an unsymmetrical bridge consisting of two carbon atoms. The two valence-bond isomers therefore have different

[30] *J. B. Lambert*, Tetrahedron Letters *1963*, 1901.

[*] Note added in proof: Reduction of *(7)* with hydrazine hydrate in diethylene glycol/KOH gives *inter alia* tricyclo-[3.3.1.$0^{4,6}$]nona-2,7-diene, which undergoes reversible valence-isomerization with ΔE^* = 8.76 kcal/mole, k (−80 °C) = 8016 sec^{-1}. *(W. v. E. Doering* and *J. H. Hartenstein*, personal communication).

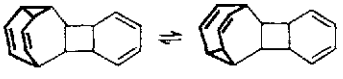
structures. Bridged homotropilidene systems of the type *(10)*, on the other hand, contain a symmetrical bridge of two carbon atoms, and therefore the valence isomers are structurally identical, *i.e.* the equilibrium constant K is unity. The valence-bond isomerization can be studied with the aid of the temperature-dependent NMR spectra, as in the case of tricyclo[3.3.2.0^{4,6}]deca-2,7-diene (Section II). The kinetic data for bridged homotropilidenes of the types *(7)* and *(10)*, as well as for bullvalene, are also given in Table 3.

Table 3. Kinetic data for bridged homotropilidene systems.

Compound	k [sec^{-1}] at -40°C	k [sec^{-1}] at 0°C	ΔE* [kcal/mole]	Ref.
(7)	4360 [a]	58.320 [a]	8.1 ± 0.4	[30]
(53)	6150	332 500	12.6 ± 0.4	[34]
(37)	3920	220 500	12.7 ± 0.4	[34]
(31)	3210	187 800	12.9 ± 0.2	[34]
(56)	2140	140 900	13.2 ± 0.6	[34]
	29 [a]	540 [a]	11.8 ± 1.0	[35]
(46)	—	—	13.1 ± 1.0	[24]
	20	790	11.7 ± 0.2	[36]

[a] Extrapolated values.

The best synthetic route to bridged homotropilidene systems of the type *(10)* is by way of cyclooctatetraene, which dimerizes on heating or on prolonged standing at room temperature [31]. Four dimers of cyclooctatetraene, $C_{16}H_{16}$, are known with certainty, their melting points being 38.5, 41.5, 53, and 76 °C [32]. The $C_{16}H_{16}$ melting at 76 °C [33] is obtained by heating cyclooctatetraene at 100 °C for 68 h; the yield is 37 % [37] based on the cyclooctatetraene which has reacted. This dimer *(31)* [9, 20, 23] consists of a bicyclo[4.2.0]octa-2,4-diene unit and a homotropilidene unit (shown by thick lines). The homotropilidene system is responsible for the valence-bond isomerization.



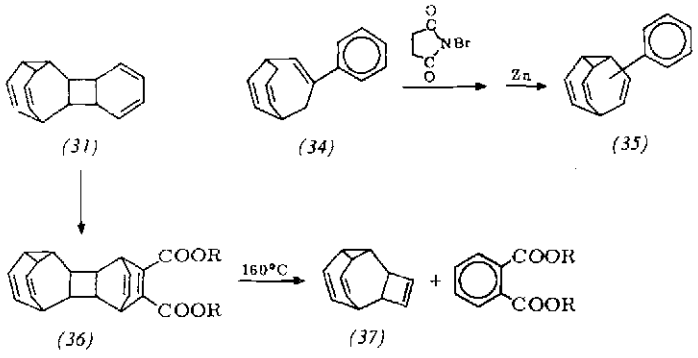
(31a) *(31b)*

The structures *(31a)* and *(31b)* are identical. Two π bonds and one of the σ bonds of the cyclopropane ring fluctuate in the homotropilidene system [as in *(6)*, *(7)*, and probably *(8)*], as can be seen from the temperature-dependence of the NMR spectrum [9]. The areas and the chemical shifts of the proton resonance signal change appreciably with temperature.

The previous interpretation [20] of the mode of formation of *(31)* was based on the incorrect structure *(32)* proposed by *Jones* [33] for a dimeric cyclooctatetraene of m.p. 53 °C. This structure should be replaced [37a] by *(33)*. Surprisingly, cyclooctatetraene dimerizes at 100 °C by 1,2:1,2 cycloaddition to give an all-*cis*-cyclobutane derivative.

(32) *(33)*

When *(31)* is treated with strong bases (*e.g.* potassium t-butoxide in dimethyl sulfoxide), it isomerizes readily to form a hydrocarbon *(34)*, m.p. 69 °C. The reaction of *(34)* with *N*-bromosuccinimide yields a dibromide, which loses both bromine atoms on treatment with zinc to form phenylbullvalene *(35)* [25].

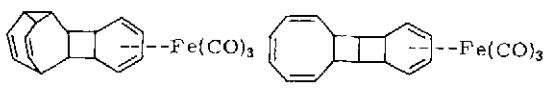


(31) *(34)* *(35)*

(36) *(37)*

Compound *(31)* reacts extremely readily with dienophiles. The adduct *(36)* formed form *(31)* and dimethyl acetylenedicarboxylate decomposes on heating into dimethyl phthalate and a hydrocarbon *(37)* [9, 20], in which the homotropilidene system is bridged by a cyclobutene ring. The NMR spectrum of *(37)* is temperature-dependent [9], showing that this is also a molecule with fluctuating bonds.

The compound *(31)* reacts with iron pentacarbonyl at 160–170 °C to form *inter alia* the complex $C_{16}H_{16}$–$Fe(CO)_3$, m.p. 118 °C. The temperature-dependent NMR spectrum of this complex agrees with the structure *(38)* [38]. X-ray analysis led to the structure *(39)* for a complex having the same overall formula [39]. It was later found, however, that the complex used for the X-ray analysis, obtained by irradiating a mixture of cyclooctatetraene and cyclooctatetraene-$Fe(CO)_3$, has m.p. 172 °C [40].



(38) *(39)*

Other bridged homotropilidene systems of the type *(10)* are derived from bullvalene [cf. compounds *(53)*, *(56)*, and *(57)*]. These are discussed in Section III.3.

[31] *W. Reppe, O. Schlichting, K. Klager*, and *T. Toepel*, Liebigs Ann. Chem. *560*, 1 (1948).

[32] *G. Schröder*: Cyclooctatetraen. Verlag Chemie, Weinheim/Bergstr., 1965.

[33] *W. O. Jones*, Chem. and Ind. *1955*, 16.

[34] *J. F. M. Oth, J. M. Gilles*, and *R. Merényi*, unpublished work.

[35] *M. Saunders*, Tetrahedron Letters *1963*, 1699.

[36] *J. M. Gilles* and *J. F. M. Oth*, unpublished work.

[37] *B. Flügel*, Diploma Thesis, Technische Hochschule Karlsruhe, 1964.

[37a] *G. Schröder* and *W. Martin*, unpublished results.

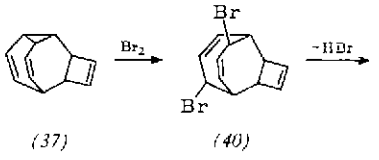
[38] *G. N. Schrauzer, P. Glockner*, and *R. Merényi*, Angew. Chem. *76*, 498 (1964); Angew. Chem. internat. Edit. *3*, 509 (1964).

[39] *A. Robson* and *M. R. Truter*, Tetrahedron Letters *1964*, 3079.

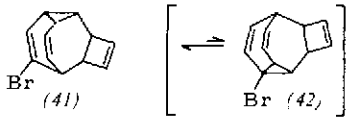
[40] *M. R. Truter*, personal communication.

g) Bridged Homotropilidene Systems of the Type *(11)*

The hydrocarbon *(37)* reacts with one mole of bromine to form the dibromide *(40)*, which loses HBr under the influence of bases (potassium alkoxide) with formation of the monobromide $C_{12}H_{11}Br$ *(41)* [22]. This is an unsymmetrically substituted homotropilidene system with a cyclobutene bridge.

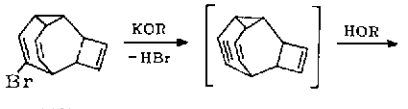


(37) *(40)*

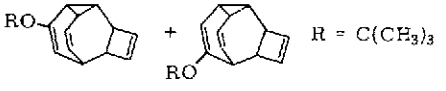


(41) *(42)*

Valence isomerization of *(41)* should lead to the structural isomer *(42)* with the bromine attached to the cyclopropane ring. Compounds *(41)* and *(42)* therefore have different energies. The NMR spectrum of $C_{12}H_{11}Br$ is independent of temperature, showing that the equilibrium mixture consists almost entirely of *(41)*. The latter reacts with potassium t-butoxide to form $C_{12}H_{11}OC_4H_9$. The NMR spectrum of the ether *(45)* corresponding to the bromide *(41)* should be independent of temperature. Since, however, the spectrum of $C_{12}H_{11}OC_4H_9$ is temperature-dependent, this must be a mixture of *(44)* and *(45)* [41], probably formed *via* the intermediate *(43)*. Compounds *(44)* and *(45)* are evidently formed by an elimination-addition mechanism.



(41) *(43)*

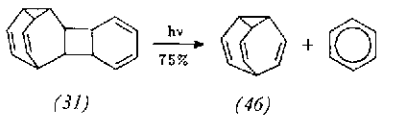


(44) *(45)*

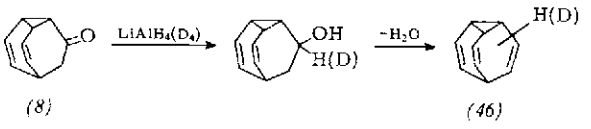
3. Bullvalene and Some of its Derivatives

a) Preparation of Bullvalene

The photolysis of the dimeric cyclooctatetraene *(31)* gives a very good yield of benzene and tricyclo[3.3.2.0^{4,6}]-deca-2,7,9-triene *(46)*, m.p. 96 °C [21,23]. *Doering* and *Roth* [16,17], on the basis of theoretical considerations, postulated the structure *(46)*, predicted its NMR-spectroscopic behavior, and suggested the name "bullvalene". *Doering* and *Klumpp* [19] later synthesized bullvalene (and monodeuterated bullvalene) from the tricyclic ketone *(8)*.



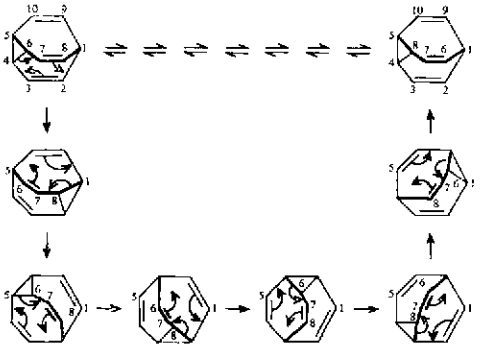
(31) *(46)*



(8) *(46)*

b) The "Bullvalene Principle"

Bullvalene is an unusual member of the class of molecules with fast and reversible valence isomerization. In this molecule, no two carbon atoms remain bonded to each other for any length of time. The ten C atoms are continually changing places and neighbors. No precedent for a molecule with properties of this kind is known in organic chemistry [16,17]. Any carbon atom in bullvalene can be bonded to any other as a result of valence isomerization, as shown in Scheme 2 [42].



Scheme 2.

In homotropilidene *(6)* and the bridged homotropilidene systems of the types *(7)*, *(8)*, *(10)*, and *(11)*, only one cyclopropyl bond can be broken, and only two valence isomers are involved. Bullvalene, on the other hand, possesses a threefold axis of symmetry. The three cyclopropyl bonds are equivalent and have equal statistical weights in a valence isomerization, *i.e.* all three bonds are equally likely to be broken. Thus instead of giving only two structurally identical valence isomers, bullvalene gives 10!/3, *i.e.* about 1.2 million [16,17].

In the course of a few valence isomerizations, each proton in the bullvalene molecule passes through cyclopropyl, olefinic, and bridgehead positions (*e.g.* the C–5 proton in Scheme 2). If the valence isomerization is sufficiently fast, the ten protons of bullvalene become equivalent from the point of view of NMR spectroscopy. At 100 °C the NMR spectrum of bullvalene consists of a single sharp proton resonance signal at $\tau = 5.78$ with a line width of 1.5 c.p.s. (Fig. 2) [9]. This confirms the predictions of *Doering* and *Roth* [16,17].

[41] The valence isomers of *(44)* are structurally identical.

[42] Regarding the bullvalene principle see also [16,17].

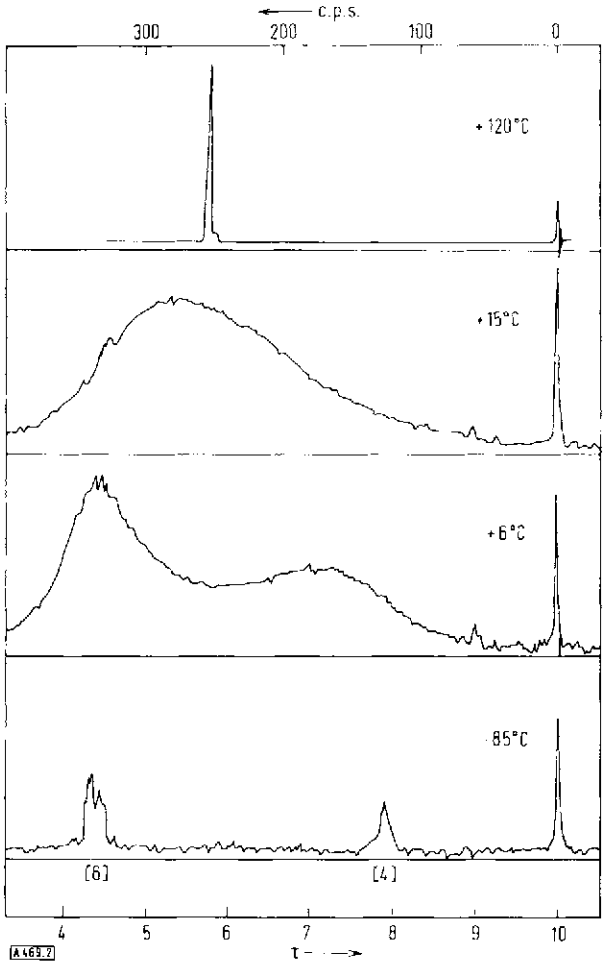


Fig. 2. NMR spectra of $C_{10}H_{10}$, bullvalene *(46)* (0.4 mole/l in CS_2) [9, 10]. Internal standard tetramethylsilane.

The low-temperature spectrum of bullvalene comprises two groups of bands, the areas of which are in the ratio 3:2. A multiplet is found at $\tau - 4.35$, corresponding to the six olefinic protons of bullvalene. The relatively broad band at $\tau = 7.42$ must be assigned to the three cyclopropyl protons and the bridgehead protons. The two groups of bands coalesce at 13 °C, giving the single signal at $\tau = 5.78$ above this temperature (cf. Fig. 2).

The rate constant k and the activation energy ΔE^* of the valence isomerization of bullvalene shown in Table 3 [35, 36] were determined from the NMR spectra at various temperatures with the aid of the line-width theory developed by *Anderson* [43] and *Sack* [44].

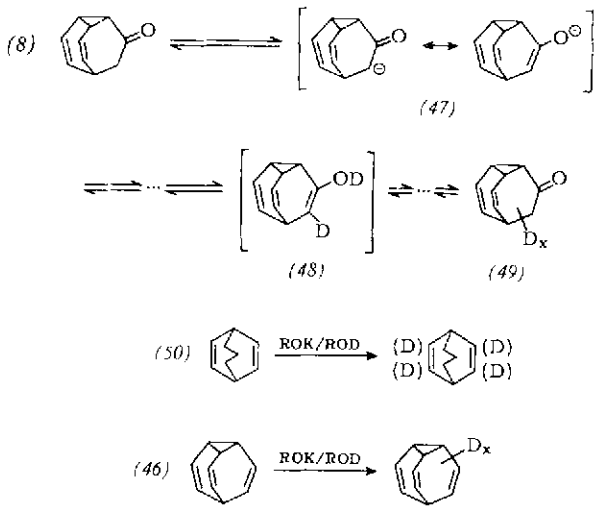
The single proton resonance signal in the high-temperature spectrum of bullvalene is *physical* proof of the constant statistical change of position of the ten C atoms in the molecule. Chemical evidence can be obtained from the base-catalysed hydrogen-deuterium exchange in the tricyclic ketone *(8)* [19] and in bullvalene [21].

Both hydrogen atoms of the methylene group of *(8)* are relatively acidic, and a base-catalysed H/D exchange proceeds *via* the anion *(47)*. Similarly, in the case of bullvalene, deuterated hydroxybullvalene *(48)* is formed as an intermediate. The transposition of the C–D and C–H units should therefore lead to *(49)*, with random distribution of the deuterium in *(8)*. In deuterium oxide at room temperature, all the hydrogen atoms in *(8)* are replaced by deuterium in the presence of 0.1N base [19].

[43] *P. W. Anderson*, J. physic. Soc. Japan *9*, 16 (1954).

[44] *R. A. Sack*, Molecular Physics *1*, 163 (1958).

Bullvalene itself contains three types of hydrogen atom (olefinic, cyclopropyl, and bridgehead protons). There is thus the question as to which type of C–H bond is so strongly activated that a base catalysed H/D exchange

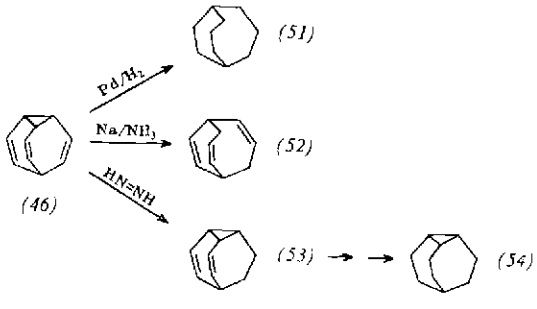


is possible. Bicyclo[3,2,2]nona-2,5-diene *(50)* takes up deuterium in the system ROK/ROD at about 160 °C [45]. In this case only the olefinic protons are replaced. By analogy it is assumed that the most strongly acidic protons in bullvalene are also the olefinic hydrogen atoms. Deuterium entering bullvalene at the double bond should immediately become randomly distributed over the entire molecule. Bullvalene undergoes an H/D exchange in the system ROK/ROD at 160 °C. The infrared spectrum of the product contains distinct C–D stretching vibrations in the olefinic and aliphatic regions [21].

c) The Chemistry of Bullvalene [21]

Bullvalene is exceptionally stable. It decomposes only at about 400 °C; the reaction takes about 10 min and yields naphthalene and hydrogen.

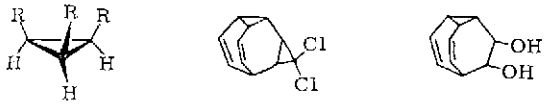
Catalytic hydrogenation over palladium results in the uptake of four moles of hydrogen to form *(51)*, m.p. 180 °C. The action of sodium in liquid ammonia followed by addition of ethanol reduces bullvalene to *(52)*, m.p. 45 °C. Thus the two sodium atoms add in the 1,4-position to the vinylcyclopropyl system in bullvalene. The three double bonds of *(46)* are hydrogenated in succession by diimine. Dihydrobullvalene *(53)*, m.p. 62 °C, can be prepared in this way. This is also a molecule



[45] *G. Schröder*, unpublished work.

with a fluctuating bond, and is the simplest homotropilidene bridged by two carbon atoms. The NMR spectrum of *(53)* is temperature-dependent (Section II). A large excess of diimine leads to *(54)*, m.p. 126 °C.

The three-membered ring in *(46)* can be detected chemically both by the formation of the compound *(54)* and by degradation. The ozonolysis of bullvalene, followed by reduction with sodium borohydride and esterification of the triol (which is not isolated), leads to *cis*-1,2,3-tris-(acetoxymethyl)cyclopropane *(55)*.



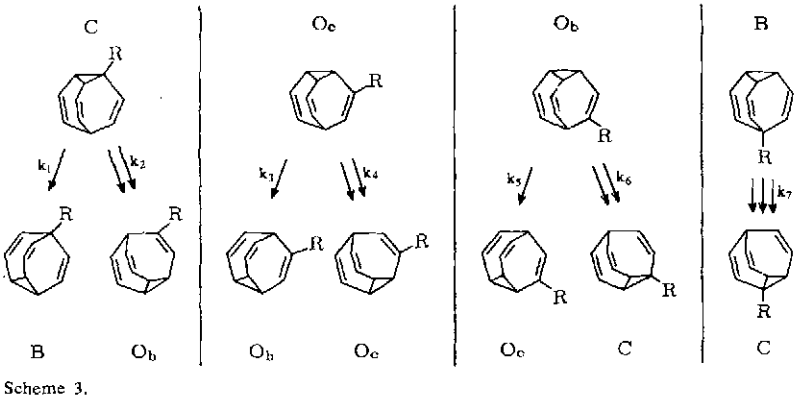
R = CH_2OAc *(55)* *(56)* *(57)*

Bullvalene reacts smoothly with dichlorocarbene and with osmium tetroxide/mannitol to form the products *(56)* and *(57)* respectively. As expected, the NMR spectra of *(56)* and *(57)* are temperature-dependent [9,34]. Kinetic data for *(56)* are given in Table 3.

d) Substituted Bullvalenes

A substituted bullvalene has about 1.2×10^6 valence-bond isomers which unlike those of bullvalene are not all structurally identical [1].

Four positional isomers are possible for monosubstituted bullvalene. Whereas the valence isomerization of bullvalene is characterized by one rate, seven elementary rates of isomerization must be distinguished in monosubstituted bullvalenes. Scheme 3 shows the four positional isomers (C: substituent on the cyclopropane ring; O_c and O_b: on the olefinic double bond near the cyclopropane ring and near the bridgehead respectively; B: on the bridgehead) and the seven rates of isomerization (k_1–k_7) of a monosubstituted bullvalene.

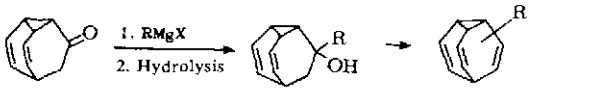


Scheme 3.

The number of positional isomers and the number of possible valence isomerizations increase with the number of substituents. In a bullvalene with nine different substituents, there are 10!/6 = 604800 different chemical environments for the single remaining bullvalyl proton.

e) Preparation of Some Monosubstituted Bullvalenes

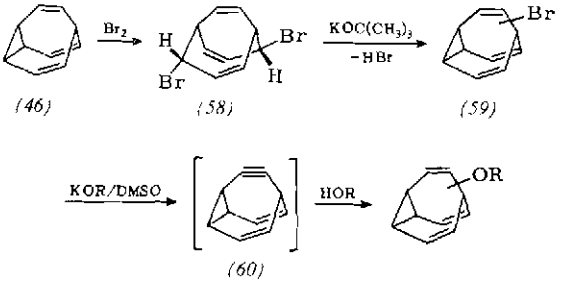
Phenylbullvalene and methylbullvalene were prepared by the reaction of a Grignard compound with *(8)*, followed by the elimination of water from the adduct [19].



(8) R = C_6H_5 *(35)*; R = CH_3 *(13)*

Another synthesis of phenylbullvalene *(35)* has already been mentioned in Section III,2f.

A useful route to monosubstituted bullvalenes is the bromination of bullvalene [1,24]. The dibromide *(58)* loses hydrogen bromide in the presence of potassium alkoxide, giving good yields of bromobullvalene *(59)*, which is used for the preparation of other monosubstituted bullvalenes. Thus *(59)* reacts with alcohol-free potassium alkoxides in dimethyl sulfoxide, presumably *via* dehydrobullvalene *(60)* [*] to form the alkoxybullvalenes *(61)* to *(64)*, with R = $C(CH_3)_3$, $CH(CH_3)_2$, C_2H_5, and CH_3 respectively.



(46) *(58)* *(59)* *(60)*

f) NMR Studies on Monosubstituted Bullvalenes [1]

In bullvalene and substituted bullvalenes there are three courses open to each valence-bond isomerization, *i.e.* any one of the three cyclopropyl bonds can break. Bullvalene itself has a threefold axis of symmetry and each of the three cyclopropyl bonds has an equal probability of being broken. The isomers C, O_c, and O_b (Scheme 3) possess only a plane of symmetry, so that two isomerization processes are possible in each case. The isomer B also has a threefold axis of symmetry and therefore only a single rate of isomerization. The high-temperature spectra of all the monosubstituted bullvalenes studied so far contain only one singlet for the nine bullvalyl protons. On the one hand this proves the bullvalene skele-

[*] Note added in proof: In the presence of furan an adduct $C_{14}H_{12}O$, which exhibits a temperature-dependent NMR spectrum, can be isolated (*H. Röttele*, Doctorate dissertation, Technische Hochschule Karlsruhe).

ton, while on the other it shows that the molecule passes through all the possible valence-isomeric structures.

Table 4. NMR signals of the bullvalyl protons and average rates of isomerization $\bar{k}$ in monosubstituted bullvalene derivatives [46]. τ = chemical shift, τ = 10 for tetramethylsilane as internal standard.

Substituent	−60 °C		+80 °C			Preferred isomers [a]
	τ olef.	τ aliph.	τ	Line width c.p.s.	$10^{-3}\,\bar{k}$ [sec^{-1}]	
(46) H	4.35	7.92	5.78	2.8	100	–
(35) C_6H_5	4.17	7.27 7.80	5.72	6.0	45	O_b
(59) Br	4.22	7.35 7.79	5.73	6.8	40	O_b or $O_b + O_c$
(61) O−C(CH$_3$)$_3$	4.33 4.99	7.90	5.97	19.0	14.5	$O_b \approx O_c$
(62) O−CH(CH$_3$)$_2$	4.33 5.50	7.92	6.00	41.0	6.9	O_b
(63) O−CH$_2$CH$_3$	4.35 5.52	7.92	6.00	55.0	5.4	O_b
(64) O−CH$_3$	4.37 5.48	7.90	6.02	72.0	4.2	O_b

[a] Cf. Scheme 3

The line width of the singlet and the average rate of isomerization $\bar{k}$ at a given temperature depend on the substituent (see Table 4).

If all seven rate constants were equal, 30% of the molecules on the average would be in each of the C, O_c, and O_b structures, while 10% would have the B structure. Certain valence isomerizations, however, are at a disadvantage with respect to others, so that the distribution of the positional isomers depends on the rate constants. Information on rate constants k_1–k_7 can be obtained from the temperature-dependent NMR spectra of monosubstituted bullvalenes (see Table 4); for a discussion cf. [1].

The isomers of monosubstituted bullvalenes in which the substituent occupies an olefinic position (O_b and O_c) are preferentially formed. This is mainly due to the fact that substituents are more firmly bonded to an olefinic than to an aliphatic carbon atom (bond effect).

In the compounds *(35)*, *(62)*, *(63)*, and *(64)*, O_b is strongly preferred owing to the possibility of conjugation between the substituent and the vinylcyclopropyl system of the bullvalene skeleton. In *(61)*, O_b and O_c are present in approximately equal quantities. Owing to steric hindrance, the bulky t-butyl group in this case is twisted into a configuration which does not favor optimum conjugation, so that the conjugation effect is subordinate to the bond effect. It cannot be decided whether O_b and O_c, or O_b alone predominate in the equilibrium mixture in *(59)*.

IV. Conclusion

We speak of molecules with fluctuating bonds when the valence isomers have a mean lifetime of less than about 100 sec at 0 °C. Such molecules can so far be unambiguously recognized and studied only by NMR spectroscopy. The study of the bond shifts in substituted cyclooctatetraenes and bullvalenes is particularly interesting since the rate of shift depends on the substituent. This gives information on the relative importance of bonding, conjugation, steric, and inductive effects.

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[46] $\bar{k}$ is that rate constant which, in the case of bullvalene, would give the same line width as the one observed for the derivative studied.

Conformational Analysis in Mobile Cyclohexane Systems

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By "Conformational Analysis" is meant the analysis of the physical and chemical properties of a compound in terms of its preferred "conformations", i.e. rotational arrangements about single bonds. This particular review deals with cyclohexanoid compounds capable of existing in two or more stable conformations.

I. Historical

That cyclohexane is a puckered, chair- (or boat-)shaped molecule was first suggested by *Sachse* [1] 75 years ago. Because of a lack of appreciation of the restrictions to rotation about single bonds and other misunderstandings, *Sachse*'s theories were rejected for nearly 30 years, to be revived only in 1918 by *Mohr* [2] and soon to be confirmed by the classical work of *W. Hückel* on decalin [3] and of *Boëseken* and coworkers on the acetone and boric acid derivatives of cyclic diols [4]. Still the ideas

[1] *H. Sachse*, Ber. dtsch. chem. Ges. *23*, 1363 (1890); Z. physik. Chem. *10*, 203 (1892).

[2] *E. Mohr*, J. prakt. Chem. [2] *98*, 315 (1918); Ber. dtsch. chem. Ges. *55*, 230 (1922).

[3] *W. Hückel*, Liebigs Ann. Chem. *441*, 1 (1925).

[4] *J. Boëseken* and *J. van Giffen*, Recueil Trav. chim. Pays-Bas *39*, 183 (1920); *J. Boëseken*, ibid. *40*, 553 (1921); Ber. dtsch. chem. Ges. *56*, 2409 (1923).

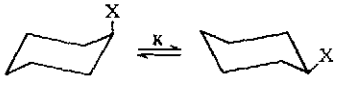
gained only slow acceptance, being used but occasionally by carbohydrate chemists [5]; however, during this period a better understanding of rotational barriers was gained, first in the biphenyls [6] and later in ethane [7], which is now known to exist in the "staggered" rather than the "eclipsed" conformation. This phase of development culminated with some very significant work by *Mizushima* [8] on spectroscopic studies of substituted ethanes, by *Hassel* [9] on X-ray and electron diffraction of simple substituted cyclohexanes, and by *Pitzer* [10] on the shape and thermodynamic properties of cyclohexane derivatives. However, the real breakthrough in the field did not come until 1950 when *D. H. R. Barton*, in a pioneering paper [11], pointed out the consequences of conformational differences on stability and reactivity. This was an area of great interest to organic chemists, first those engaged in natural products research and then also those investigating fundamental molecular behavior, and *Barton*'s ideas were absorbed, utilized and further developed rapidly and intensively. The resulting mushrooming growth of the subject has carried it, within less than 15 years, to the point where a comprehensive review requires the format of a book and two such books have recently appeared [12, 13]. A number of earlier review articles have been listed elsewhere [14, 15].

II. Scope

Clearly only a limited review is within the scope of the present article [16]. Conformational concepts play a part in acyclic, alicyclic and heterocyclic systems; among the cyclic ones, rings from four-membered on are nonplanar and therefore of particular interest in conformational analysis. We shall confine ourselves here to six-membered and, in most instances, carbocyclic rings.

Of the two possible puckered forms of cyclohexane, the chair and the boat, the chair is the more stable because its bonds are all staggered. (In contrast, the boat has four pairs of eclipsed hydrogen plus other unfavorable interactions.) In the chair form, there are two types of bonds, those pointing up and down, called "axial" and those pointing outward, called "equatorial". The two types of bonds are readily distinguished in a model.

In the following discussion, we shall refer, primarily, to "mobile systems" which are defined as systems which can alternate between two or more stable conformations. The monosubstituted cyclohexane *(1)* provides an example; it can exist in two conformations, one with



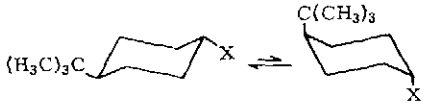
(1a) *(1b)*

the substituent equatorial, the other one with the substituent axial. The two conformations are readily interconvertible (see below) and the equatorial conformation is more stable. Systems of this type are of particular interest because their reactivity depends on the population of the various pertinent conformations.

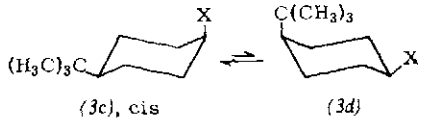
In contrast to mobile systems are rigid systems, such as *trans*-decalin *(2)* or the steroids – in which ring inversion is impossible because the alternate chair form would

(2)

be excessively strained – or biassed systems, such as a 1-halo-4-t-butylcyclohexane *(3)*. X = halogen – in which ring inversion is possible but the molecule exists in one conformation almost to the complete exclusion of the other(s), because of a large difference in stability. In



(3a), trans *(3b)*



(3c), cis *(3d)*

the case of t-butylcyclohexane, it is estimated that the conformation with the equatorial t-butyl group *(3a,c)*, X = H, predominates over that with the axial t-butyl group *(3b,d)*, X = H, by a factor of at least 10000 at room temperature, because the compression of nonbonded atoms in the t-butyl-axial conformation raises the potential energy of this form by over 5 kcal/mole [17, 18]. There are not many other groups which have a similar "reluctance" to occupy the axial position.

[5] See, for example, *O. L. Sponsler* and *W. H. Dore*, Colloid Sympos. Monogr. *4*, 174 (1926); *H. S. Isbell*, J. Res. nat. Bur. Standards *18*, 505 (1937); *20*, 97 (1938); *R. E. Reeves*, J. Amer. chem. Soc. *71*, 215 (1949); *72*, 1499 (1950); Advances Carbohydrate Chem. *6*, 107 (1951).

[6] *F. Bell* and *J. Kenyon*, Chem. and Ind. (London) *4*, 864 (1926); *W. H. Mills*, ibid. *4*, 884 (1926); *E. E. Turner* and *R. J. W. LeFèvre*, ibid. *4*, 831, 883 (1926).

[7] *J. D. Kemp* and *K. S. Pitzer*, J. chem. Physics *4*, 749 (1936); J. Amer. chem. Soc. *59*, 276 (1937); *K. S. Pitzer*, J. chem. Physics *5*, 473 (1937); *J. B. Howard*, Phys. Review *51*, 53 (1937).

[8] a) *S. Mizushima* and *K. Higasi*, J. chem. Soc. Japan *54*, 226 (1933), and subsequent papers; cf. b) *S. Mizushima*: Structure of Molecules and Internal Rotation. Academic Press, New York 1954; c) *S. Mizushima*, Pure appl. Chem. *7*, 1 (1963).

[9] *O. Hassel*, Tidsskr. Kjemi, Bergves. Metallurgi *3*, 32 (1943); *O. Hassel* and *B. Ottar*, Acta chem. scand. *1*, 929 (1947); *O. Hassel*, Quart. Rev. (chem. Soc., London) *7*, 221 (1953).

[10] *C. W. Beckett, K. S. Pitzer*, and *R. Spitzer*, J. Amer. chem. Soc. *69*, 2488 (1947).

[11] *D. H. R. Barton*, Experientia *6*, 316 (1950).

[12] *E. L. Eliel, N. L. Allinger, S. J. Angyal*, and *G. A. Morrison*: Conformational Analysis. Wiley, New York 1965.

[13] *M. Hanack*: Conformation Theory. Academic Press, New York 1965.

[14] *E. L. Eliel*: Stereochemistry of Carbon Compounds. McGraw-Hill, New York 1962, Chapters 6, 8.

[15] *E. L. Eliel*: J. chem. Educat. *37*, 126 (1960).

[16] For a previous review in this journal see *H. H. Lau*, Angew. Chem. *73*, 423 (1961).

[17] *S. Winstein* and *N. J. Holness*, J. Amer. chem. Soc. *77*, 5562 (1955).

[18] *N. L. Allinger* and *L. A. Freiberg*, J. Amer. chem. Soc. *82*, 2393 (1960).

It should be pointed out that, although we tend to think of cyclohexanoid molecules as perfectly puckered chairs with tetrahedral angles, such models are oversimplified. In cyclohexane itself the C–C–C bond angle has been found [19] to be 111.5°, somewhat larger than the tetrahedral angle of 109° 28′ and it has been pointed out [20] that the resulting slight flattening of the chair significantly influences the physical and chemical properties of certain cyclohexane derivatives. Moreover, the existence of deformed chairs [21] and even boat forms [22, 23] especially in some substituted cyclohexanones [23a], but also in a few saturated systems [18, 23b] is becoming increasingly recognized. Major deviations from chair geometry probably do not occur in the molecules to be discussed in this review, but the minor flattening of the cyclohexane ring does affect them and will be returned to later.

III. Terminology

The terminology of conformation analysis is now generally known and has been reviewed recently [14]. We wish to introduce only two new terms here [12]. The term "conformational energy" will denote the free energy of a conformation above that of the conformation of minimum energy. For example, the negative of the free energy ΔG° for the process *(1a)* $\rightleftharpoons$ *(1b)* is the conformational energy of the axial form *(1a)*. – The term "*syn*-axial" groups will be used to denote axial groups on the same side of a cyclohexane ring and therefore in close spatial proximity (and frequently steric interaction).

IV. Aims

Monosubstituted cyclohexanes *(1)* can exist in two conformations, one with the substituent equatorial, the other with the substituent axial. The two conformations are readily interconverted through rotations about single bonds attended with slight angle deformations. The potential energy diagram for the interconversion process is shown in Fig. 1. Here, ΔG_X° represents the difference in free energy (*i.e.* the conformational energy) of the two chair forms.

The high energy valley between the more stable chair conformations corresponds to a form in which one side of the chair has been flipped up but the other has not yet been flipped down; this form was originally [1] called the "flexible form" and was later labelled "boat form". In fact, this form (in contrast to the chair) is flexible; model considerations show that various possible boat forms can be interconverted by minor contortions of the molecule. The boat form, however, suffers from unfavorable bond eclipsings [7] on the side of the boat and van der Waals interactions between the hydrogen atoms at the "bowsprit" and "flagpole" positions, and it has been calculated [24] that the most stable conformation of the flexible form is one in between two boat forms, now commonly called the "twist form" or "skew boat". The potential energy of this form has been estimated by computer calculation [24] to be 1.6 kcal/mole less than that of the classical boat but about 5.5 kcal/mole more than that of the chair (cf. Fig. 1); the latter value has been confirmed both through equilibration [18] and heat of combustion [25] measurements involving molecules which, for steric reasons, exist predominantly in the twist form. The energy barrier between the chair and twist forms (Fig. 1) has also been calculated; it is 10–11 kcal/mole above the chair and corresponds to a conformation in which four adjacent atoms of the ring are in a plane ("half-chair"). The value of 10–11 kcal/mole has been confirmed by nuclear magnetic resonance measurements [26, 27] and a similar value was obtained by ultrasonic measurements [28]; it is small enough so that at room temperature substituted cyclohexanes rapidly pass from one chair form into the other by virtue of the thermal excitation of the molecules.

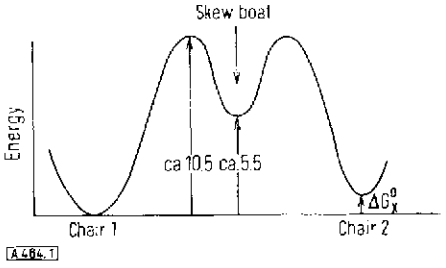


Fig. 1. Potential energy diagram for the chair-chair interconversion of monosubstituted cyclohexanes (schematic). The numbers are energies in kcal/mole.

For the remainder of this review, we shall concentrate on a discussion of the conformational energies $-\Delta G^\circ$ for cyclohexanes with different groups X, their rationale and the ways in which they may be obtained.

V. Results

The $-\Delta G^\circ$ values for all the groups so far studied are given in Table 1. This table represents a summary of data found in about 75 original papers. It is seen that the

[19] *M. Davis* and *O. Hassel*, Acta chem. scand. *17*, 1181 (1963).

[20] *R. A. Wohl*, Chimia *18*, 219 (1964).

[21] See, for example, *K. L. Williamson* and *W. S. Johnson*, J. Amer. chem. Soc. *83*, 4623 (1961).

[22] *M. Svoboda*, *M. Tichý*, *J. Fajkoš*, and *J. Sicher*, Tetrahedron Letters *1962*, 717; *J. Klinot* and *A. Vystrčil*, Chem. and Ind. (London) *1963*, 738.

[23] a) *D. H. R. Barton*, *D. A. Lewis*, and *J. F. McGhie*, J. chem. Soc. (London) *1957*, 2907; see also ref. [12], pp. 476–481; b) *R. D. Stolow* and *M. M. Bonaventura*, J. Amer. chem. Soc. *85*, 3636 (1963).

[24] *J. B. Hendrickson*, J. Amer. chem. Soc. *83*, 4537 (1961).

[25] *J. L. Margrave*, *M. A. Frisch*, *R. G. Bautista*, *R. L. Clarke*, and *W. S. Johnson*, J. Amer. chem. Soc. *85*, 546 (1963).

[26] *F. R. Jensen*, *D. S. Noyce*, *C. H. Sederholm*, and *A. J. Berlin*, J. Amer. chem. Soc. *84*, 386 (1962).

[27] *F. A. L. Anet*, *M. Ahmad*, and *L. D. Hall*, Proc. chem. Soc. (London) *1964*, 145; *F. A. Bovey*, *F. P. Hood*, *E. W. Anderson*, and *R. L. Kornegay*, ibid. *1964*, 146.

[28] *M. E. Pedinoff*, J. chem. Physics *36*, 777 (1962); *J. E. Piercy*, J. acoust. Soc. Amer. *33*, 198 (1961).

conformational free-energy values are not monotonous functions of atom or group size. For example, there is little progression in $-\Delta G^\circ$ value in the halogens from chlorine to iodine; bromocyclohexane has a much smaller conformational energy than methylcyclohexane (although both substituents are ordinarily considered isosteric); the value for cyclohexanecarboxylic acid is smaller than that for methylcyclohexane which is not much smaller than that for isopropylcyclohexane. Tosyloxycyclohexane has about the same conformational energy as cyclohexanol.

Table 1. Conformational free energy differences $-\Delta G^0_X$ for various substituents X in cyclohexanes [a].

Substituent X	$-\Delta G^0_X$ [kcal/mole] [b]
F	*0.2*
Cl	0.0–0.5; *0.4*
Br	0.2–0.7; *0.4*
I	0.40–0.45; *0.4*
OH [e]	0.25–1.25; *0.6* [c], *0.9* [d]
OCH_3	0.6–0.75; *0.7*
OC_2H_5	0.9–1.0; *0.9*
$OCOCH_3$	0.4–1.5; *0.7*
$OSO_2C_6H_4CH_3$-*p*	0.6–1.7; *0.7*
SH	–0.4–0.9; *0.9*
S^-	*1.3*
SC_6H_5	*0.8*
SOC_6H_5	*1.9*
$SO_2C_6H_5$	*2.5*
NH_2 [f]	1.1–1.8, *1.2* [c], *1.8* [d]
NH_3^+	1.8–2.0; *1.9*
$NH(CH_3)$ [f]	0.9–1.1; *1.0* [c]
$N(CH_3)_2$	*2.1* [d]
$NH(CH_3)_2^+$	*2.4*
NO_2 [g]	*1.0*
CH_3	1.5–2.1; *1.7*
C≡CH [h]	*0.2*
C_2H_5	1.65–2.25; *1.8*
i-C_3H_7	1.8–2.5; *2.1*
C_6H_{11}	*2.2*
$C(CH_3)_3$	>4.4
C_6H_5	2.0–3.1; *3.1*
CO_2H	0.7–1.7; *1.2*
CO_2^-	2.1–2.3; *2.2*
CO_2CH_3	*1.1*
$CO_2CO_2H_5$	1.0–1.2; *1.1*
CN	0.15–0.25; *0.2*
HgBr	*ca. 0*

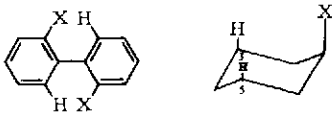
[a] References, individual values, methods of determination (see below), and conditions of temperature, solvent, and phase are given in a lengthy table in ref. [12], pp. 436–444, as well as in table 1 in [82a].
[b] Author's recommended values in italics.
[c] In aprotic solvent.
[d] In hydrogen donor solvent.
[e] Ref. [35].
[f] Ref. [93b].
[g] Ref. [93a].
[h] Ref. [46].

In principle, the conformational energy can be calculated from first principles, taking into account the repulsive (or attractive) energy for the atoms in question (or for all the atoms of a group such as methyl) with salient carbon and hydrogen atoms in the ring both in the equatorial and in the axial position and taking the difference. Such calculations [29, 30] have shown that the main interactions are of the equatorial group with adjacent hydrogens (at carbon atoms 2 and 6) and of the axial group with adjacent hydrogens, *syn*-axial hydrogens, and carbon atoms 3 and 5. Other interactions are either negligible or cancel out. Unfortunately, because of insufficient knowledge of the van der Waals potential functions which form the basis of the calculations, the results are not very accurate, which is particularly unfortunate in view of the fact that the differences one looks for are only of the order of 0–2 kcal/mole (Table 1). Therefore at the moment the experimental approach seems to be the only one feasible; and while the calculations are sometimes valuable to indicate trends, it is also worthwhile to acquire some intuitive ideas about conformational energies, based on existing data. It is with this aim in mind that the data will now be discussed.

[29] *J. B. Hendrickson*, J. Amer. chem. Soc. *84*, 3355 (1962).
[30] Cf. Ref. [12], pp. 446–457.

VI. Discussion

As already mentioned, there is not a one-to-one correlation between conformational energies and group sizes as inferred, for example, from the ease of racemization of *ortho*-substituted biphenyls [31]. Thus the halogenocyclohexanes have similar $-\Delta G^\circ$ values although the size of the halogens certainly increases in the order fluorine < chlorine < bromine < iodine. While the value for fluorocyclohexane is somewhat smaller than that for chlorocyclohexane, the value for iodocyclohexane is hardly any larger than that for bromocyclohexane and the latter value is actually slightly but significantly smaller than that for chlorocyclohexane [32]. One reason for this lack of parallel is seen from formulae *(4)* and *(5)*: whereas in the case of *ortho*-substituted biphenyls the interfering groups point toward each other and the interference will become more severe as the bond lengths of the atoms or groups involved increase, the contrary is true in axially substituted



(4) *(5)*

cyclohexanes. Here, the longer the bond to the axial substituent, the further the substituent will be away from the *syn*-axial hydrogens and the carbon atoms 3 and 5 which cause the axial crowding. This, to some extent, compensates for the larger van der Waals radius of the bigger substituents. By the same token, the flattening of the ring [20] leads to a bending outward of the axial substituent, and this motion, by a simple leverage principle, will provide most effective steric relief to the substituents with the longest bonds, *i.e.* the large substituents. These two factors may explain in part why bromocyclohexane (van der Waals radius of Br 1.95 Å) has a much smaller conformational energy (0.4 kcal/mole) than methylcyclohexane (1.7 kcal/mole; van der Waals radius of the methyl group: 2.0 Å).

[31] *R. L. Shriner* and *R. Adams* in *H. Gilman*: Organic Chemistry. Wiley, New York 1943, Vol. 1, p. 362.
[32] a) *E. L. Eliel* and *R. J. L. Martin*, unpublished data; b) *J. Reisse, J. C. Celotti*, and *G. Chiurdoglu*, Tetrahedron Letters *1965*, 397.

There is probably, however, a third reason: the larger atoms such as bromine tend to be more polarizable and therefore the attractive London forces are more important for such atoms. London forces are particularly important just within (and just outside) the van der Waals radial distance. As shown in Figure 2, they would lead to a deeper and shallower well in the van der Waals potential function.

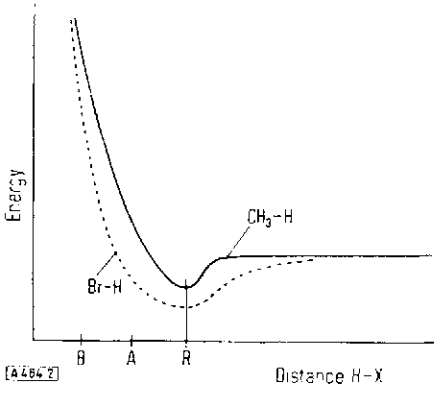


Fig. 2. Potential curves (schematic) for (——) CH_3—H interactions and (. . . .) Br—H interactions. R = van der Waals radius, A = distance between an axial substituent and *syn*-axial hydrogen atoms in monosubstituted cyclohexanes, B = distance between *ortho*-substituents in biphenyl derivatives of type *(4)*.

Since axial atoms and groups usually find themselves just within the van der Waals distance from the offending *syn*-axial hydrogens, *etc.* (point A, Fig. 2), the shape of the curve at this point is quite significant and a group of low polarizability such as methyl (analogous to a hard or wooden sphere) finds much less steric relief due to London attraction than a polarizable group, such as bromine (analogous to a soft or rubbery sphere). In biphenyls *(4)* these considerations are much less important because the interatomic distance of the *ortho*-substituents is much less, and the groups find themselves in a strongly repulsive part of the van der Waals curve (point B, Fig. 2) where attractive London forces ($E \propto 1/r^6$) are no longer important compared to the repulsive force ($E \propto 1/r^{12}$).

Another point of interest in Table 1 is that the atom next to the cyclohexane ring in large measure determines the conformational energy; other atoms attached to the first one are much less important. Thus OH, OAc, OCH_3, OC_2H_5, OTosyl all have very similar conformational energies, as have SH, SCH_3, and SC_6H_5 or CH_3, C_2H_5, and $CH(CH_3)_2$. Model considerations quickly show the reason for this finding; the group may be so rotated that any atom attached to the first points away from the ring. This will, in essence, leave the conformational energy unaffected except for a small decrease in entropy of mixing in the case of the axial substituents because of the elimination of one or two alternate rotational conformations of the axial substituent in which the attached group would point into the ring. In the extreme case, where the equatorial substituent has three equally probable conformations and the axial one has only one, this difference would amount to Rln 3 or 2.2 cal. $mole^{-1}$ $deg.^{-1}$, corresponding to a conformational free energy difference of 0.65 kcal/mole at room temperature. In fact, the difference will always be less than that.

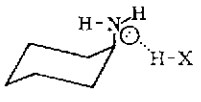
An exception occurs with a substituent with three attached groups, such as t-butyl, $C(CH_3)_3$. In this case one cannot avoid having one group (methyl) point into the ring when the substituent is axial; this results in a very sizeable compression with the *syn*-axial hydrogens and accounts for the great reluctance of the t-butyl group to occupy the axial position (*trans*-1,3-di-t-butylcyclohexane actually prefers the skew-boat conformation to one with axial t-hutyl [18]).

In this context, the relatively small conformational energy of cyclohexyl phenyl sulfone (2.5 kcal/mole) comes as a surprise; in the series of cyclohexanes with SR, S(O)R, $S(O)_2R$ as substituents, the big jump in $-\Delta G^0$ comes between sulfide and sulfoxide, not between sulfoxide and sulfone. This may be a consequence of the difference in hybridization and in bond angle between —SR, —S(O)R, and $-S(O_2)R$.

A comparison of R—COOH with $R-COO^-$, R—SH with $R-S^-$ and $R-NH_2$ with $R-NH_3^+$ (R = cyclohexyl) suggests that the ions are always apparently larger than the parent groups. Presumably this is to be ascribed to solvation which leads to a "swelling" of the ionic substituent.

The effect of hydrogen bonding on group size is evident when one compares the conformational energies of cyclohexylamine in aprotic and protic solvents; the former value is 1.1 kcal/mole, the latter 1.5–1.8 kcal/mole [33]. The size of the hydroxy group is also increased by hydrogen bonding [15, 34]; thus $-\Delta G^\circ$ for cyclohexanol is 0.6 kcal/mole in cyclohexane but 0.9 kcal/mole in isopropyl alcohol [35]. On the other hand, the size of the halogen atoms appears to be largely independent of solvent [32], indicating that hydrogen bonding is too weak to make a difference except possibly in trifluoroacetic acid. While it has not yet been established whether hydrogen bonding affects conformational enthalpy or conformational entropy, the chances are that with a group which has two or three free pairs of unbonded electrons (such as hydroxy) entropy is mainly involved and that the higher conformational energy of an axial substituent capable of hydrogen bonding in a protic solvent is due to the fact that the hydrogen bond forms preferably on the outside of the ring and thus interferes with certain rotational conformations of the axial suhstituent. However, with a group which has only a single pair of unbonded electrons, *e.g.* NH_2 *(6)*, hydrogen bonding may force the axial group into an unfavorable rotational conformation *(7)*.

(6)



(7)

Besides varying with solvent, conformational free energies may also vary with phase. For example, in polymethylcyclohexanes the axial isomers not only have the higher enthalpies

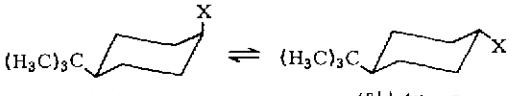
[33] *E. L. Eliel, E. W. Della*, and *T. H. Williams*, Tetrahedron Letters *1963*, 831.

[34] *J. Reisse, J. C. Celotti, D. Zimmermann*, and *G. Chiurdoglu*, Tetrahedron Letters *1964*, 2145.

[35] *E. L. Eliel* and *S. H. Schroeter*, J. Amer. chem. Soc., in the press.

but also the higher latent heats of vaporization. This means that the excess energy content of the axial isomer over the equatorial is greater in the vapor phase than in the liquid and, in fact, the best experimental value for the conformational energy of methylcyclohexane is 1.7 kcal/mole in the liquid phase and 1.9 kcal/mole in the vapor.

The figures in Table 1 are free energy differences. As yet, few careful experimental apportionments of these free energies between enthalpy and entropy terms have been made. It might be expected that no conformational entropy differences would be found for spherically or cyclindrically symmetrical groups, such as methyl, halogen, cyano, ethynyl. In fact, however, experimental differences have been claimed for methyl [36], cyano [37], chlorine, and bromine [32b]. The significance of these findings is somewhat uncertain in view of the difficulty of measuring entropy differences to better than 0.5 cal·mole^{-1}·degree^{-1}, but a possible explanation in terms of rotational entropy has been offered [32b]. In the case of non-symmetrical groups, entropy differences would definitely be expected; thus the differences in $-\Delta G^\circ$ for methyl-, ethyl-, and isopropyl-cyclohexanes are adequately accounted for by entropy considerations [38]. Careful measurement has recently been made [39] of the thermodynamic parameters for the equilibrium *(8a)* ⇌ *(8b)* which, presumably, corresponds to the

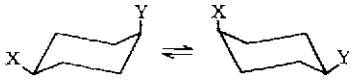


(8a), cis *(8b)*, trans

X = $-CO_2H$

conformational equilibrium of the carboxyl group (see Section VII). Determinations of equilibrium from 212 to 333 °C in dodecane as a solvent indicates $\Delta H^\circ = -1.63 \pm 0.05$ kcal/mole, $\Delta S^\circ = -0.8 \pm 0.2$ cal·mole^{-1}·degree^{-1}, and $\Delta G^\circ = -1.4 \pm 0.1$ kcal/mole (extrapolated to 25 °C). The negative value of ΔS° is surprising at first, as one might have expected an equatorial COOH group to have more conformational freedom than the corresponding axial group. It appears, however, that the equatorial acid is more strongly associated in dodecane solution with a resultant greater loss in translational entropy [*].

As yet, little definite is known about conformational equilibria in di- and polysubstituted cyclohexanes, *e.g.* *(9)*, X + Y. It is generally assumed that the conformational energies are additive, *i.e.* $\Delta G^\circ = \Delta G^\circ_Y - \Delta G^\circ_X$ for the compounds *(9a)* and *(9b)*. Some support for this assumption has been obtained for 1,3- and 1,4-disubstituted cyclohexanes [15, 40, 41] although there are also difficulties [15]. In 1,2-disubstituted cyclohexanes, the principle of additivity cannot be expected to hold for two reasons: one is that, because of the flattening of the ring, *cis*-substituents (equatorial-axial) are closer together and therefore have a greater steric



(9a) *(9b)*

interaction than *trans*-substituents (equatorial-equatorial) [20, 42, 43]; the other is that substituents which are not spherically symmetrical may be forced into different rotational conformations by adjacent substituents [44, 45]. Thus in a *cis*-2-isopropylcyclohexanol, the e-hydroxy,a-isopropyl conformation is unfavorable by much more than the difference in $-\Delta G^\circ$ values of cyclohexanol and isopropylcyclohexane (1.4 kcal/mole [42]). The reason is that the axial isopropyl group cannot readily assume its normal conformation (methyls out of the ring) since this leads to strong steric interaction with the OH group (equivalent to a hydroxymethyl *syn*-axial interaction) [44].

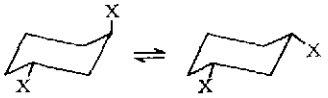
In 1,1-disubstituted cyclohexanes, it has been assumed [46] that the $-\Delta G^\circ$ values are additive. This assumption seems to be justified in 1-chloro-1-methylcyclohexane in which $-\Delta G^\circ$ (1.1 kcal/mole in favor of the a-chlorine, e-methyl conformation) [47] is close to the difference of the conformational energies of methylcyclohexane (1.7 kcal/mole) and chlorocyclohexane (0.4 kcal/mole).

VII. Methodology

Since the equilibrium *(1a)* ⇌ *(1b)* is established in a fraction of a millisecond at room temperature, direct measurement of the position of equilibrium is possible only by physical methods (see below). However, there are various indirect chemical approaches to the problem.

A. Thermochemical Method

In the simplest approach, the conformational equilibrium *(1a)* ⇌ *(1b)* is replaced by a configurational equilibrium – hypothetical or actually achievable – for example *(10a)* ⇌ *(10b)*. Since a *cis*-1,3-disubstituted



(10a) *(10b)*

[36] *B. J. Armitage, G. W. Kenner*, and *M. J. T. Robinson*, Tetrahedron *20*, 747 (1964).

[37] *B. Rickborn* and *F. R. Jensen*, J. org. Chemistry *27*, 4606 (1962).

[38] *N. L. Allinger* and *S.-E. Hu*, J. Amer. chem. Soc. *84*, 370 (1962); J. org. Chemistry *27*, 3417 (1962).

[39] *E. L. Eliel* and *M. Reese*, unpublished work.

[*] Note added in proof: The negative ΔS° may indicate that the axial COOH group exists in two (mirror-image) CO/C eclipsed conformations whereas the equatorial COOH exists mainly in a single CO/H eclipsed conformation.

[40] *E. L. Eliel* and *C. A. Lukach*, J. Amer. chem. Soc. *79*, 5986 (1957).

[41] *E. L. Eliel* and *R. S. Ro*, J. Amer. chem. Soc. *79*, 5995 (1957).

[42] *T. J. Brett*, Ph. D. Thesis, University of Notre Dame, 1963; *E. L. Eliel* and *T. J. Brett*, J. Amer. chem. Soc., in the press.

[43] *J. C. Richer, L. A. Pilato*, and *E. L. Eliel*, Chem. and Ind. (London) *1961*, 2007.

[44] *R. D. Stolow*, J. Amer. chem. Soc. *86*, 2170 (1964).

[45] *J. Sicher*, unpublished observations.

[46] *R. J. Ouellette*, J. Amer. chem. Soc. *86*, 3089 (1964).

[47] *Anna Fang*, M. S. Dissertation, Massachusetts Institute of Technology, 1965.

cyclohexane exists virtually exclusively in the diequatorial form (the diaxial conformation has a severe 1,3-*syn*-axial steric interaction of the substituents) and each enantiomer of the *trans*-isomer necessarily exists in one of two superimposable equatorial-axial conformations, the enthalpy difference between the two configurational isomers may be equated to the enthalpy difference between equatorial and axial X (assuming that the second substituent does not exert a disturbing influence). The enthalpy difference may be found directly by accurate determination of the heats of combustion of the *cis*- and *trans*- isomers and this approach has been used successfully in the case of the 1,3-dimethylcyclohexanes [48]. The heat of combustion of the *trans*-isomer is 1256.75 kcal/mole and that of the *cis*-isomer 1254.79 kcal/mole (gas phase); the difference of 1.96 kcal/mole thus represents the greater stability of equatorial methyl over axial in the gas phase. The corresponding value in the liquid phase similarly determined is 1.72 kcal/mole.

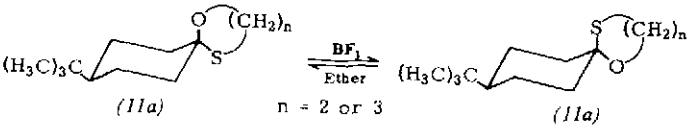
It is clear that in order to achieve an accuracy of approximately $\pm 10\,\%$ in the conformational energy difference required an accuracy of nearly 1 part in 10000 in the heat-of-combustion data themselves. Such accuracy is extraordinarily difficult to achieve, requiring not only very careful measurement but also extremely pure samples. The attendant difficulties have discouraged wide-spread use of the method.

In the case of the 1,3-dimethylcyclohexanes the entropies of the *cis*- and *trans*-(±)-isomers have also been measured [49] and the difference is found to be 1.24 cal·mole^{-1}·degree^{-1} in favor of the *trans*-form, in good agreement with the expected value of 1.38 cal·mole^{-1}·degree^{-1} calculated on the assumption that the only entropic difference between the *cis*- and *trans*-isomers stems from the fact that the *trans*-isomer is a (±)-pair and is therefore favored by an entropy of mixing of R ln 2. From the experimental values of ΔH° and ΔS° for the 1,3-dimethylcyclohexanes one may calculate ΔG° at 25 °C to be −1.59 kcal/mole for the equilibrium *trans* ⇌ *cis* (gas phase). It must be recognized that this value bears no direct relation to the conformational energy of methylcyclohexane. To obtain ΔG° for the conformational equilibrium *(1a)* ⇌ *(1b)*, X = CH_3, it is best to assume that $\Delta S^\circ = 0$ and therefore $\Delta H^\circ = \Delta G^\circ = -1.96$ kcal/mole in the gas phase. The assumption that ΔS° between equatorial and axial methylcyclohexane is zero is best justified by the observation (*vide supra*) that the entropy difference for the dimethylcyclohexane is completely accounted for (within limits of experimental error) by the entropy-of-mixing term (which does not enter into the methylcyclohexane conformational equilibrium).

B. Equilibrium Methods

An alternative and usually experimentally easier approach is to establish the equilibrium *(10a)* ⇌ *(10b)* directly and to measure the equilibrium constant K (*e.g.* by gas chromatographic determination of the equilibrium position); then $\Delta G^\circ = -RT \ln K$. In principle, ΔH° can be measured from the temperature dependence of K, but to effect such measurements with the required degree of accuracy is quite painstaking, and some of the data in the literature in this regard must be viewed with reserve. Short of performing a really careful measurement of ΔH°, it is probably better, for a spherically symmetrical group such as methyl, to assume that ΔS° for the process *(10a)* ⇌ *(10b)* is $-R \ln 2$ and then to calculate ΔH° at the desired temperature. An even safer approach, applicable to all groups, is to assume that $-\Delta G^\circ_X$ for the equilibrium *(1a)* ⇌ *(1b)* may be obtained from $-\Delta G^\circ$ for the process *(10a)* ⇌ *(10b)* by adgdin RT ln 2. This, in essence, entails the assumption that the process *(10a)* ⇌ *(10b)*, but for the equilibrium (optically active *trans*) ⇌ (*meso-cis*) does, in fact, have the same equilibrium constant as *(1a)* ⇌ *(1b)*. These principles were applied to the equilibration of the diethyl hexahydroisophthalates *(10)*, X = $CO_2C_2H_5$, [50] for which equilibrium at 78 °C corresponds to 71 % *cis*- and 29 % *trans*-isomer, $-\Delta G^\circ$ being 0.63 kcal/mole. From this, applying the RT ln 2 correction, $-\Delta G^\circ_{CO_2C_2H_5}$ is 1.11 kcal/mole.

An alternative but related approach is to measure the equilibrium position for *cis*- and *trans*-4-t-butyl isomers *(8)*. Thus, for example, for *(8)*, X = $CO_2C_2H_5$, equilibrium corresponds to 84.7 ± 0.6 % *trans*-isomer [51], whence $-\Delta G^\circ_{CO_2C_2H_5}$ may be directly calculated to be 1.2 kcal/mole. In some cases, where groups cannot readily be equilibrated directly at temperatures in the vicinity of 25 °C, some indirect means of equilibration may be resorted to. For example, the equilibrium constant for the equilibrium *(11a)* ⇌ *(11b)* has been shown to be close to unity [52]. Since it was known from other measurements [53] that $-\Delta G^\circ_{OR} \approx 0.7$ kcal/mole, it may be inferred that $-\Delta G^\circ_{SR}$ is of the same order of magnitude.



(11a) *(11a)*

A somewhat more intricate method of indirect equilibration is shown by formulae *(12a)*–*(12c)*. It is known [54] that equilibration of 4-t-butylcyclohexanol with $LiAlH_4/AlCl_3$/4-t-butylcyclohexanone in ether (probably an oxidation-reduction type of equilibration involving the complex $ROAlCl_2$, cf. [55]) leads to an equilibrium mixture containing over 99.5 % of the *trans*-complex. Therefore, for any R in *(12)* which is appreciably smaller than t-butyl, virtually all the *cis*-isomer exists in the conformation C′ *(12c)*, and what is chemically an

[48] *E. J. Prosen, W. H. Johnson*, and *F. D. Rossini*, J. Res. nat. Bur. Standards *39*, 173 (1947); *J. E. Kilpatrick, H. G. Werner, C. W. Beckett, K. S. Pitzer*, and *F. D. Rossini*, ibid. *39*, 523 (1947).

[49] *H. M. Huffmann, S. S. Todd*, and *G. D. Oliver*, J. Amer. chem. Soc. *71*, 584 (1949).

[50] *N. L. Allinger* and *R. J. Curby*, J. org. Chemistry *26*, 933 (1961).

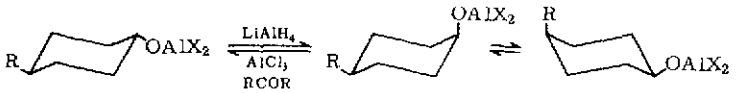
[51] *E. L. Eliel, H. Haubenstock*, and *R. V. Acharya*, J. Amer. chem. Soc. *83*, 2351 (1961); *N. L. Allinger, L. A. Freiberg*, and *S.-E. Hu*, ibid. *84*, 2836 (1962).

[52] *E. L. Eliel* and *L. A. Pilato*, Tetrahedron Letters *1962*, 103; *E. L. Eliel, E. W. Della*, and *M. Rogić*, J. org. Chemistry *30*, 855 (1965).

[53] *E. L. Eliel* and *M. H. Gianni*, Tetrahedron Letters *1962*, 97.

[54] *E. L. Eliel* and *M. Rerick*, J. Amer. chem. Soc. *82*, 1367 (1960).

[55] *E. L. Eliel* and *D. Nasipuri*, J. org. Chemistry, in the press.



(12a), T *(12b)*, C *(12c)*, C'

equilibration between T *(12a)* and C *(12b)*, thermodynamically may almost be considered as an equilibration of T and C' so that the measured equilibrium constant K_{epi} leads directly to ΔG°_{R}. More exactly, we have an equilibrium between T and (C + C'). Therefore

$$K_{epi} = [T]/([C] + [C'])$$

and

$$1/K_{epi} = [C]/[T] + [C']/[T]$$

$$= 1/K_{OAlCl_2} + 1/K_R$$

$$= 1/K_R + 1/200$$

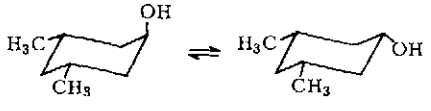
$$1/K_R = 1/K_{epi} - 1/200.$$

Unfortunately, although the method has been successfully applied to alkylcyclohexanes [54, 56], complications of various kinds [42, 57] seem to prevent its application to cyclohexanes containing more polar substituents.

Among other indirect equilibration methods, one which seems to be quite widely applicable involves equilibration (at C-5) of 3β-substituted 6-ketosteroids [58]. Since in a 3β-substituted 5α-ketosteroid the 3-substituent is equatorial but in the corresponding 5β-ketosteroid it is axial, equilibration of the two ketones leads to the $-\Delta G^{\circ}_{X}$ value of the 3β-substituent after a correction is applied for the equilibrium of the unsubstituted 5α- and 5β-ketosteroids.

In yet another interesting indirect equilibration method, $-\Delta G^{\circ}_{CO_2CH_3}$ is correlated with $-\Delta G^{\circ}_{CO_2H}$ through measurement of esterification equilibria [36].

Implicit in the application of the equilibration method, *e.g.* to the process *(8a)* ⇌ *(8b)*, is the assumption that the 4-t-butyl substituent does not affect the position of equilibrium. The only available justification for this assumption lies in the fact that $-\Delta G^{\circ}_{X}$ determined by the equilibrium method using either 4-t-butyl-substituted models *(8)* or 1,3-disubstituted compounds of the type *(10)* agrees with values obtained by other methods. In the case of cyclohexanols, it has been found [59] that $-\Delta G^{\circ}_{OH}$ determined by equilibration of the *cis*-3,5-di-



(13a) *(13b)*

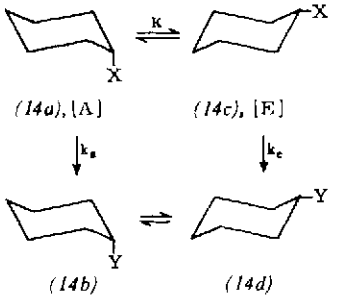
methylcyclohexanols *(13a)* and *(13b)* agrees perfectly with the value (0.93 kcal/mole) derived from similar equilibration of 4-t-butylcyclohexanol; the value of 1.23 kcal/mole derived from equilibration of the 3-t-butylcyclohexanols [42] on the other hand, disagrees completely and is out of line with other values of $-\Delta G^{\circ}_{OH}$. The difficulty here may be due to a strong distortion of the cyclohexane ring, although this point has not been clearly established.

C. The Kinetic Method

One of the earliest methods to assess conformational equilibria, discovered independently in *Winstein*'s laboratory [17] and in the present author's [40] is based on rate measurements. As suggested in formulae *(14a)–(14d)*, the reaction

$$C_6H_{11}X \rightarrow C_6H_{11}Y$$

of a mobile substituted cyclohexane may be looked at as really being two reactions: that of the axial conformational isomer and that of the equatorial conformational isomer.



(14a), [A] *(14c)*, [E]

(14b) *(14d)*

If the concentration of the axial conformer is [A] and its rate constant k_a, and if the concentration and rate constant for the equatorial conformer are [E] and k_e, it follows that

$$\text{rate of reaction} = k_e[E]\,P + k_a[A]\,P,$$

where P is the product of all other concentration terms entering into the rate equation. Experimentally one finds

$$\text{rate of reaction} = k[C]\,P,$$

where [C] is the total concentration of the monosubstituted cyclohexane and k is the observed rate constant. It follows that

$$k_e[E] + k_a[A] = k[C].$$

Remembering that

$$[C] = [E] + [A]$$

and

$$K = [E]/[A],$$

one obtains

$$k_eK + k_a = k\,(K + 1).$$

This equation, in the form

$$k = (k_eK + k_a)/(K + 1)$$

provides a heuristic relationship permitting evaluation of the empirical rate constant k in terms of the rate constants k_a and k_e for the pure conformational isomers and the equilibrium constant K between them. Alternatively, the equation may be regrouped to give

$$K = (k_a - k)/(k - k_e)$$

and, in this form, may serve to assess the conformational equilibrium constant K, if the rate constants k, k_e and k_a are known. It is, of course, simple to determine k; it

[56] *E. L. Eliel* and *T. J. Brett*, Abstracts, 145th Meeting Amer. chem. Soc., New York 1963, p. 19Q. See also [42].

[57] *E. L. Eliel* and *T. J. Brett*, J. org. Chemistry *28*, 1923 (1963).

[58] *D. N. Jones* and *D. E. Kime*, Proc. chem. Soc. (London) *1964*, 334; see also *J. F. Biellman* and *W. S. Johnson*, Proc. nat. Acad. Sci. U.S.A. *53*, 89 (1965).

[59] *E. L. Eliel* and *F. Biros*, unpublished work.

is only necessary to provide a reaction suitable for the substituent under consideration for which a convenient rate measurement is available, *e.g.* saponification for the ester group $CO_2C_2H_5$. The determination of k_e and k_a is much more difficult in principle. *Winstein* has suggested [17] that conformationally biassed systems such as *(3)* will provide suitable models for the determination of k_e [= k_{trans}, *(3a)*] and k_a [= k_{cis}, *(3c)*]; thus the rate constant for the hydrolysis of ethyl *trans*-4-t-butylcyclohexanecarboxylate is $k_e = 8.50 \times 10^{-4}$ l·mole^{-1}·sec^{-1}; k_a for the *cis*-isomer is 0.428×10^{-4} l·mole^{-1}·sec^{-1} and k, the saponification rate of ethyl cyclohexanecarboxylate is 7.25×10^{-4} l·mole^{-1}·sec^{-1}, whence

$$K = (0.428-7.25)/(7.25-8.50) = 6.82/1.25 = 5.45 \text{ at } 25\,^{\circ}C$$

corresponding to $-\Delta G^{\circ}_{CO_2C_2H_5} = 1.00$ kcal/mole.

Although the equation

$$k = (k_eK + k_a)/(K + 1) \text{ [40]}$$

or its equivalent

$$k = N_ek_e + N_aK_a \text{ [17]}$$

(N_a and N_e = mole fractions of the mobile compound in the equatorial and axial conformations)

is rigorously correct, the hypothesis that k_e and k_a can be measured using the appropriate 4-t-butyl analogues is strictly an assumption, which, in turn, involves four postulates:

1) The 4-t-butylcyclohexyl compounds exist virtually exclusively in the conformation with equatorial t-butyl.

2) The t-butyl group exercises no polar effect on the reaction.

3) The t-butyl group exercises no steric effect on the reaction.

4) The t-butyl group does not distort either the ground or transition state of the reaction or, if it does, at least the distortion is compensated in such a way that the activation energy is not affected.

Postulate 1) is well justified by the fact that the conformational energy of the t-butyl group is in excess of 4.4 kcal/mole [42]. Most substituents are small compared to that and it is probably safe to assume, therefore, that the 4-t-butyl-substituted molecules do, in fact, exist in conformations *(3a)* and *(3c)*.

Postulate 2) (absence of polar effects) seems to be justified by the similarity in pK_a of cyclohexanecarboxylic acid (7.82 in aqueous dimethylformamide) and of *trans*-4-t-butylcyclohexanecarboxylic acid (7.79). If there were a major polar effect, it should certainly affect acidity. It must be said, however, that more extensive experimental data [60] suggest that substituents at carbon atom 3 may, in fact, exercise some polar effect, in contrast to those at C-4.

Postulate 3) (absence of **direct** steric effects) is best justified on the basis of molecular models.

[60] *H. van Bekkum, P. E. Verkade,* and *B. M. Wepster,* Proc., Kon. nederl. Akad. Wetensch., Ser. B *64*, 161 (1961).

Postulate 4) (absence of distortive effects) is probably a weak one; since transition states are of relatively high energy, appreciable distortions are likely to occur in them and, especially when the reaction occurs at the ring itself (oxidation of alcohols, S_N1 or S_N2 displacement of cyclohexyl tosylates) the assumption that these distortions affect the ground state and transition state equally in the unsubstituted and 4-t-butyl-substituted homologues may not be warranted. In fact, criticism has been leveled at the kinetic method largely on this ground [61] and it has been pointed out that an analysis of activation parameters in the solvolysis of cyclohexyl tosylates indicates that whereas the free energy of activation of the unsubstituted compound is intermediate between that of the *cis*- and *trans*-4-t-butyl-substituted homologues, the same is not true of the enthalpy and entropy of activation, and the success of the Winstein-Holness (or Eliel-Lukach) relationship therefore is, in this case, a fortuitous circumstance of temperature.

The difficulty in tosylate solvolysis is underscored by recent studies [62] of secondary isotope effects in the solvolysis of [2,2,6,6-D_4]-cyclohexyl tosylates and brosylates [*]. These studies have been interpreted to indicate that the *cis*-4-t-butyl-substituted compound reacts through a chair-shaped transition state whereas the *trans*-isomer reacts through a boat-shaped transition state; most surprisingly, the unsubstituted compound seems to react through a boat-shaped transition state also. Complications have also been found in the reaction of cyclohexyl tosylate and its *cis*- and *trans*-4-t-butyl analogues with thiophenolate [63]; whereas the overall rate constant of the unsubstituted compound (18.8×10^{-5} l·mole^{-1}·sec^{-1}) is appropriately intermediate between that of the 4-t-butyl-substituted prototypes (*cis*: 73.4×10^{-5}; *trans*: 1.72×10^{-5}), the fraction of elimination (as compared to substitution) is greater (0.60) for the unsubstituted compound than either for the *cis*- (0.45) or *trans*- (0.39) 4-t-butyl-substituted one.

Complications of this type are probably exacerbated in the (high-energy) transition states and are therefore more serious in the kinetic method than in other methods; nevertheless, the kinetic method, using 4-t-butyl-substituted models, gives $-\Delta G^{\circ}$ values in accordance with those obtained by other methods so frequently that it appears to be more than a matter of coincidence. As in the case of the equilibrium method, the same is not always true when one uses 3-substituted models which suggests, once again, that any distortion which occurs in the monosubstituted cyclohexane also occurs in the 4-t-butyl- or other 4-alkylcyclohexanes but not necessarily in a 3-alkylcyclohexane. Some pertinent data from recent work [59] are shown in Table 2; clearly the acetylation rates of variously substituted cyclohexanols

[*] Tosyl = *p*-toluenesulfonyl; brosyl = *p*-bromobenzene-sulfonyl.

[61] *H. Kwart* and *T. Takeshita*, J. Amer. chem. Soc. *86*, 1161 (1964); see also *W. Hückel* and *M. Hanack*, Liebigs Ann. Chem. *616*, 18 (1958).

[62] *V. J. Shiner* and *J. Jewett*, J. Amer. chem. Soc. *87*, 1382, 1383 (1965); *W. H. Saunders* and *K. T. Finley*, ibid. *87*, 1384 (1965).

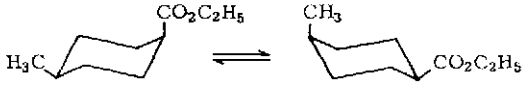
[63] *E. L. Eliel* and *J. West*, unpublished observations.

of analogous conformation are not constant and it turns out that a value for ΔG°_{OAc} consistent with other values in the literature may be obtained from the 4-t-butyl-substituted models but not, for example, from the *cis*-3,5-dimethyl-substituted models (which would give $\Delta G^{\circ}_{OAc} \approx 0$, an unreasonable value).

Table 2. Rate constants for the acetylation of substituted cyclohexanols at 25 °C [59]. Acetylating agent: acetic anhydride/pyridine. The rate constant for the acetylation of cyclohexanol is k = 8.6×10^{-5} l·mole^{-1}·sec^{-1}.

Equatorial alcohols	$k \times 10^5$ [l·mole^{-1}·sec^{-1}]
trans-4-t-Butylcyclohexanol	10.8
cis-3-t-Butylcyclohexanol	10.55
cis-3-Isopropylcyclohexanol	10.85
cis-3-Methylcyclohexanol	10.85
cis-3,3,5-Trimethylcyclohexanol	12.2
cis,cis-3,5-Dimethylcyclohexanol	13.1
cis-3-Methyl-*cis*-5-isopropylcyclohexanol	12.4
cis-3-Methyl-*cis*-5-t-butylcyclohexanol	11.5
cis,cis-3,5-di-t-Butylcyclohexanol	11.3
Axial alcohols	
cis-4-t-Butylcyclohexanol	2.92
trans-3-t-Butylcyclohexanol	3.38
trans,trans-3,5-Dimethylcyclohexanol	3.37
trans,trans-3-Methyl-5-isopropylcyclohexanol	3.41
trans,trans-3,5-di-t-Butylcyclohexanol	4.14

Apart from the intrinsic difficulty involved in the kinetic method there is a technical difficulty which is evident from the case of ethyl cyclohexanecarboxylate given earlier. If k is close to either k_e or k_a, either the numerator or the denominator in the equation yielding K will be a small difference of large numbers and the accuracy of K thus determined will be low. In general, this difficulty arises when the monosubstituted cyclohexane exists extensively in the equatorial conformation (*i.e.* if the substituent is relatively large) since in that case k will be close to k_e; the ethoxycarbonyl group is an example. Clearly, better results would be obtained in a system where k is nearly midway between k_e and k_a.



(15a) *(15b)*

Formulae *(15a)* and *(15b)* show such a system; here the ethoxycarbonyl group is counterpoised by the methyl group [*] and equilibrium will lie near 50:50. From the saponification rate constant for this system ($k = 2.65 \times 10^{-4}$ l·mole^{-1}·sec^{-1}) one may readily compute the equilibrium constant

$$K = (k_a - k)/(k - k_e) = 0.38$$

whence ΔG° for this system is +0.57 kcal/mole. Assuming now additivity of conformational free energies (see Section VI for the limitations of this assumption) one has

$$\Delta G^{\circ}_{1} = \Delta G^{\circ}_{CO_2C_2H_5} - \Delta G^{\circ}_{CH_3}$$

[*] A group of this type is called a "conformation-restoring group" by *J. Sicher* (personal communication; see also ref. [81]).

or

$$\Delta G^{\circ}_{CO_2C_2H_5} = \Delta G^{\circ}_{1} + \Delta G^{\circ}_{CH_3}.$$

Taking ΔG°_{Me} as −1.7 kcal/mole, this gives

$$\Delta G^{\circ}_{CO_2C_2H_5} = 1.13 \text{ kcal/mole}$$

in very good agreement with the values given earlier. Some reflection will show that, with $\Delta G^{\circ}_{CH_3} = -1.7$ kcal/mole, *cis*-4-methyl-substituted cyclohexanes will give more accurate conformational energies than monosubstituted cyclohexanes when the conformational energy is in excess of 0.85 kcal/mole. Some conformational energies obtained by the kinetic method, *e.g.* that for the amino group in protic solvents [33], could not have been obtained without resorting to the *cis*-4-methyl-substituted model.

An approach similar to the kinetic method but using equilibrium constants instead of rate constants ($K = N_e K_e + N_a K_a$, where K, K_e, and K_a are equilibrium constants for appropriate chemical equilibria for monosubstituted and *trans*- and *cis*-4-t-butyl-substituted compounds) has also been used occasionally; the derivation of $-\Delta G^{\circ}_{CO_2H}$ from pK data (in essence dissociation equilibrium constants) described in the next Section is of this type.

D. Physical Methods

Since a number of physical properties of substituted cyclohexanes are affected by the equatorial or axial position of the substituent, physical measurements can, in turn, be used to infer conformation. Thus electron diffraction studies have been used to ascertain the position of conformational equilibrium in chloro- [64] and fluorocyclohexane [65]; and the conformational equilibrium of cyclohexanes carrying carboxy and carboxylate groups [36, 60, 66], amino, dimethylamino, ammonium, and dimethylammonium groups [67], and mercaptan and mercaptide groups [68] have been deduced from pK measurements. Measurements of dipole moments served in the assignment of conformation to *trans*-1,2-dibromocyclohexane [69] and the 2-halogenocyclohexanones [70]; optical rotatory dispersion [71] and ultraviolet [72] measurements have also been applied to the latter compounds. Kerr con-

[64] *V. A. Atkinson*, Acta chem. scand. *15*, 599 (1961).

[65] *P. Andersen*, Acta chem. scand. *16*, 2337 (1962).

[66] *R. D. Stolow*, J. Amer. chem. Soc. *81*, 5806 (1959); *M. Tichý, J. Jonáš*, and *J. Sicher*, Collect. Czechoslov. chem. Commun. *24*, 3434 (1959).

[67] *J. Sicher, J. Jonáš*, and *M. Tichý*, Tetrahedron Letters *1963*, 825.

[68] *H. Boaz*, unpublished observations; cf. *B. P. Thill*, Ph. D. Thesis, University of Notre Dame, 1964.

[69] *W. Kwestroo, F. A. Meijer*, and *E. Havinga*, Recueil Trav. chim. Pays-Bas, *73*, 717 (1954); *K. Kozima, K. Sakashita*, and *S. Maeda*, J. Amer. chem. Soc. *76*, 1965 (1954); *P. Bender, D. L. Flowers*, and *H. L. Goering*, ibid. *77*, 3463 (1955); *E. C. Wessels*, Doctorate Dissertation, University of Leiden, Netherlands, 1960.

[70] a) *W. D. Kumler* and *A. C. Huitric*, J. Amer. chem. Soc. *78*, 3369 (1956); b) *N. L. Allinger, J. Allinger, L. A. Freiberg, R. F. Czaja*, and *N. A. LeBel*, J. Amer. chem. Soc. *82*, 5876 (1960); c) *A. S. Kende*, Tetrahedron Letters *1959*, No. 14, p. 13.

[71] *C. Djerassi, L. E. Geller*, and *E. J. Eisenbraun*, J. org. Chemistry *25*, 1 (1960).

[72] *J. Allinger* and *N. L. Allinger*, Tetrahedron *2*, 64 (1958); *N. L. Allinger* and *J. Allinger*, J. Amer. chem. Soc. *80*, 5476 (1958); see also ref. [70b].

stant measurements have been utilized [73] in the determination of conformational equilibrium in bromocyclohexane but seem to be less reliable than other physical methods.

Whereas these methods are limited in applicability to special cases, two fairly general methods of conformational assignment are available in infrared and nuclear magnetic resonance spectroscopy. The infrared spectrum of a substituted cyclohexane $C_6H_{11}X$ in general varies with the equatorial or axial nature of the substituent X. In particular, if bands can be assigned to the C–X stretching frequency, equatorial C–X will be found at higher frequency (by 10–55 cm^{-1}) than axial. In a mobile system, *e.g. (1a)* ⇌ *(1b)*, because of the operation of the Franck-Condon principle (time of vibrational transition ≪ time of conformational interconversion), axial and equatorial C–X stretching frequencies will both be found and the ratio of intensities of the equatorial and axial C–X stretching band will depend on the conformational equilibrium constant K. Two methods are available to obtain K quantitatively from infrared data.

a) In one, the temperature is varied and the ratio of extinctions (integrated band intensities) of the equatorial and axial C–X stretching bands, A_e/A_a, is determined as a function of temperature. Then, assuming that the extinction coefficients for the axial and equatorial stretching bands do not vary with temperature and applying the vant'Hoff relationship, one may deduce [74]:

$$\Delta H = RT_1T_2[\ln(A_e/A_a)T_2 - \ln(A_e/A_a)T_1]/[T_2 - T_1]$$

Unfortunately, since ΔH is generally not very large (less than 1 kcal/mole for most polar substituents), the band intensity ratio changes rather slowly with temperature and application of the above method requires large temperature intervals and accurate measurements of band intensity. As a result, the method is not experimentally very attractive and has been used relatively infrequently.

b) In principle, one could deduce conformational population ratios and, hence, free energies directly from band intensities if one knew the extinction coefficients, since:

$$K = N_e/N_a = \varepsilon_a A_e/\varepsilon_e A_a$$

where ε_e and ε_a are the molar extinction coefficients for the equatorial and axial C–X stretching mode, respectively. It has been suggested [75] that ε_e and ε_a can be measured from the intensity of the C–X stretching bands in the conformationally homogeneous *trans*- and *cis*-4-t-butyl-substituted models. For the moment, this suggestion (which amounts to saying that the 4-t-butyl group does not affect the extinction coefficient for the C–X band, X at C-1) must remain an assumption, since the method has not been applied extensively. In its first application to cyclohexanol [75a] the method failed when the axial C–O stretch was considered, and even application to the supposed equatorial C–O stretching band [75a, 76] gave a range of conformational energies for OH of 0.29–0.41 kcal/mole, well below the now accepted value of 0.6 kcal/mole in solvents which are not hydrogen donors. It has been suggested [77] that the difficulty lies not necessarily in the method but in the problem of discerning a pure equatorial C–O stretching frequency in cyclohexanol; presumably the band at 1069 cm^{-1} which was used has a skeletal vibrational mode mixed in with it.

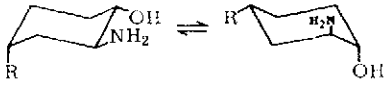
The temperature-dependent infrared method as applied to cyclohexanols [78] gives a value of 0.31–0.41 kcal/mole for $\Delta H°$. This value may not, however, be too low, since $\Delta S°$ for OH is probably not zero. If one assumes, in the extreme, that an equatorial hydroxy group has three rotational conformations of equal energy, whereas an axial hydroxy group has only two conformations of equal energy (the third conformation, with the hydrogen pointing into the ring, being considered of sufficiently higher energy to be disregarded), then the entropy difference is R ln 3 − R ln 2 or 0.81 cal·mole^{-1}·degree^{-1} in favor of the equatorial isomer and

$$\Delta G^0_{OH} = \Delta H^\circ_{OH} - T\Delta S^0_{OH}$$

would then be calculated to be 0.55–0.65 kcal/mole, in good agreement with values obtained by other methods in aprotic solvents.

Application of the second infrared method to chloro- [32a] and bromocyclohexane [79] gives conformational energy values (0.40 kcal/mole for the chloride, 0.46 kcal/mole for the bromide) which are in good agreement with other values for these atoms; the first infrared method (temperature dependence of intensities) gives reasonable ΔH values for chlorine [78a, 80] but a somewhat low value (0.2 kcal/mole) for bromine [78a]; it seems unlikely that entropy differences between equatorial and axial bromine could account for the discrepancy in this case.

A particularly valuable and apparently reliable application of infrared spectroscopy consists in the measurement of the relative intensities of bonded and unbonded OH-stretching frequencies in appropriately 2-substituted cyclohexanols; this method has been used to assess the position of conformational equilibrium in *trans*-1,2-cyclohexanediols and *trans*-2-aminocyclohexanols *(16)* [81].



(16a) *(16b)*

[73] *C. G. Le Fèvre, R. J. W. Le Fèvre, R. Roper*, and *R. K. Pierens*, Proc. chem. Soc. (London) *1960*, 117.

[74] Ref. [14], p. 130, also ref. [8b].

[75] a) *R. A. Pickering* and *C. C. Price*, J. Amer. chem. Soc. *80*, 4931 (1958); b) *G. R. Haber*, personal communication.

[76] *G. Chiurdoglu* and *W. Masschelein*, Bull. Soc. chim. Belges *69*, 154 (1960); *70*, 29 (1961).

[77] *Anita H. Lewin*, Ph. D. Thesis, University of California, Los Angeles, 1963.

[78] a) *G. Chiurdoglu, L. Kleiner, W. Masschelein*, and *J. Reisse*, Bull. Soc. chim. Belges *69*, 143 (1960); b) *J. Masschelein*, J. molecular Spectroscopy *10*, 161 (1963).

[79] *F. R. Jensen* and *L. H. Gale*, J. org. Chemistry *25*, 2075 (1960).

[80] *K. Kozima* and *K. Sakashita*, Bull. chem. Soc. Japan *31*, 796 (1958).

[81] *J. Pit'ha, J. Sicher, F. Šipoš, M. Tichý*, and *S. Vašíčková*, Proc. chem. Soc. (London) *1963*, 301.

Nuclear magnetic resonance is one of the most powerful tools to give direct insight into both the structure and stereochemistry of an organic compound. It is therefore no wonder that the technique has been applied extensively in conformational problems – so extensively, in fact, that its application forms the subject of a separate review in this journal [82]. For this reason we shall discuss here only one application of NMR – that in determining conformational equilibria.

Axial and equatorial protons (similar principles apply to other nuclei susceptible to NMR detection, such as fluorine) generally differ in chemical shift of their NMR signals by 20–40 cps (at 60 Mc) if the chemical environment is otherwise the same. The signal of the axial proton usually appears at higher field. Spin-spin splitting also differs between the two types of signals since axial protons are subject to coupling with both adjacent axial or *anti* ($J_{a,a} \approx 9$ cps) and equatorial or *gauche* ($J_{e,a} \approx 3$ cps) protons whereas equatorial protons couple only with *gauche* protons. As a result, the half-width of an equatorial proton signal (*ca.* 7 cps) is appreciably less than that of an axial proton signal (*ca.* 22 cps). It might be expected, then, in analogy with the situation in infrared spectroscopy, that a mobile cyclohexane system would show two signals for a given proton (*e.g.* the >CHX proton in $C_6H_{11}X$): one for the axial proton of the equatorial isomer and one for the equatorial proton of the axial isomer. However, this is not the case. Because the frequency interval between the two proton signals is only about 30 cps, whereas the rate of interconversion of the two chair forms is well in excess of 1000 sec^{-1} at room temperature, the chair will flip many times in the interval between an equatorial and an axial transition and these transitions will therefore merge into an average signal.

Nevertheless there are two ways in which NMR can be utilized to establish conformational equilibria. It is possible to slow down the equatorial-axial interconversion by lowering the temperature; at about −67 °C, the rate of chair interconversion in cyclohexane is of the same order of magnitude as the chemical shift between the signals of equatorial and axial protons and so the original single peak will begin to split into two separate peaks. (It is from the signal shape at temperatures near this "coalescence point" that the activation parameters for chair-chair interconversion given earlier have been obtained.) At temperatures much below the coalescence point, two clearly divided peaks are found, and from the areas of these peaks, the relative population of equatorial and axial conformations at the temperature in question may be directly computed. This method is theoretically sound but experimentally difficult for two reasons: accurate NMR measurements at definite temperatures much below room temperature are hard to effect (because of difficulty in obtaining and measuring the temperatures required, because of viscosity broadening of the signals, and because of solubility problems) and the conformational equilibrium at the low temperatures needed is biassed very much in favor of the equatorial isomer (*e.g.* an equilibrium constant of 4 at room temperature corresponds to one of 11 at −100 °C, assuming ΔG° to be temperature invariant). Nevertheless the low-temperature NMR method has been used with good results for halogenocyclohexanes [83].

An experimentally simpler method is to base the estimate of the conformational equilibrium on the position of the average proton signal at room temperature. This position will depend directly on the position of equilibrium; in fact, it can be shown [84] that

$$\nu = N_a\nu_a + N_e\nu_e$$

where N_a and N_e are the mole fractions of axial and equatorial conformers, as before, and ν_a and ν_e are the shifts for salient protons (*e.g.* the >CHX proton) in these conformers whereas ν is the shift for the corresponding proton in the mobile system. Clearly, this equation is entirely analogous to the Winstein-Holness equation for rate constants (*vide supra*) and may be transformed [53, 85] into the form

$$K = (\nu_a - \nu)/(\nu - \nu_e).$$

In order to apply this equation to the evaluation of K, it is necessary to establish the values of ν_a and ν_e. This can be done in two ways, either by effecting measurements at very low temperatures [83a, 86] where the signals of the two conformations are separate, or by using model compounds, such as 4-t-butyl-substituted cyclohexanes, to fix the appropriate conformations [32–34, 53, 85, 87, 88]. The use of such model compounds now entails the assumption that the 4-t-butyl substituent does not affect the chemical shift. Contrary to recent assertions [89], this assumption seems to be valid for cyclohexanone dimethyl ketal and 4-t-butylcyclohexanone dimethyl ketal: the (average) signal of the methyl groups in the former (−183.9 cps at 60 Mc) occurs, as exactly as the accuracy of the measurements permits one to say, exactly half-way in between the (resolved) signals of the methyl groups in the latter (−182.9 and −184.9 cps) [90]. Other data, concerned with the shift of the carbinol proton signal in variously substituted cyclohexanols [91], while inconclusive, are not so encouraging as regards the complete absence of an effect of a 4-t-butyl group. The data for the pair chloro-

[82] *H. Feltkamp* and *N. C. Franklin*, a) Angew. Chem. *77*, 798 (1965); Angew. Chem. internat. Edit. *4*, 774 (1965); b) Liebigs Ann. Chem. *683*, 55 (1964).

[83] a) *A. J. Berlin* and *F. R. Jensen*, Chem. and Ind. (London) *1960*, 998; b) *L. W. Reeves* and *K. O. Strømme*, Canad. J. Chem. *38*, 1241 (1960).

[84] *H. S. Gutowsky* and *A. J. Saika*, J. chem. Physics *21*, 1688 (1953).

[85] *E. L. Eliel*, Chem. and Ind. (London) *1959*, 568.

[86] *E. A. Allan*, *E. Premuzic*, and *L. W. Reeves*, Canad. J. Chem. *41*, 204 (1963).

[87] *A. H. Lewin* and *S. Winstein*, J. Amer. chem. Soc. *84*, 2464 (1962).

[88] *E. L. Eliel* and *B. P. Thill*, Chem. and Ind. (London) *1963*, 88.

[89] *M. Anteunis* and *D. Tavernier*, Tetrahedron Letters *1964*, 3949.

[90] *E. L. Eliel*, *M. Gianni*, and *R. J. L. Martin*, unpublished observations.

[91] *E. L. Eliel*, *M. Gianni*, *T. H. Williams*, and *J. B. Stothers*, Tetrahedron Letters *1962*, 741.

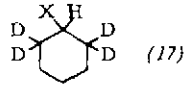
Table 3. Conformational equilibrium of chlorocyclohexane in carbon disulfide.

Compound	NMR signal			$-\Delta G^0$ [kcal/mole]	Ref.
	ν_e [cps]	ν [cps]	ν_a [cps]		
4-t-Butyl-chlorocyclohexane	−218.2 (25 °C)	−231.9 (25 °C)	−259.9 (25 °C)	0.42	[32a]
Chloro-cyclohexane	−224 (−81 °C)	−233.3 (25 °C)	−265.8 (−81 °C)	0.48 [a] 0.74 [b]	[83a]
	−227.4 (−91 °C)	−236.1 (25 °C)	−266.4 (−91 °C)	0.73 [b]	[83b]

[a] Extrapolated value, unspecified process of extrapolation.
[b] Raw value.

cyclohexane/4-t-butyl derivative summarized in Table 3 indicate that though there is a shift, surprisingly, more reasonable ΔG° values are obtained from the data for the 4-t-butyl compound than from the low-temperature data on the unsubstituted compound.

One of the difficulties inherent in the NMR method lies in the fact that the salient peaks are broad (due to extensive coupling) making accurate measurement of signal position problematic. This difficulty has been obviated to a considerable extent by employing [2,2,6,6-D_4]-cyclohexanes *(17)* in which the splitting is reduced by a factor of six [32b, 34, 87].



(17)

An attempt [32a] to achieve the same end more simply by employing double resonance (saturation of the ring protons other than the >CHX one) was unsuccessful since it was found that the chemical shift of the signal of the >CHX proton depended on the amount of RF-power used to saturate the remaining protons; and while it was possible to extrapolate a set of data obtained at varying RF to zero RF, the inaccuracy introduced by this extrapolation is of the same order of magnitude as the inaccuracy in peak measurement in a simple NMR experiment.

It might be mentioned here that the most accurate measurements of the cyclohexane inversion barrier [27] similarly employ[D_{11}]-cyclohexane.

While the spin-spin splitting would thus appear to be a nuisance in measurements of conformational equilibria, it has, on the other hand, also been employed to assess such equilibria [92, 93]. The principle here is that just as the signal position averages in a rapidly flipping substituted cyclohexane, so does the splitting, and if the splitting of both the equatorial and axial conformers is known, the position of conformational equilibrium may, in principle, be deduced from the splitting in the mobile system. This method is discussed in detail in the accompanying review [82].

E. Summary

In reviewing the methods available for determining conformational equilibria, one finds a certain amount of unity in them. In most cases some property of the mobile system (reaction rate, equilibrium constant, appropriate physical property) is compared to a similar property of a rigid or biassed system. If X is the property of the mobile system and the subscripts a and e refer to the axial and equatorial models, respectively, then, in many cases:

$$X = N_e X_e + N_a X_a,$$

which simply means that the property of the mobile system is the weighted average of the properties of its constituent conformational isomers. It follows that the desired equilibrium constant is

$$K = (X_a - X)/(X - X_e).$$

To obtain correct results it is necessary to select appropriate models to obtain the axial and equatorial values X_a and X_e. In many instances 4-t-butyl-substituted systems have been chosen for this purpose with results which, in general, show a remarkable amount of consistency. However, there is no inherent guarantee that the choice of such model systems is sound in all cases. The only theoretically unobjectionable approach is to use the mobile system itself and "freeze" it, either by slowing the interconversion of conformational isomers at low temperatures (low-temperature NMR method) or by using a method which is inherently fast compared to the velocity of ring inversion (such as infrared frequency measurements).

It is of interest that a method has recently been developed [94] in which it is not necessary to determine the properties X_a and X_e of the pure conformers but rather ΔH° is obtained by measurement of the change of the averaged property X (in the case cited, optical rotatory dispersion amplitude) with temperature. The accuracy and generality of this method remain to be established.

VIII. Future Work

It may be well (if risky) to conclude this brief review on conformational analysis in mobile systems by trying to foresee likely future problems (in the absence of any fundamental new breakthroughs).

On the theoretical side, it is likely that the availability of more accurate data on van der Waals radii from molecular beam experiments on one hand and the increasing availability of high-speed computers on the other will lead to more accurate calculations of conformational equilibria in a variety of systems.

In a semi-theoretical area, it is likely that an increasing number of assessments of ΔH° and ΔS° (as distinct from ΔG°) will be made and that, in the process, a better understanding of entropy differences between equatorially and axially substituted cyclohexanes will be gained. A word of caution is in order in this connection: since the thermodynamic differences between conformational isomers are in general quite small, accurate measurements of ΔH° and ΔS° will be difficult. It is deceptively easy to obtain such data from measurements of ΔG° at two temperatures, and, no doubt, a number of data will be turned out in this way and later found to be wanting. Reliable measurements of conformational ΔH°s and ΔS°s will probably require accurate equilibrium measurements at at least four and possibly

[92] *F. A. L. Anet*, J. Amer. chem. Soc. *84*, 1053 (1962).

[93] a) *H. Feltkamp* and *N. C. Franklin*, J. Amer. chem. Soc. *87*, 1616 (1965); b) *H. Feltkamp, N. C. Franklin, K. D. Thomas*, and *W. Brügel*, Liebigs Ann. Chem. *683*, 64 (1965).

[94] *A. Moscowitz, K. Wellemann*, and *C. Djerassi*, J. Amer. chem. Soc. *85*, 3515 (1963).

as many as six different temperatures over a range of preferably not less than 100 °C. In any case, a careful error treatment is called for in publications of such data. On the more practical side, we may look forward to see measurements on additional groups (such common groups as $-CHO$, $-COR$, $-CH=CH_2$ have not yet had ΔG°-values assigned to them). New methods, such as that based on measurement of the chemical shift of the OH NMR signal [46] may be expected to be devised. A more careful study of the solvent dependence of a number of conformational equilibria, especially those involving polar and hydrogen-bonding groups, may be looked forward to. Conformational equilibria of disubstituted cyclohexanes (1,1- as well as 1,2-, 1,3- and 1,4-disubstituted ones) will be studied to test additivity relationships in ΔG° (*vide supra*).

One very large area which has barely been scratched is that of conformational equilibria in heterocyclic systems. There has recently been much interest in the conformation of the basic piperidine and *N*-methylpiperidine systems [95] with the finding that the unshared electron pair is smaller than hydrogen and much smaller than a methyl group. Nothing is known yet on C-substituted piperidines and only a limited amount of information has been brought to bear on tetrahydropyrans [96] – the parent skeleton of the pyranose sugars – and 1,3-dioxanes [97a]. A number of heterocyclic systems have been considered only from the point of view of the chair-chair interconversion barrier [97b, 98] if at all and there is obviously much scope for further work in this area. Chemists interested in the behavior of natural products, such as sugars, will no doubt continue to consider the conformational implications in these systems; some studies on hexopyranoses and cyclitols [99] are already at hand.

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[95] *N. L. Allinger* and *J. C. Tai*, J. Amer. chem. Soc. *87*, 1227 (1965); *N. L. Allinger, J. G. D. Carpenter*, and *F. M. Karkowski*, ibid. *87*, 1232 (1965); *R. J. Bishop, L. E. Sutton, D. Dineen, A. Y. Jones*, and *A. R. Katritzky*, Proc. chem. Soc. (London) *1964*, 257; *K. Brown, A. R. Katritzky*, and *A. J. Waring*, ibid. *1964*, 257.

[96] *J. T. Edward* and *I. Puskas*, Canad. J. Chem. *40*, 711 (1962); *C. B. Anderson* and *D. T. Sepp*, Chem. and Ind. (London) *1964*, 2054; *E. L. Eliel* and *C. Giza*, unpublished observations.

[97] a) *E. L. Eliel* and *C. Knoeber*, unpublished observations; b) *H. Friebolin, S. Kabuss, W. Maier*, and *A. Lüttringhaus*, Tetrahedron Letters *1962*, 683.

[98] Ref. [12], pp. 248–252.

[99] Ref. [12], Chapter 6.

Conformational Analysis of Cyclohexane Derivatives by Nuclear Magnetic Resonance Spectroscopy

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Nuclear Magnetic Resonance is today one of the best methods available for the conformational analysis of cyclohexane derivatives. It is possible with this technique to investigate the spatial orientation of the substituents in fixed molecules, as well as the equilibrium position in mobile systems. For these determinations the areas under the signals, the chemical shifts, the coupling constants, and the band widths of particular signals can be used.

I. Basic Principles

1. Energetic Considerations

In a flexible molecule, the individual groups of atoms can take up different positions with respect to each other. Arrangements which differ from one another by rotations about single bonds are known as the conformations of the molecule. In most cases only a very small amount of energy is required in order to move the molecule from one conformation into the other, and for this reason one is often dealing with mixtures, in which many conformations may be in equilibrium with each other.

The cyclohexane system is particularly suitable for studies of conformational equilibria, as it possesses two favorable conformations, which correspond to the two chair forms of cyclohexane. These two forms can interconvert, but a relatively high energy (about 11 kcal/mole) is required to overcome the torsional rigidity and also to change the bond angles during the intermediate states. During this interconversion, cyclohexane passes through an energy minimum (*ca.* 5.0 kcal/mole), known as the twist (or skew) form [1], which is however considerably above the energy level of the two

[1] *W. S. Johnson, V. J. Bauer, J. L. Margrave, M. A. Frisch, L. H. Dredger*, and *W. N. Hubbard*, J. Amer. chem. Soc. *83*, 605 (1961).

chair forms. Smaller energy maxima (*ca.* 5.5 kcal/mole) correspond to the boat forms of the molecule [2]. At room temperature, the thermal energy is high enough to overcome this energy barrier for the inversion to occur with a high frequency, but at low temperatures the interconversion of the two forms is almost completely prevented.

Two types of protons can be distinguished on the cyclohexane ring: six are perpendicular to the plane of the ring (axial = a), and the remaining six are parallel to the plane of the ring (equatorial = e)[3]. On inversion, these protons (or substituents if present) exchange their positions [4].

(1) (2)

The two chair forms of mono-substituted cyclohexane have different energies because the non-bonding interactions between the substituent and the "syn-axial" hydrogen atoms are larger for an axial substituent than for an equatorial one. The free energy difference ΔG between the two conformations is given by:

$$\Delta G = -RT\ln K \qquad (a)$$

If the molecule contains more than one substituent, *e.g.* X and Y, it has generally been assumed that the ΔG values are additive [5]:

$$\Delta G_{XY} = \Delta G_X + \Delta G_Y \qquad (b)$$

This assumption is however not always correct [6,7]. The equilibrium constant K is given by:

$$K = x/(1-x) \qquad (c)$$

where x is the mole fraction of one of the forms present in the equilibrium mixture. In order to calculate K, the equation

$$K = (P_a - P)/(P - P_e) \qquad (d)$$

has been derived [8], where P_a and P_e are the magnitudes of a property of a molecule with an axial and an equatorial functional group, respectively, and P is the measured value of this property in the mixture. Equation (d) was originally used [8] to calculate K from reaction rates. Figure 1, which was calculated from Equations (a) and (c), shows the relationship between the percentage of the most stable conformer and the ΔG value.

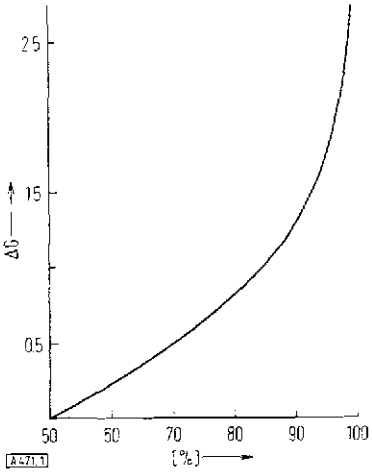
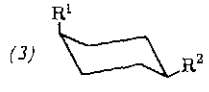
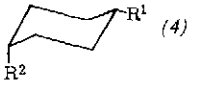


Fig. 1. Dependence of the percentage of the most stable conformer at 25 °C on ΔG.

It is obvious from Figure 1 why a non-chair form usually does not take part in the equilibrium: a ΔG value of approx. 5 kcal/mole corresponds to less than 0·1 % of the energy-rich form. When a substituent is introduced, the difference in energy between the *a*-chair and the non-chair forms is reduced and the percentage of the *a*-chair form is decreased but to the advantage of the *e*-chair, whilst the non-chair form does not occur.

(3)  (4) 

(5)

A fundamental change can, however, occur in disubstituted cyclohexanes (Fig. 2). If the two substituents are so arranged that one of them is in the axial position, the energy content of both chair forms is increased. The ΔG

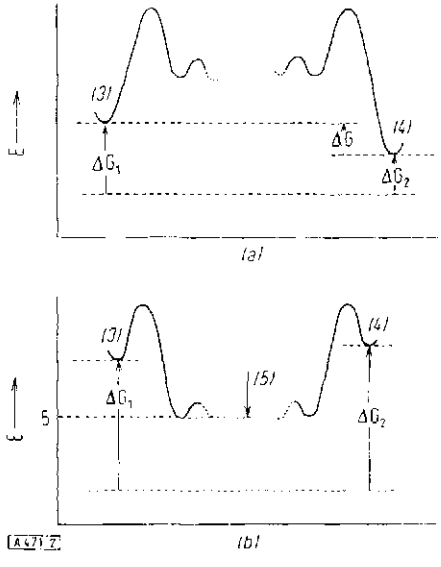


Fig. 2. Energy diagram for the inversion of a 1,4-disubstituted cyclohexane ring with one axial and one equatorial substituent. (a) ΔG_1, $\Delta G_2 < 5.0$ kcal/mole. (b) ΔG_1, $\Delta G_2 > 5.0$ kcal/mole.

[2] *E. L. Eliel*: Stereochemistry of Carbon Compounds. McGraw-Hill, New York 1962.

[3] For a fuller discussion see: (a) *D. H. R. Barton* and *R. C. Cookson*, Quart. Rev. (Chem. Soc., London) *10*, 44 (1956) and (b) *L. Velluz*, *T. Valls*, and *G. Nomine*, Angew. Chem. *77*, 185 (1965), Angew. Chem. internat. Edit. *4*, 181 (1965).

[4] *F. A. Bovey*, *E. W. Anderson*, *F. P. Hood* and *R. L. Kornegay*, J. chem. Physics, *40*, 3099 (1964).

[5] *E.g. A. H. Lewin* and *S. Winstein*, J. Amer. chem. Soc. *84*, 2464 (1962).

[6] *E. L. Eliel*, J. chem. Educat. *37*, 126 (1960).

[7] *E. L. Eliel*, Angew. Chem. *77*, 784 (1965), Angew. Chem. internat. Edit. *4*, 761 (1965).

[8] *S. Winstein* and *N. J. Holness*, J. Amer. chem. Soc. *77*, 5562 (1955); *E. L. Eliel* and *C. A. Luckach*, J. Amer. chem. Soc. *79*, 5986 (1957).

value, which determines the equilibrium constant, is then the difference between the individual ΔG values (Fig. 2a). If both ΔG values are greater than 5.0 kcal/mole, the twist form becomes the most stable conformer (Fig. 2b).

2. NMR Spectroscopy of Fixed Cyclohexane Derivatives

In the NMR spectrum of a fixed diequatiorially substituted cyclohexane molecule (Fig. 3), it is possible to distinguish between different types of protons which absorb at different fields. The tertiary protons (on C_1

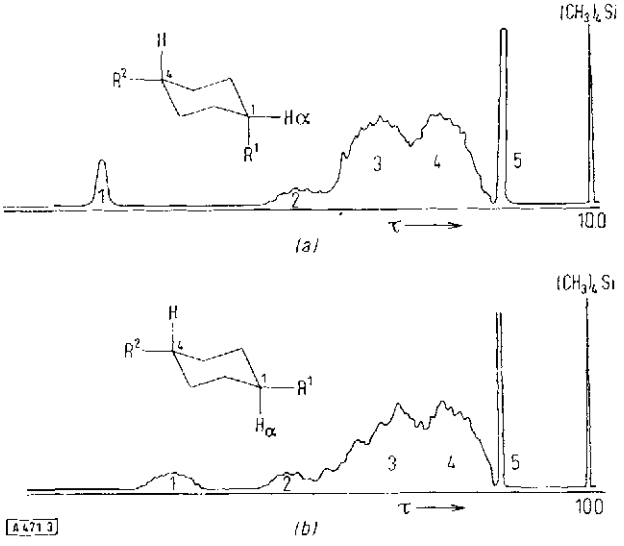


Fig. 3. Schematic NMR spectra of fixed disubstituted cyclohexanes (a) R^1 axial, R^2 equatorial. (b) R^1, R^2 both equatorial. Abscissa: chemical shift (p.p.m.).

and C_4) are those hydrogen atoms which are bonded to the same carbon as the substituents. The secondary protons are those methylene protons which make up the rest of the ring. The tertiary protons have a lower diamagnetic shielding, and thus generally appear at lower field. If the substituent R_1 is much more electronegative than the methylene group, the diamagnetic shielding of the proton on C_1 will be decreased, and its signal (hereafter referred to as the α-proton) will appear at even lower field. For this reason the α-proton signals are of particular value in conformational analysis. In most cases they are so far removed from the remainder of the protons that they become the X part of the spectra in the nomenclature of *Pople, Schneider,* and *Bernstein (PSB)* [9] (signal 1 in Fig. 3). The introduction of an electronegative group affects also the chemical shift of the methylene protons, but this will be neglected for the present.

If the substituent R^2 is an alkyl group (signal 5 in Fig. 3), the signal of the tertiary proton on C_4 will hardly be moved and will appear just below the general methylene absorption (signal 2 in Fig. 3).

Axial and equatorial protons appear at different fields [10] (compare signal 1 in Fig. 3a and 3b). This is equally true for tertiary as for secondary protons, and it is usually [12, 13] observed that the equatorial protons (signal 3) absorb at lower field than the axial protons (signal 4) [11]. The area under a signal is proportional to the number of protons producing it; thus the ratio of the areas of the signals 1–4 (Fig. 3) is 1:1:4:4.

The coupling constant between neighboring axial protons J_{aa} is generally two to three times as large [10] as the coupling constant between an axial and a neighboring equatorial proton, J_{ae}. The coupling constant between two neighboring equatorial protons J_{ee} is even lower [14]; the difference between J_{ae} and J_{ee} is however small. For this reason, amongst others, the axial and equatorial protons adjacent to the α-proton are not identical, and the signal of the α-proton in Figure 3 is the X part of an A_2B_2X system [9]. The difference in coupling constants results in the signal due to the axial α-proton (in Fig. 3b) being broader than that due to the equatorial α-proton (Fig. 3a).

Thus three measurements made from an NMR spectrum can be used in conformational analysis. From the chemical shift or the band width it is possible to decide wether the α-proton is axial or equatorial; from the area under the signal it should be possible to estimate the relative amounts of the conformers. Only fixed molecules, however, have so far been considered. This is a limiting case of conformational analysis, namely configurational analysis.

3. The NMR Spectra of Mobile Cyclohexane Systems

Consideration will now be given to cyclohexane derivatives which are not fixed but are in equilibrium with other conformers. This equilibrium usually involves only the two chair forms. The NMR spectrum would be expected to show two signals in the region of the X-part *i.e.*, a narrow signal at low field due to the equatorial α-proton and a broader signal at higher field due to the axial α-proton. The ratio of the areas of these two signals would be a direct measure of the relative abundance of the two conformers in the mixture (cf. Fig. 4a).

The spectrum actually obtained (Fig. 4b), however, shows in the X region only one signal having a chemical

[9] *J. A. Pople, W. G. Schneider,* and *H. J. Bernstein*: High Resolution Nuclear Magnetic Resonance. McGraw-Hill, New York 1959. If protons of similar chemical shift are coupled, then they are denoted by alphabetically close letters *e.g.* AB; if the chemical shift is, however, large, alphabetically removed letters are used *e.g.* AX. When a number of protons of the same chemical shift are involved, the corresponding letter carries a numerical subscript denoting the number of protons of the same type. Thus an A_2B_2X system consists of 5 protons, two pairs of which are alike.

[10] *R. U. Lemieux, R. Kullnig, H. J. Bernstein,* and *W. G. Schneider*, J. Amer. chem. Soc. *79*, 1005 (1957).

[11] *L. M. Jackman*: Applications of NMR Spectroscopy in Organic Chemistry. Pergamon, London 1959.

[12] *J. Tanadier* and *W. Cole*, J. org. Chemistry *27*, 4610 (1962); *A. Nickon, M. A. Castle, R. Harada, C. E. Berkoff,* and *R. O. Williams*, J. Amer. chem. Soc. *85*, 2185 (1963); *W. M. Wellman* and *F. G. Bordwell*, Tetrahedron Letters *1963*, 1703.

[13] *R. J. Abraham* and *W. A. Thomas*, J. chem. Soc. (London) *1965*, 335.

[14] *F. A. L. Anet*, J. Amer. chem. Soc. *84*, 1053 (1962).

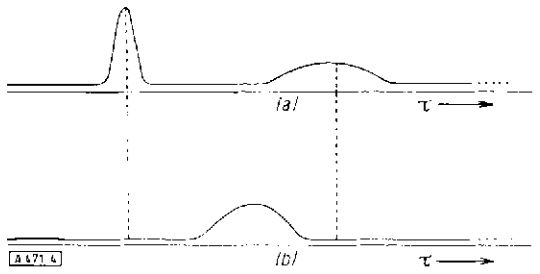


Fig. 4. X part of the spectrum of a mobile cyclohexane derivative. (a): expected, (b): found.

shift and a bandwidth between the two previously expected values [15] (cf. also Fig. 5).

The transition of an excited nuclear spin from the parallel to the antiparallel state, and back again, by which the NMR signal is produced, is relatively slow compared with the rate of inversion of a cyclohexane ring at room temperature. Thus, during one spin transition of the α-proton, the molecule to which the α-proton is attached interconverts very often, and the α-proton itself is many times axial and many times equatorial. Thus the magnetic environment of the α-proton during its transition is an average value of the environments of an *a*- and an *e*-proton (since intermediate forms need not be considered). All properties of the measured signal are therefore average values of the properties due to a completely axial and a completely equatorial proton.

This explanation was verified experimentally. By cooling of the sample the rate of interconversion of the cyclohexane molecule is considerably reduced, while the transition time of a nuclear spin remains unaltered [16]; *i.e.* it is extremely unlikely that the molecule interconverts during the transition of a nuclear spin. A monosubstituted cyclohexane then gives a spectrum (Fig. 5) of the type shown in Figure 4a [17].

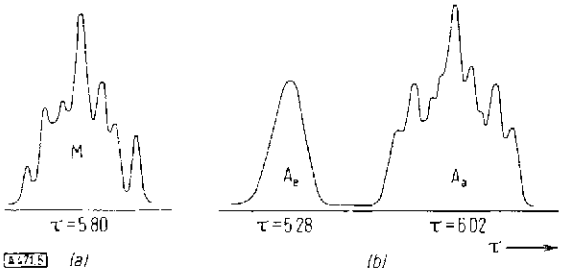


Fig. 5. X part of the NMR spectrum of iodocyclohexane. (a) at 25 °C; (b) at −75 °C. M average value; A_a, A_e areas of the axial and equatorial α-proton signals, respectively.

4. The Selection of Reference Values

The chemical shift, the coupling constants, and thus the band widths of a mobile cyclohexane system are all average values. If the equilibrium constant of an interchanging cyclohexane derivative is to be calculated according to Eq. (d), then the magnitudes of the properties of the individual conformers themselves must be known.

There are two ways of determining these values for the individual conformers. The first has already been mentioned for iodocyclohexane [17]; the mobile system is cooled so that the interconversion rate is reduced almost to zero. The signal due to the α-proton in the two conformers then appears separated in the spectrum, and from these two peaks it is theoretically possible to obtain all the required information. This method however is limited. Many substances for instance do not show a sufficient separation of the α-proton signal when cooled [18], while others crystallize out of the solution too rapidly at low temperatures.

For these reasons another method is more frequently used. The values are measured on reference substances similar to the individual conformers but which cannot interconvert. The t-butycyclohexane derivatives have generally been used for this purpose [19], as the molecule is fixed by the bulky alkyl group; thus in *cis*-4-t-butylbromocyclohexane the bromine group is fixed axially, whilst in the *trans* isomer it is fixed equatorially. This practice involves the assumption that the group preventing the inversion has no influence on the NMR property which is to be measured. Thus the chemical shift of the α-proton in *cis*-4-t-butylbromocyclohexane is the same as that of the α-proton in the conformer of bromocyclohexane with an axial bromine group [20]. This is, however, not true in every case (see Section II,2). Thus selection of suitable reference substances is of critical importance in conformational analysis.

5. Nomenclature

The following suggestions for the unification of terms used in NMR spectroscopy when applied to conformational analysis are limited to those referring to the α-proton; they can however be readily extended if necessary.

1. All subscripts to quantities relating to the α-proton, (such as chemical shift, coupling constant, band width), refer to the orientation of the α-proton. For example, w_a is the band width of the α-proton signal of a substance which has this proton in the *axial* position, *i.e.* the electronegative group is in the *equatorial* position, and τ_a is its chemical shift. This suggestion is opposite to the nomenclature in Equation (d) (see, *e.g.*, [21]). The latter nomenclature has the disadvantage that a measured value pertaining to an axial proton is indicated with the subscript "e".

2. The coupling constant should be characterized by a two-letter subscript, the first letter corresponding to the orientation of the α-proton and the second to the neighboring proton with which it is coupled. J_{ae} therefore denotes the coupling constant of an axial α-proton with an equatorial neighboring proton [22].

[15] *H. S. Gutowsky* and *A. Saika*, J. chem. Physics *21*, 1688 (1953).

[16] *F. R. Jensen, D. S. Noyce, C. H. Sederholm*, and *A. J. Berlin*, J. Amer. chem. Soc. *82*, 1256 (1960).

[17] *W. C. Neikam* and *B. P. Dailey*, J. chem. Physics *38*, 445 (1963).

[18] *L. W. Reeves* and *K. O. Strømme*, Canad. J. Chem. *38*, 1241 (1960).

[19] *E. L. Eliel*, Chem. and Ind. 568 (1959).

[20] *E. L. Eliel* and *M. H. Gianni*, Tetrahedron Letters *1962*, 97.

[21] *E. L. Eliel, E. W. Della*, and *Th. W. Williams*, Tetrahedron Letters *1963*, 831.

[22] *D. H. Williams* and *N. S. Bhacca*, J. Amer. chem. Soc. *86*, 2742 (1964), footnote (7).

3. A "time-average" value will be denoted by indices corresponding to the conformations from which this average is derived. Thus J^{ea}_{ae} is the average coupling constant of an axial α-proton with a neighboring equatorial proton, which through inversion changes its position, and w^e_a is the average band width corresponding to this signal. If Eq. (d) is to be used with the chemical shift or the band width, it may be rewritten in the forms:

$$K = (\tau_e - \tau_a)/(\tau_a - \tau_a) \quad (e)$$

$$K = (w_e - w^e_a)/(w^e_a - w_a) \quad (f)$$

6. The Order of the Signals [*]

When the difference in chemical shift between the α-proton and the A and B protons with which it is coupled decreases, the A_2B_2X system becomes an A_2B_2C system. Generally the interest for conformational analysis lies in the X (or C) part of the spectrum. With a sufficiently large difference in chemical shift the splitting of the signal is first order, and completely symmetrical, but if the difference in chemical shift decreases sufficiently, the signal becomes one of higher order [23]. This usually results in the signal becoming asymmetrical and showing a greater number of lines. As a reasonable approximation, a signal shows a first order splitting when the chemical shift between it and the nuclei to which it is coupled is ten times larger than the coupling constants which cause the splitting [24].

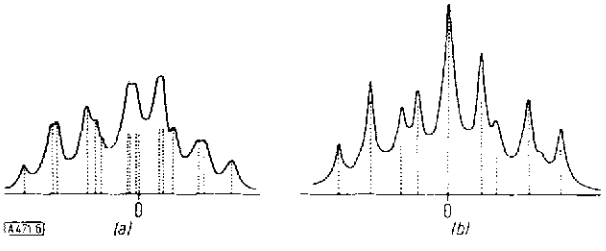


Fig. 6. X Part of the NMR spectrum of nitrocyclohexane (not to scale). (a): At 60 Mc/s, (b): at 100 Mc/s. The broken lines show the positions of the theoretical transitions.

Figure 6 shows the α-proton part of the spectrum of nitrocyclohexane at 60 Mc/s [25]; here the previously mentioned ratio is about 1:5 and the splitting is therefore clearly second order; the signal is unsymmetrical and more lines are present than expected from a simple treatment. Therefore it is not possible here to equate the measured splittings with the coupling constants, or to measure the chemical shift from the geometrical centre. These values must hence be obtained by a complete mathematical analysis of the spectrum, which has seldom been possible for cyclohexane derivatives [26].

[*] A symmetrical signal, in which the splittings can be equated to the coupling constants, is known as a first-order signal. If these conditions are not fulfilled, the signal is of second order.

[23] *J. I. Musher* and *E. J. Corey*, Tetrahedron *18*, 791 (1962).

[24] *R. J. Abraham* and *H. J. Bernstein*, Canad. J. Chem. *39*, 216 (1961).

[25] *H. Feltkamp* and *N. C. Franklin*, unpublished results.

[26] For example, some spectra of deuterated compounds have been analysed using the computer program of *K. B. Wiberg* and *B. J. Nist*: The Interpretation of NMR Spectra. *W. A. Benjamin*, New York 1962.

There is however one property which is common to both first order signals and those of higher order. The width of the signal between the extreme outside lines is independent of order, and corresponds to the sum of the coupling constants involved.

When the spectrum of nitrocyclohexane is recorded at 100 Mc/s [25] instead of 60, the ratio of the coupling constants to the chemical shift increases to about 1:10, owing to the increase in chemical shift, whereas the coupling constants remain constant. The spectrum is now of first order, completely symmetrical, and with splittings corresponding to the coupling constants (cf. Fig. 6b).

The recording of the spectra using higher magnetic fields should yield results which are easier to interpret (given the same resolution). For nitrocyclohexane the change from 60 to 100 Mc/s already resulted in considerable clarification, and this will be much more the case with equipment working at 200 Mc/s or more.

II. NMR Methods of Conformational Analysis

1. The Area of the Signal

The only direct method of investigating conformational equilibria is, up to the present, the measurement of the area under the NMR signal (cf. Fig. 5). All protons which change their position on inversion of the ring may be considered. The most important of these is again the α-proton, but it is possible to use the signal of other proton groups; for example the protons of an axial $-OCOCH_3$ or $-NHCOCH_3$ group absorb at different fields to those of the same group when in the equatorial position [10,27]. Such measurements are only meaningful, however, when the signals are clearly separated, *i.e.* when the measurements are carried out at low temperatures. Thus it was necessary to work at −110 °C in order to prevent the interconversion of 1,1-difluorocyclohexane [28], (although providing the individual peaks are separated it is not necessary to completely prevent the inversion). In the case of iodocyclohexane [17] a temperature of −75 °C was necessary (cf. Fig. 5).

The limitations of this method are almost the same as those discussed in connection with the choice of standard values. When the difference in chemical shift of the conformers is too small, even complete freezing of the equilibrium does not result in separation of the α-proton signal [18]. By deuteration of the positions adjacent to the α-proton the couplings can be removed and the signal becomes narrower, so that on cooling a separation is observed [29].

[27a] *F. W. Lichtenthaler* and *H. O. L. Fischer*, J. Amer. chem. Soc. *83*, 2005 (1961); *F. W. Lichtenthaler*, Chem. Ber. *96*, 2047 (1963).

[27b] *F. A. L. Anet*, *R. A. B. Bannard*, and *L. D. Hall*, Canad. J. Chem. *41*, 2331 (1963).

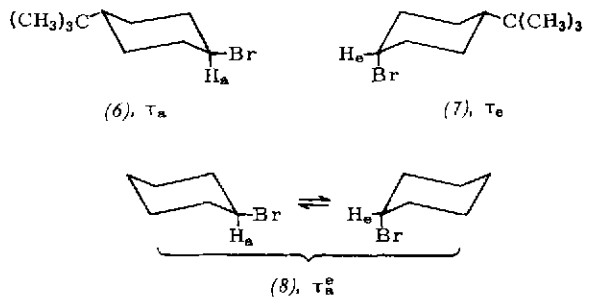
[28] *J. D. Roberts*, Angew. Chem. *75*, 20 (1963); Angew. Chem. internat. Edit. *2*, 53 (1963).

[29] *E. A. Allen*, *E. Premuzic*, and *L. W. Reeves*, Canad. J. Chem. *41*, 204 (1963).

Apart from these difficulties, the measurement of the area under the signal at low temperature is the best method of conformational analysis available.

2. Measurement of the Chemical Shift

The first application of nuclear magnetic resonance to the quantitative conformational analysis of mobile cyclohexane systems was based on the difference in chemical shift between the axial and equatorial protons. *Eliel* studied bromocyclohexane [19] and derived Equation (e). At that time it was reported that the spectrum of bromocyclohexane showed no sign of a splitting of the α-proton signal at the temperatures used; more recently a difference of 0.78 p.p.m. was observed between the axial and equatorial protons at −75 °C [17]). Therefore instead of bromocyclohexane itself, *cis-(7)* and *trans*-4-t-butylbromocyclohexane *(6)* were used to determine the chemical shifts of the α-proton in the individual conformers.



The assumption that the t-butyl group does not affect the chemical shift of the α-proton was later disputed [30], for a study on a series of 4-alkylcyclohexanols showed that the chemical shift of the α-proton varies with the nature of the alkyl substituent. This observation therefore seemed to invalidate the use of fixed substances as standards in conformational analysis. Fortunately, later work on the 4-alkyl-2,2,6,6-tetradeuteriocyclohexanols [5] showed that the chemical shift is indeed independent of the nature of the 4-alkyl group. Thus it is reasonable to assume that a 4-substituted t-butyl group does not cause ring deformation. This was later confirmed for t-butylmenthols [31].

The above disagreement [5,30] is due to the difficulty of measuring the true chemical shift. The signals of the α-protons in the non-deuterated substances [30] are complicated by spin-spin coupling with adjacent protons, and although it was claimed that the signals are symmetrical, and that therefore the geometrical centre can be taken as the chemical shift, this is not necessarily so [32]. By adjacent deuteration these splittings were removed and a sharp signal for the α-proton was obtained which showed the true chemical shift [5].

It therefore appears that if the equilibrium constant is to be measured with any degree of accuracy from the chemical shifts, selective deuteration must be carried out [5,29,33–35]. The fact that small differences of the chemical shifts occur in Equation (e) makes accurate measurements particularly important. Thus the difference in chemical shift between the individual conformers of nitrocyclohexane is only 0.2 p.p.m. [36], and therefore the equilibrium constant is better determined by another method.

The chemical shift of the α-proton in alkyl-substituted cyclohexanes depends on the position of the substituent. Thus the values of τ_a and τ_e obtained from 4-t-butylcyclohexanols or the corresponding 1-amino-4-t-butylcyclohexanes differed from those obtained from the corresponding 3-substituted compounds [37,38]. Again the nature of the alkyl substituent in the 3- and 4-position appears to have no influence on the chemical shift. Thus 1-amino-4-t-butylcyclohexanes can be used as reference substances for cyclohexylamine or 1-amino-4-methylcyclohexane, but for *trans*-1-amino-3-methylcyclohexane, 1-amino-3-t-butylcyclohexanes have to be used [38]. Similar results were found for the corresponding substituted cyclohexanols [37]. These considerations however do not apply to 2-substituted cyclohexanes [39]. Thus fixed menthols cannot be used as standards for flexible menthols [31].

A number of other methods have been described in which the variation of chemical shift is used to determine the equilibrium constant.

The configurations of steroids have been determined by the analysis of the chemical shift of the methyl groups on C–10 or C–13 [40]. Their chemical shift depends on structural elements such as substituents, double bonds, *etc.* the influences of which have been collected in tables. Usually the difference between these expected values and those that are measured is less than 1 cps. The shielding due to axial and equatorial substituents is considerably different and it is therefore possible to distinguish between them. However, deviations from these general rules have been reported [41].

An alternative method of determining the equilibrium constant is based on the difference in chemical shift of the hydroxyl protons in a cyclohexanol [42]. By measurement at different concentrations, the chemical shift at infinite dilution of both the cyclohexanol and the reference substances (fixed cyclohexanols) are found. Here also the choice of reference substances is important. Thus ΔG_{OH} was measured with the aid of the 4-butyl-

[30] *J. I. Musher*, J. Amer. chem. Soc. *83*, 1146 (1961).

[31] *H. Feltkamp* and *N. C. Franklin*, Tetrahedron *21*, 1541 (1965).

[32] Ref. [5], footnote 30.

[33] *J. Reisse, J. C. Celotti, O. Zimmerman*, and *G. Chiurdoglu*, Tetrahedron Letters *1964*, 2145.

[34] *E. Premuzic* and *L. W. Reeves*, J. chem. Soc. (London) *1964*, 4817.

[35] *J. Reisse, J. C. Celotti*, and *G. Chiurdoglu*, Tetrahedron Letters *1965*, 397.

[36] *A. C. Huitric* and *W. F. Trager*, J. org. Chemistry *27*, 1926 (1962).

[37] *E. L. Eliel, M. H. Gianni, Th. H. Williams*, and *J. B. Stothers*, Tetrahedron Letters *1962*, 741.

[38] *H. Feltkamp, N. C. Franklin, K. D. Thomas*, and *W. Brügel*, Liebigs Ann. Chem. *683*, 64 (1965).

[39] *H. Feltkamp, N. C. Franklin, W. Kraus*, and *W. Brügel*, Liebigs Ann. Chem. *683*, 75 (1965).

[40] See, *e.g.*, *R. F. Zürcher*, Chimia (Zürich) *18*, 349 (1964).

[41] *A. D. Cross* and *C. Beard*, J. Amer. chem. Soc. *86*, 5317 (1964).

[42] *R. J. Quellette*, J. Amer. chem. Soc. *86*, 3089 (1964).

cyclohexanols [43], and $\Delta G_{C\equiv CH}$ in 1-ethynylcyclohexanol using the 4-t-butyl-1-ethynylcyclohexanols [42]. However it is questionable whether the $\Delta G_{C\equiv CH}$ value obtained is equally valid for ethynylcyclohexane, because 1-ethynylcyclohexanol, as well as the reference substances, are probably deformed by the 1,1 disubstitution pattern [44].

Recently the chemical shifts of the axial and equatorial protons on C–6 and C–8 have been measured in 1,2-diaza-6-methylspiro[2.5]oct-1-ene [45]. The difference here is so large that Equation (e) can be applied accurately. The difference in chemical shift between the axial and equatorial methylene protons was determined by spin-decoupling at different temperatures. In this way a new determination of the ΔG value of the methyl group was carried out. From this one determination, though, the fact that the measured value is in good agreement with that previously determined cannot be taken as proof that the 1,1-diazirino group has no influence on the conformation of the cyclohexane ring.

3. Measurement of Average Coupling Constants

The coupling constants in mobile cyclohexane systems are averaged by the interchanging of the conformers. It is therefore necessary to take fixed substances as standard compounds.

According to a valence-bond treatment by *Karplus* [46], the coupling constant J_{AB} is related to the angle φ between the planes $H_A-C_A-C_B$ and $C_A-C_B-H_B$ by the expression

$$J_{AB} = k_1 \cos^2 \varphi - k_2 \qquad (g)$$

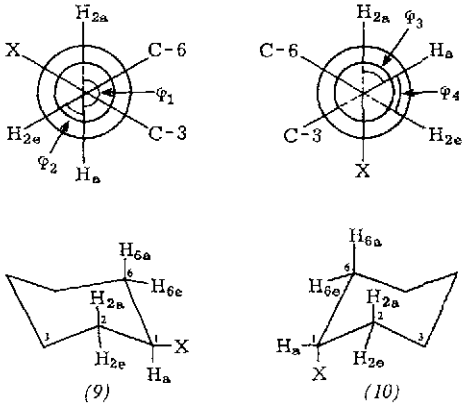
now generally known as the Karplus equation. Originally k_1 and k_2 were regarded as constants, but since then it has been observed that they depend very much on the nature of the system [47–49].

Unfortunately the fact that the coupling constant does not dependent on the angle φ alone is not generally recognized. Thus angles are often calculated from the coupling constants, or *vice versa*, to a degree of accuracy which is not justified [50,51]. Later *Karplus* [52] pointed out, in greater detail, the assumptions made in the theoretical treatment. A more refined calculation [52] leads to the equation

$$J_{HH} = A + B \cos \varphi + C \cos 2\varphi \qquad (h)$$

where the constants depend on the system under consideration. The coupling constants thus also vary with the electronegativity of the substituent [53–56] and with the size of the ring in cyclic olefins [57]. However, even in systems in which these factors are constant, different coupling constants were measured for what was thought to be the same angle.

Consideration of a Newman projection diagram along the C_1-C_2 bond of a non-strained monosubstituted cyclohexane *(9)* shows that the angle φ_1 between the planes $H_\alpha-(C-2)-(C-1)$ and $(C-2)-(C-1)-H_{2a}$ is 180°.



(9) *(10)*

It would therefore be expected that the axial/axial coupling between H_α and H_{2a} would be larger than the axial/equatorial coupling between H_α and H_{2e} as the angle here (φ_2) between the two planes is only 60°.

From the projection diagram of the corresponding conformer *(10)* it might also be expected that the equatorial/equatorial coupling constant should be equal to the equatorial/axial coupling as both correspond to an angle of 60° (*i. e.* $\varphi_3 = \varphi_4$).

From the few values of J_{ee} that have been either measured [14,31] or calculated [58–60], it is apparent that this expectation is not fulfilled. It is also now apparent that, contrary to previous assumptions, it is never possible to equate J_{ea} with J_{ae} [14,22,31].

The best explanation of this phenomenon is the assumption of a ring deformation by the introduction of an axial substituent [31]. Whenever J_{ee} or J_{ea} can be measured, the electronegative group is in the axial position, and owing to the non-bonding interactions with the neighboring protons, the ring is deformed. This deformation is only slight when the electronegative group is in the equatorial position. The angles φ_2, φ_3, and φ_4 (corresponding to J_{ae}, J_{ea}, and J_{ee}) are therefore dif-

[43] *R. J. Quellette*, J. Amer. chem. Soc. *86*, 4378 (1964).

[44] *M. Anteunis* and *D. Tavernier*, Tetrahedron Letters *1964*, 3949.

[45] *J. J. Uebel* and *J. C. Martin*, J. Amer. chem. Soc. *86*, 4618 (1964).

[46] *M. Karplus*, J. chem. Physics *30*, 11 (1959).

[47] *K. L. Williamson* and *W. S. Johnson*, J. Amer. chem. Soc. *83*, 4623 (1961); *R. J. Abraham* and *K. A. McLauchlan*, Molecular Physics *5*, 513 (1962).

[48] *R. U. Lemieux* and *J. W. Lown*, Canad. J. Chem. *42*, 893 (1964).

[49] *H. Booth* and *G. C. Gidley*, Tetrahedron Letters *1964*, 1449.

[50] *C. D. Jardetsky*, J. Amer. chem. Soc. *84*, 62 (1962).

[51] *R. J. Abraham* and *J. S. E. Holker*, J. chem. Soc. (London) *1963*, 806.

[52] *M. Karplus*, J. Amer. chem. Soc. *85*, 2870 (1963).

[53] *T. Schaefer*, Canad. J. Chem. *40*, 1 (1962).

[54] *C. N. Banwell* and *N. Sheppard*, Discuss. Faraday Soc. *34*, 118 (1962).

[55] *K. L. Williamson*, J. Amer. chem. Soc. *85*, 516 (1963).

[56] *P. Laszlo* and *P. von R. Schleyer*, J. Amer. chem. Soc. *85*, 2709 (1963).

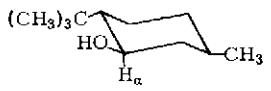
[57] *O. L. Chapman*, J. Amer. chem. Soc. *85*, 2014 (1963); *G. V. Smith* and *H. Kriloff*, *ibid. 85*, 2016 (1963); *P. Laszlo* and *P. von R. Schleyer*, *ibid. 85*, 2017 (1963).

[58] *J. I. Musher*, J. chem. Physics *34*, 594 (1961).

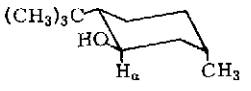
[59] *L. W. Reeves* and *K. O. Strømme*, J. chem. Physics *34*, 1711 (1961).

[60] *J. Delman* and *C. Barbier*, J. chem. Physics *41*, 1103 (1964).

ferent. It is even questionable if the chair form of unsubstituted cyclohexane has angles of 60° between the neighboring coupled protons. Recent evidence suggests that even here there is an inherent deformation [61]. Support for the suggestion that the change in the coupling constants is due to ring deformation was found by examination of the spectra of two isomers of 2-t-butyl-5-methylcyclohexanol, which differ only in the orientation of the methyl group, and both of which are fixed in one conformation [31].



(11)



(12)

A large difference between J_{aa} and J_{ae} was observed in both isomers. This cannot be due to a change in the participating protons themselves, and must therefore be due to the deformation of the ring when the methyl group on C–5 is in the axial orientation.

The suggestion [62] that J_{ea} is smaller than J_{ae} because in this case the electronegative substituent is coplanar with one of the protons which participate in the coupling, cannot explain the difference between J_{ae} and J_{ee} nor the previously mentioned differences in the two t-butylmenthol isomers.

The variation in coupling constants in cyclohexane systems has recently been discussed [63]. Although reservations are expressed therein on the universal application of the Karplus equation to cyclohexane systems it is still true that the theoretical relationship between coupling constant and bond angle has assisted in the understanding of conformational problems.

The previous discussion has been solely concerned with fixed systems. In one of the first measurements of coupling constants in cyclohexane derivatives [64] it was not realised that some of the measurements had been carried out on a mobile system, with the result that the values quoted were *average* coupling constants. The literature also contains values for average coupling constants which have been incorrectly calculated [65 68]. The fact that some of the measured experimental splittings fortuitously agreed with such incorrect average values complicated the situation ever further [65–67]. Later the method of averaging of coupling constants [69] was applied to mobile cyclohexane systems [15, 70], and two expressions (i) and (j) for the average coupling constants

$$J_{aa}^{ee} = x_a J_{aa} + (1-x_a) J_{ee} \quad \text{(i)}$$

$$J^{ea} = x_a J_{ae} + (1-x_a) J_{ea} \quad \text{(j)}$$

were obtained. In several examples "deceptively simple spectra" [24] were obtained in which the splitting cannot be equated with the coupling constants [70].

It is possible to determine the position of the conformational equilibrium from the average coupling constants if the coupling constants in Equations (i) and (j) are known. These can only be determined when certain conditions are fulfilled. First the signal of the α-proton must show a first order splitting so that the average coupling constants may be measured. This is very rarely the case, for very often in monosubstituted cyclohexanes the signal is not even resolved, partly owing to long range couplings. The latter were removed in cyclohexanol by selective deuteration [14].

It is rarely possible to measure the coupling constants of the conformers at low temperatures. Therefore fixed reference substances are used, in which the α-proton signal shows first-order splitting. This also was achieved by partial deuteration, and so it was possible to determine the equilibrium position in cyclohexanol from the average coupling constants [14].

If the signals of the standard substances are not resolved it is possible to estimate the coupling constants from the band widths [70]. It is however simpler to determine the equilibrium from the band widths directly.

4. Measurement of Average Band Widths

One of the first methods to determine the configuration of fixed cyclohexane derivatives was the measurement of the width of the multiplet of the α-proton signal [64], and the variation in the band width was later used as a method of conformational analysis [71–73]. This method has now been extensively applied in the investigation of the conformations of mono-and polysubstituted cyclohexanes [25, 31, 38, 74, 75] and decalins [25, 38, 39] and it has many advantages over the other methods. For example, the conformational equilibrium in nitrocyclohexane has been determined [74], which was not possible from low temperature measurements [17]. Similarly using selected reference substances, the conformations of 2-substituted cyclohexanes were determined [31], which was not entirely accomplished using the chemical shifts.

The band widths are measured between the extreme outer lines of the α-proton multiplet, the assumption being made that the combination lines [*] are so weak that they may be neglected. The band width is then the sum of the coupling constants which cause the splitting. In order to determine the individual coupling constants

[61] *R. A. Wohl*, Chimia (Zürich) *18*, 219 (1964).

[62] *H. Booth*, Tetrahedron Letters *1965*, 411.

[63] *A. C. Huitric, J. B. Carr, W. F. Trager*, and *B. J. Nist*, Tetrahedron *19*, 2145 (1963).

[64] *R. U. Lemieux, R. K. Kullnig*, and *R. Y. Moir*, J. Amer. chem. Soc. *80*, 2237 (1958).

[65] *H. Finegold* and *H. Kwart*, J. org. Chemistry *27*, 2361 (1962).

[66] *B. Franzus* and *B. E. Hudson jr.*, J. org. Chemistry *28*, 2238 (1963).

[67] *H. M. van Dort* and *T. J. Sekuur*, Tetrahedron Letters *1963*, 1301.

[68] *W. Hofman, L. Stefaniak, T. Urbanski*, and *M. Witanowski*, J. Amer. chem. Soc. *86*, 544 (1964).

[69] Ref. [9], p. 380.

[70] *H. Booth*, Tetrahedron *20*, 2211 (1964).

[71] *E. W. Garbisch* and *D. B. Patterson*, J. Amer. chem. Soc. *85*, 3228 (1963).

[72] *E. W. Garbisch*, J. Amer. chem. Soc. *86*, 1780 (1964).

[73] *H. Feltkamp* and *N. C. Franklin*, Liebigs Ann. Chem. *683*, 55 (1965).

[74] *H. Feltkamp* and *N. C. Franklin*, J. Amer. chem. Soc. *87*, 1616 (1965).

[75] *H. Feltkamp, N. C. Franklin, M. Hanack*, and *K. M. Heinz*, Tetrahedron Letters *1964*, 3535.

[*] Combination lines are due to the simultaneous spin transition of more than one proton.

the system is classified according to the *PSB* system [9]. Fortunately the mobile cyclohexanes systems are mainly of the A_2B_2X, A_2BX, or ABX type and consequently the band widths depend only on the AX and BX coupling constants. For example, the band width between lines 1 and 9 in the nonet often observed in an A_2B_2X system is made up of 2 J_{AX} and 2 J_{BX}, and is independent of J_{AB}.

Analysis of systems has been carried out in which the α-proton multiplet is not completely resolved, but where the position of the extreme outside lines is apparent from inflexions in the curve. If the signal is completely unresolved, it is possible to measure the band width at a predetermined height. For example, in a non-resolved A_2B_2X multiplet, the band width is measured at 1/4 the band height. This procedure is, however, not accurate, as it presupposes first order splitting conditions.

Reference values w_a and w_e have so far not been obtained from low temperature measurements, but only from reference substanecs with the same geometric and magnetic properties. In some cases though it is difficult to find suitable standards [31].

The objection could be raised that the spectra of monosubstituted cyclohexanes are not simple A_2B_2X systems but are complicated by long range coupling and are more of the $A_2B_2C_2D_2E_2X$ type. However, the long range couplings in cyclohexane systems (1–2 cps) are not as strong as in some strained ring systems [76, 77], and have seldom been observed. If such long range coupling is present, it usually occurs between the equatorial protons on C–1 and C–3 [78]. By the selection of suitable reference substances such couplings can be compensated for.

Since the band width is a multiple of the participating coupling constants, it can be measured considerably more accurately than the individual coupling constants.

At this stage it would be advantageous to comment on the relationship between the band width of the absorption due to the methylene protons of the ring and the configuration and conformation of some cyclohexanes. Such a signal is considerably broader in fixed systems than in interchanging flexible systems [79]. A narrow signal is not, however, solely a property of rapidly inverting rings, as the spectra of fixed dialkylcyclohexanes with an axial substituent also show a narrow band [80]. This observation was confirmed by later work on cyclohexylamines [38] for the signal of the ring protons in *cis*-1-amino-4-t-butylcyclohexane at half band height was only 8 cps, and no change was observed at different temperatures. This observation suggests that a fixed axial substituent so influences the chemical shift of the axial and equatorial protons that they appear almost at the same field. This is most likely the reason why *cis*-decalin shows no broadening of the spectra at low temperature [81], for both possible conformations have an axial methylene group at the ring junction.

Table 1. Conformational free energies ΔG for substituents R in cyclohexane derivatives.

R	ΔG [kcal/mole]	Method [a]	Ref.
OH	0.6; 0.75; 0.82; 0.78; 1.07	A	[20, 43, 33, 5, 37]
OH	1.02	B	[17]
OH	0.43; 1.12	D	[70, 14]
F	0.24; 0.25	B, G	[4, 88]
Cl	0.43	A	[35]
Cl	0.52	B	[19]
Cl	0.42; 0.48	B, G	[18, 88]
Br	0.2	A	[19, 20]
Br	0.48; 0.48; 0.58	B, G	[17, 88, 18]
Br	0.41	C	[35]
Br	0.70	D	[70]
I	0.43	B	[88]
I	0.46	B, G	[17]
I	0.40	G	[88]
NH_2 [b]	1.1–1.7; 1.3	A	[21, 38]
NH_2	1.0	D	[70]
NH_2 [b]	1.2	F	[38]
OCH_3	0.6	A	[20]
OCH_3 [c]	1.2	B	[90]
NO_2	1.0; 1.2	A, F	[74, 25]
ONO	0.59	B	[29]
SH	0.9	A	[89]
SCH_3	0.7	A	[89]
SC_6H_5	0.8	A	[20]
$OCOCH_3$	0.7	A	[20]
$OCOCH_3$	0.69	B	[29]
$OCOCH_3$	0.66	G, E	[14]
$OCOC_2H_5$	1.1	A	[20]
OCHO	0.25	B	[29]
$OSO_2C_6H_4CH_3$-p	0.6	A	[20]
$OCOCF_3$	0.69	B	[29]
CH_3 [d]	1.8	B	[45]
CH_3 [e]	1.7; 1.74	C	[33, 5]
C_2H_5 [e]	1.74	C	[5]
$CH(CH_3)_2$ [b]	2.2	A, F	[38]
$CH(CH_3)_2$ [e]	2.28	C	[5]
Cyclohexyl [e]	2.15	C	[33]
NCH_3 [f]	1.0	A	[38]
NCH_3 [f]	0.9	F	[38]
C_6H_5 [g]	2.8	F	[71]
C≡CH [h]	0.18	A	[42]

[a] A: Chemical shift (τ) using reference substances; B: τ at low temperature; C: τ of deuterated substances; D: average coupling constant with reference substances; E: average coupling constant at low temperature; G: area at low temperature.

[b] Determined on alkylcyclohexylamines.

[c] Determined on alkyl-1,1-dimethoxycyclohexane.

[d] Determined on 1,2-diaza-6-methylspiro[2.5]oct-1-ene.

[e] Determined on alkylcyclohexanols.

[f] Determined on alkyl-*N*-methylaminocyclohexanes.

[g] Determined on alkylphenylcyclohexanes.

[h] Determined on 1-ethynylcyclohexanol.

[76] *J. Meinwald* and *A. Lewis*, J. Amer. chem. Soc. *83*, 2769 (1961); *J. Meinwald* and *Y. C. Meinwald*, *ibid. 85*, 2514 (1963); *Y. Osawa* and *M. Neeman*, *ibid. 85*, 2856 (1963); *E. I. Snyder* and *B. Franzus*, *ibid. 86*, 1166 (1964).

[77] *S. Sternhell*, Rev. pure appl. Chem. *14*, 15 (1964).

[78] *A. Rassat*, *C. W. Jefford*, *J. M. Lehn*, and *B. Waegell*, Tetrahedron Letters *1964*, 233; *M. Barfield*, J. chem. Physics *41*, 3825 (1964).

[79] *S. Brownstein* and *R. Miller*, J. org. Chemistry *24*, 1886 (1959).

[80] *N. Muller* and *W. C. Tosch*, J. chem. Physics *37*, 1167 (1962).

[81] *W. B. Monitz* and *J. A. Dixon*, J. Amer. chem. Soc. *83*, 1671 (1961); *R. K. Harris* and *N. Sheppard*, Proc. chem. Soc. (London), *1961*, 418.

[82] *A. C. Huitric* and *J. B. Carr*, J. org. Chemistry *26*, 2648 (1961); *W. F. Trager*, *F. F. Vincenci*, and *A. C. Huitric*, *ibid. 27*, 3006 (1962); *A. C. Huitric*, *W. S. Stavropoulos*, and *B. J. Nist*, *ibid. 28*, 1539 (1963); *H. Booth* and *N. C. Franklin*, Chem. and Ind. *1963*, 954; *T. L. Westman*, *R. Paredes*, and *W. S. Brey jr.*, J. org. Chemistry *28*, 3512 (1963); *Y. R. Naves*, Helv. chim. Acta, *47*, 308, 1617 (1964); *E. N. Marvell* and *H. Sexton*, J. org. Chemistry *29*, 2919 (1964); *H. Booth*, *N. C. Franklin*, and *G. C. Gidley*, Tetrahedron *21*, 1077 (1965).

III. Cyclohexane Derivatives Investigated by NMR Spectroscopy

In Table 1 some examples of NMR-spectroscopic conformational analysis on cyclohexane derivatives are collected. Substances which have been primarily used in configurational analysis are not included [82,83]. Compounds, known not to be in the "perfect" chair form, such as cyclohexenes and cyclohexanones, are also excluded [74,84,85], as are six-membered heterocyclic rings since the ring deformation caused by hetero atoms is not fully understood [86,87].

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[83] *W. Hofheinz* and *H. Grisebach*, Z. Naturforsch. *17b*, 355 (1962); *H. O. House* and *H. W. Thompson*, J. org. Chemistry *28*, 360 (1963).

[84] *E. W. Garbisch*, J. Amer. chem. Soc. *85*, 927 (1963).

[85] *E. Premuzic* and *L. W. Reeves*, Canad. J. Chem. *42*, 1498 (1964).

[86] *G. Claeson*, *G. M. Androes*, and *M. Calvin*, J. Amer. chem. Soc. *82*, 4428 (1960); 83, 4357 (1961); *A. Lüttringhaus* and *S. Kabus*, *Z.* Naturforsch. *16b*, 761 (1961); *H. Friebolin*, *S. Kabus*, *W. Maier*, and *A. Lüttringhaus*, Tetrahedron Letters *1962*, 683.

[87] *R. U. Lemieux*, *J. D. Stevens*, and *R. R. Frazer*, Canad. J. Chem. *40*, 1955 (1962); *C. Barbier*, *J. Delman*, and *J. Ranft*, Tetrahedron Letters 3339 (1964); *R. J. Abraham*, J. Amer. chem. Soc. *87*, 256 (1965).

[88] *A. J. Berlin* and *F. R. Jensen*, Chem. and Ind. *1960*, 988.

[89] *E. L. Eliel* and *B. P. Thill*, Chem. and Ind. *1963*, 88.

[90] *M. Anteunis*, Bull. Soc. chim. belges *73*, 731 (1964).

COMMUNICATIONS

Dialkylamination – a New Aromatic Substitution Reaction [1]

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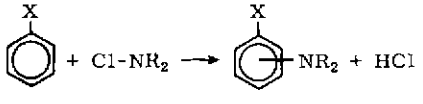
Aryl dialkylamines are usually prepared from the corresponding nitro compounds by reduction to the amine and alkylation of the resulting arylamine. Dialkylamination of aromatic compounds can now be achieved in a single step using *N*-chlorodialkylamines [3].



This new reaction can be carried out in three ways:

a) By heating the components for 3–6 h in 96 % sulfuric acid at 80–100 °C; addition of metal salts can increase (*e.g.* Na_2SO_4, CuCl, $NiCl_2$, $FeSO_4 \cdot H_2O$, or Hg_2Cl_2) or decrease (*e.g.* $CoCl_2$) the yield.

b) By irradiation of the components in concentrated sulfuric acid for 8–10 h with visible or ultraviolet light.

c) By heating solutions of the components in nitroalkanes at 80–100 °C with Lewis acids, preferably aluminum chloride [4] or ferric chloride.

	Yield [%] of dimethylaminoarene according to method		
	(a) [*]	(b)	(c)
Benzene	81	78	90
Toluene	80	61	50
t-Butylbenzene		58	43
Naphthalene	21	22	35
N,N-Dimethylaniline			21

[*] In a 5 % solution of sodium sulfate in sulfuric acid.

The reaction can be carried out with aromatic compounds, which may contain first-order substituents that are not affected by acids. Occasionally chlorination of the aromatic ring is the predominant reaction, *e.g.* chlorobenzene affords 18 % chlorodimethylaminoanilines by method a) but yields 34 % *o*- and *p*-dichlorobenzene by method c), or anisole yields 57 % chloroanisole by method (b) and 67 % by method (c). The yields of dialkylaminoarenes produced decrease as the length of the alkyl residues on the amine component increases owing to competition with the Hoffmann-Löffler reaction [5]. The new process gives particularly good results with cyclic chloroamines; for example, *N*-chloropiperidine is easy to prepare and reacts with benzene by methods (a)–(c) to give *N*-phenylpiperidine in yields of 60–70 %.

Competition experiments applying method (a) gave relative rate constants for chlorobenzene, benzene, and toluene of 0.1:1.0:9.3. Infrared spectroscopy and gas chromatography were used to determine the proportions of isomers formed in the reaction of toluene with *N*-chlorodimethylamine; the results are as follows (error: *o*- = ± 2 %, *m*-, *p*- = ± 6 %):

(H_2SO_4/Na_2SO_4)	*o*-:*m*-:*p*- = 9:53:38
(H_2SO_4/CuCl	21:46:33
Method (b)	9:53:38
Method (c)	14:27:59

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[1] *N*-Halogenoamines, Part 4. – Part 3: *H. Bock* and *K.-L. Kompa*, Z. anorg. allg. Chem. *332*, 238 (1964).

[2] *K.-L. Kompa*, Doctorate Thesis, Universität München 1965.

[3] German Patent Application (Aug. 19th, 1963), inventors: *H. Bock* and *K.-L. Kompa*.

[4] The reaction of *N*-chloramines and benzene in the presence of aluminium chloride was discovered simultaneously and independently by *J. Thesing* and *R. P. Kreher*, but their yields are at most 10–20%; see *R. P. Kreher*, Doctorate Thesis, Technische Hochschule Darmstadt, 1961.

[5] *M. E. Wolff*, Chem. Reviews *63*, 55 (1963); *E. J. Corey* and *W. R. Hertler*, J. Amer. chem. Soc. *82*, 1657 (1960).

A New Synthesis of Butenolides

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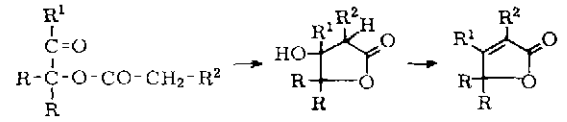
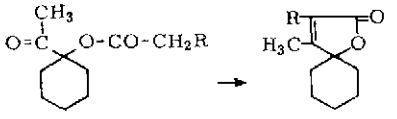
The action of bases (alkali metal hydroxides, alkoxides, amides, or hydrides) on esters of α-hydroxy ketones in aprotic polar solvents such as dimethyl sulfoxide or dimethylformamide leads to a cycloaddition analogous to aldol

condensation and subsequent dehydration to afford butenolides *(1)*.



(1)

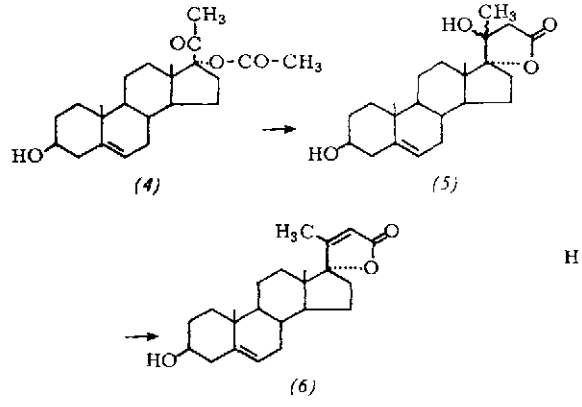
For example, treatment of 1-acetoxy-1-acetylcyclohexane *(2)*, R = H, in dimethyl sulfoxide with 1 mole of sodium hydride for 5 h at room temperature yields 40 % β-[1'-hydroxycyclohexyl]crotonolactone *(3)*, R = H [m.p. 49.5–51 °C, from hexane, ε_{211} = 13300, lactone band at 1752 cm^{-1} in a KBr-pellet].



(2) *(3)*

Similarly, 1-acetyl-1-propionyloxycyclohexane *(2)*, R = CH_3, gives rise to 45 % α-methyl-β-[1'-hydroxycyclohexyl]crotonolactone *(3)*, R = CH_3 [m.p. 65–66 °C, from hexane, ε_{217} = 13370, lactone band at 1750 cm^{-1} in CS_2 or at 1745 in a KBr-pellet].

The analogous reaction with 17α-acetoxy-Δ^5-pregnen-3β-ol-20-one *(4)* affords a 78 % yield of 3β,17α-dihydroxy-$\Delta^{5,20(22)}$-norcholadienic-23 → 17-lactone *(6)*, [m.p. 257–259 °C, from hexane/dichloromethane, ε_{218} = 12000, lactone band at 1743 cm^{-1} in chloroform or 1725 in a KBr-pellet].



(4) *(5)* *(6)*

The β-hydroxybutyrolactone intermediate *(5)* can be isolated if the reaction of *(4)* is conducted with only catalytic amounts of powdered sodium hydroxide in dimethyl sulfoxide at 20 °C and interrupted after 10 min. The 3β,17α,20-trihydroxy-Δ^5-norcholenic-23 → 17-lactone *(5)* melts at 287–288 °C [from ethyl acetate/methanol; lactone band at 1740 cm^{-1} in a KBr-pellet].

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Hydroplumbation of Unsaturated Organic Compounds

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Numerous unsaturated organic compounds, *e.g.* those with C=C, C≡C, C=N, or C=O groups, can be hydrostannated [1]. In the organolead hydride series, only attempts to add trimethyl-lead hydride onto ethylene have so far been described; the results are conflicting [2, 3].

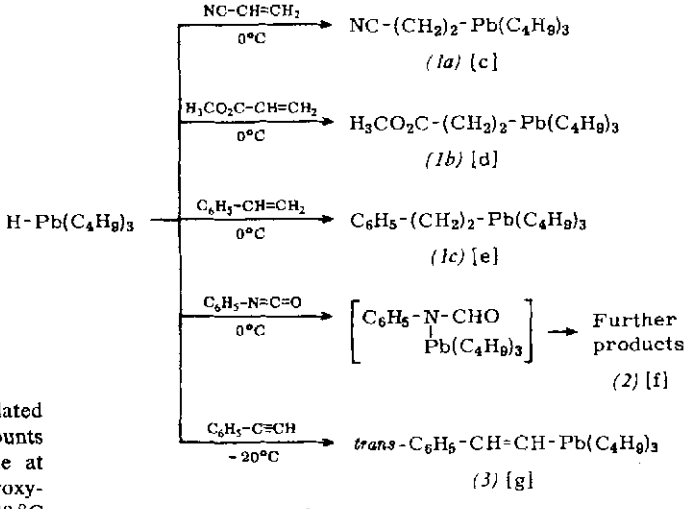
Organolead hydrides of general formulae R_3PbH and R_2PbH_2 were known previously only with R = CH_3 or C_2H_5 [2–5]. They decompose above −20 °C, some even already above −50 °C. In order to obtain compounds which are easier to handle we used larger alkyl residues. We reduced the corresponding chlorides in diethylene glycol dimethyl ether at −60 °C with $LiAlH_4$ and obtained good to excellent yields of the hydrides.

Weaker complexing agents such as ether or tetrahydrofuran allowed the reverse reaction to proceed, and decomposition occurred during isolation. The products are decomposed by light and extremely readily by air but can be kept for a few days at least at 0 °C in the dark.

	R_3PbH				R_2PbH_2
	n-C_3H_7	n-C_4H_9	iso-C_4H_9	cyclo-C_6H_{11}	n-C_4H_9
ν_{Pb-H} [cm^{-1}]	1675 [a]	1680 [a]	1675 [a]	1650 [a]	1640 [b]

[a] In cyclohexane. [b] In diethylene glycol dimethyl ether.

Tributyl-lead hydride adds even at low temperatures and without a catalyst onto α-olefins, isocyanates, and alkynes to *(1a)–(1c)*, *(2)* and *(3)*. The yields obtained with the pure hydride are 90–100 %. The adducts were freed from volatile impurities, distilled if possible, and characterized by their infrared spectra and by C, H, and Ph analyses. Thus a new and very mild method for introducing plumbyl groups into complicated molecules has been established, and numerous organolead compounds containing functional groups – hitherto a very small class of compounds [5] – have become accessible.



(1a) [c] *(1b)* [d] *(1c)* [e] *(2)* [f] *(3)* [g]

[c] B.p. 116–119 °C/0.01 mm.

[d] B.p. 94–97 °C/10^{-4} mm.

[e] B.p. 128–130 °C/10^{-4} mm, with partial decomposition.

[f] The product reacts with both phenyl isocyanate and R_3PbH. Depending on the conditions, a high yield of 1,3,5-triphenyl-isocyanuric acid or of a crystalline compound is formed which decomposes at 170 to 172 °C and probably has the composition $C_{27}H_{22}N_4O_2$. In addition, hexabutyldiplumbane can also be isolated.

[g] This compound decomposes on being distilled.

n-Octene does not react under identical conditions. Pb–H groups can be more reactive than Sn–H groups. Thus acrylonitrile is not attacked by tributyltin hydride at 0 °C without a catalyst within 20 hours, but tributyl-lead hydride adds on completely within 8 hours under the same conditions.

Alkyl halides can be reduced rapidly – often exothermally – to alkanes.

$$R'-I + R_3PbH \rightarrow R'-H + R_3PbI$$

If the alkane is volatile, *e.g.* when $R' = C_2H_5$, this reaction can be used for quantitative estimation of the organolead hydride.

Benzyl chloride, ω-bromoacetophenone, allyl bromide, bromobenzene, and iodobenzene are dehalogenated in this manner at 0 °C; triethyltin chloride gives rise to the hydride, 1,2-dibromoethane to ethylene, and carbon tetrachloride selectively to chloroform or dichloromethane. Benzaldehyde and nitrobenzene are also reduced at 0 °C.

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Publication deferred until now at the authors' request

[1] Reviewed by *W. P. Neumann*, Angew. Chem. *76*, 849 (1964); *H. G. Kuivila*, Adv. organomet. Chem. *1*, 47 (1964).

[2] *W. E. Becker* and *S. E. Cook*, J. Amer. chem. Soc. *82*, 6264 (1960).

[3] *R. Duffy, J. Feeney*, and *A. K. Holliday*, J. chem. Soc. (London) *1962*, 1144.

[4] *E. Amberger*, Angew. Chem. *72*, 494 (1960).

[5] Reviewed by *L. C. Willemsens*: Organolead Chemistry. Semper Avanti, Den Haag 1964.

Complexes of Iminophosphoranes with Metal Salts

By Dr. W. Seidel

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Iminotriphenylphosphorane (triphenylphosphine imine) is a member of the isoelectronic series $(C_6H_5)_3PO - (C_6H_5)_3PNH - (C_6H_5)_3PCH_2$, in which the nucleophilicity increases greatly from left to right. Reactions of the unsubstituted imine and of its *N*-organo derivatives with hydrogen halides, alkyl halides, and Lewis acids have been investigated [1]. However, nothing is known of its ability to form adducts with metal salts. The complexes of triphenylphosphine oxide have been closely examined, and it is known that methylenetriphenylphosphorane condenses with mercuric bromide to give $\{[(C_6H_5)_3PCH_2]_2Hg\}\{HgBr_3\}_2$ [2].

We have found that phosphine imines R_3PNR also form adducts with metal salts. The stability of the adducts depends largely on the nature of the *N*-substituent. *N*-Phenyliminotriphenylphosphorane, $(C_6H_5)_3PNC_6H_5$ *(1)* [3], reacts with mercuric or cadmium iodide in benzene/acetonitrile (1:1 v/v) to give the highly insoluble stable adducts

$(C_6H_5)_3PNC_6H_5 \cdot HgI_2$ *(2)*, yellow, m.p. 178 °C, yield 56 %, and

$(C_6H_5)_3PNC_6H_5 \cdot CdI_2$ *(3)*, colorless, m.p. > 260 °C, yield 78 %.

Compound (2) dissolves in methanol to give a colorless solution and is reprecipitated unchanged on addition of water. It is decomposed by 2 N nitric acid, HgI_2 being liberated. If *(2)* is shaken with ether and a solution of potassium iodide in water containing a little methanol, it is decomposed into K_2HgI_4 and *(1)*, the latter being extracted into the ether phase. An analogous cleavage of *(3)* can be effected with a solution of potassium cyanide.

Complexes of *(1)* with transition metal salts such as $NiCl_2$ or $CoCl_2$ are much less stable. No adduct formation was observed in solvents. However, when the components are fused together, green to blue substances are formed which discolor rapidly in moist air. The colored adducts have the composition $[(C_6H_5)_3PNC_6H_5]_2 \cdot MCl_2$ (M = Co or Ni) and have the magnetic moments expected for weak complexes.

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[1] *H. Zimmer* and *G. Singh*, J. org. Chemistry *29*, 3412 (1964).

[2] *D. Seyferth* and *S. O. Grim*, J. Amer. chem. Soc. *83*, 1610 (1961).

[3] *L. Horner* and *H. Oediger*, Liebigs Ann. Chem. *627*, 142 (1959).

Phosphine Sulfide/Tin Halide Complexes

By Dr. H. Teichmann

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Although numerous adducts of tertiary phosphine oxides are known, the only adduct of phosphine sulfides which has been described is the compound $[(C_6H_5)_3PS]_2PdCl_2$ [1]. We have now found that trialkylphosphine sulfides react in inert solvents such as dichloromethane or hexane with tin(IV) chloride or bromide to give stable 2:1 adducts. High to quantitative yields of the compounds *(1)–(10)* were obtained in this way. The 1:1 adducts *(11)–(14)* were formed analogously from tetraalkylbiphosphine disulfides. The complexes *(1)–(6)* can be sublimed.

$[R_2R'PS]_2SnX_4$ *(1)–(10)* $\quad$ $[R_2P(S)P)(S)R_2]SnX_4$ *(11)–(14)*

	R	R'	X	M.p. [°C]		R	R'	X	M.p. [°C]
(1)	CH_3	CH_3	Cl	196–99	*(8)*	n-C_4H_9	n-C_4H_9	Br	101–02
(2)	CH_3	CH_3	Br	182–84	*(9)*	CH_3	C_6H_5	Cl	174–77
(3)	C_2H_5	C_2H_5	Cl	194–96	*(10)*	CH_3	C_6H_5	Br	155–57
(4)	C_2H_5	C_2H_5	Br	182–84	*(11)*	CH_3	—	Cl	145–47
(5)	n-C_3H_7	n-C_3H_7	Cl	166–66/5	*(12)*	CH_3	—	Br	152–54
(6)	n-C_3H_7	n-C_3H_7	Br	176–77	*(13)*	C_2H_5	—	Cl	146–49
(7)	n-C_4H_9	n-C_4H_9	Cl	93–95	*(14)*	C_2H_5	—	Br	138–39

The electron-donor capacity of the sulfur bonded to phosphorus is less than that of oxygen, as shown by the reaction of the adducts *(1)–(14)* with trimethyl phosphate at room temperature, which releases the phosphine sulfides. However, the adducts are stable towards ether.

The presence of a P=S→Sn coordination in the adducts follows from the bathochromic shifts of the P–S stretching frequencies of up to 45 cm^{-1}.

Triphenylphosphine sulfide does not react with $SnCl_4$ etherate [1], but reacts with $SnCl_4$ in dichloromethane to give an unstable adduct, which decomposes on heating or on treatment with ether.

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German version: Angew. Chem. 77, 809 (1965)

[1] *E. Bannister* and *F. A. Cotton*, J. chem. Soc. (London) *1960*, 1959.

A One-Step Synthesis of γ-Keto Carboxylic Acids [1]

By Dr. H. Reinheckel, Dr. K. Haage, and R. Gensike

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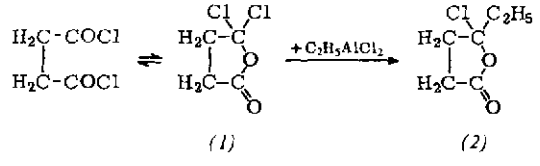
Succinyl dichloride *(1)* is readily alkylated at −30 °C by $(C_2H_5)_3Al_2Cl_3$ or $C_2H_5AlCl_2$ in a molar ratio of 1:0.4 or 1:1.2 to yield γ-oxocaproyl chloride, which occurs entirely in

the cyclic form *(2)* [2]. This compound is stable towards even an excess of ethylaluminum halide at this temperature. Hydrolysis of the reaction mixture with dilute sulfuric acid at −25 °C produces γ-oxocaproic acid in 90 % yield.

This reaction can also be applied to higher alkylaluminum halides (see table). The latter are prepared from the corresponding trialkylaluminum compounds [3]. However, the trialkyls can be used directly for the alkylation if a mixture of 1 mole of succinyl dichloride and 2 moles of $AlCl_3$ is used.

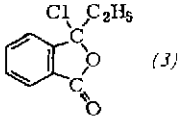


(1) *(2)*

This approach can also be adopted with triethylaluminum but is of little interest because of the ready availability of $(C_2H_5)_3Al_2Cl_3$.

Alkylating agent	Acid obtained	Yield [%]	M.p. [°C]
$(C_2H_5)_3Al_2Cl_3$	γ-Oxocaproic acid	90	34–35
$C_2H_5AlCl_2$		87	33–35
$(C_2H_5)_3Al$		61	33–35
$n\text{-}C_6H_{13}AlCl_2$	γ-Oxocapric acid	80	67
$(n\text{-}C_6H_{13})_3Al$		69	66–67
$(n\text{-}C_8H_{17})_3Al$	γ-Oxolauric acid	81	78
$(n\text{-}C_{12}H_{25})_3Al$	γ-Oxopalmitic acid	40	91

Phthalyl chloride can also be alkylated in the same manner to give γ-keto acids. Both isomers of phthalyl chloride react with $(C_2H_5)_3Al_2Cl_3$ or $C_2H_5AlCl_2$ to give the cyclic form of *o*-propionylbenzoyl chloride *(3)*, which on hydrolysis yields



(3)

propiophenone-*o*-carboxylic acid, m.p. 93 °C. The yields are 74 % from the symmetrical form of phthalyl chloride and 65 % from the unsymmetrical form.

Received: July 5th, 1965 [Z 17/849 IE]
German version: Angew. Chem. 77, 810 (1965)

[1] Reactions with Aluminum Alkyls, Part 5. – Part 4: *H. Reinheckel* and *D. Jahnke*, Chem. Ber., in press.

[2] *J. Cason* and *E. Reist*, J. org. Chemistry *23*, 1492 (1958).

[3] *H. Reinheckel* and *K. Haage*, J. prakt. Chem., in press.

Synthesis of Thieto[2,3,4-ij]naphthalene-1,1-dioxide, a 1,8-Bridged Naphthalene Derivative

By Doz. Dr. R. W. Hoffmann and Dipl.-Chem. W. Sieber

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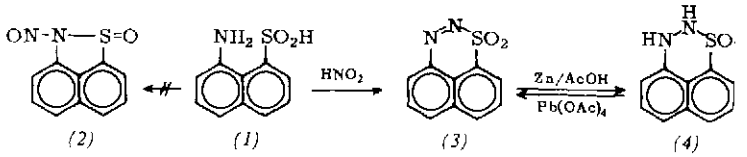
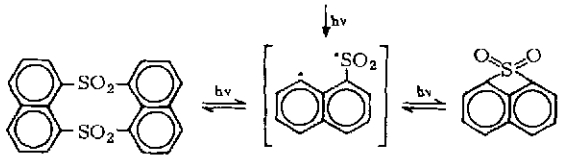
Diazotization of 1-aminonaphthalene-8-sulfinic acid *(1)* leads to 1,2,3-thiadiazino[4,5,6-*ij*]naphthalene-1,1-dioxide *(3)*, m.p. 191 °C, and not, as *Reissert* [1] suspected, to *N*-nitrosothiazolo[3,4,5-*ij*]naphthalene-*S*-oxide *(2)*. This follows from the reduction of *(3)* with zinc plus acetic acid in ethanol to its dihydro derivative *(4)*, m.p. 218 °C (decomp.), in 88 % yield and from the reoxidation of *(4)* to *(3)* by lead tetraacetate in methylene chloride in 50 % yield.

In contrast to 1,2,3-benzothiadiazole-1,1-dioxide [2], which contains a five-membered heterocyclic ring, *(3)* does not release sulfur dioxide or nitrogen until above 200 °C, when it forms the "naphthothiamyl blue" already described by *Reiszert* [1]. This pigment is also formed as the main product on photolysis of *(3)* in benzene for 36 h at 15 °C with ultraviolet light [quartz lamp Q 81 from Messrs. Quarzlampen



(2) *(1)* *(3)* *(4)*



(6) *(7)* *(5)*

GmbH, Hanau (Germany)]. Simultaneously, nitrogen is released to yield 25 % thieto[2,3,4-*ij*]naphthalene-1,1-dioxide *(5)* and 3 % dinaphtho[1,8-*bc*:1′,8′-*fg*]-1,5-dithiocin-1,1,5,5-tetroxide *(6)*. Compound *(5)* melts at 184 °C; its molecular weight was found to be 190 by mass spectrometry and 197 by vapor pressure osmometry in acetone; it has λ_{max} in ethanol at 316 mμ (log ε = 2.6), 284 (3.7), 274 (3.6), and 225 (4.6). Compound *(6)* decomposes above 200 °C, has a mass-spectrometric molecular weight of 380 and an ebullioscopic molecular weight of 375 in the tetrahydrofuran/water azeotrope; λ_{max} in tetrahydrofuran = 295 mμ (log ε = 3.1). Compound *(6)* crystallizes on concentrating the irradiated solution. After complete removal of the solvent, *(5)* can be extracted from the residue with cyclohexane.

The infrared spectra of *(5)* and *(6)* contain characteristic sulfone bands at 1315 and 1130–1165 cm^{-1}.

Photolysis of *(5)* in ethanol gives up to 54 % *(6)*, while analogous irradiation of *(6)* yields 20 % *(5)*. It is possible that the diradical *(7)* appears as an intermediate in these reactions.

The compounds *(3)* and *(5)* are of interest as potential precursors of 1,8-dehydronaphthalene [3]. Pyrolysis of *(5)* at 240 °C under nitrogen gave impure carbonyl compounds [4] plus up to 0.4 % perylene, which was detected by thin-layer chromatography and ultraviolet spectroscopy. It is a moot point whether the perylene is formed *via* 1,8-dehydronaphthalene as an intermediate, for the latter has recently been suggested a likely intermediate in the oxidation of 1-aminonaphtho[1,8-*de*]triazine [3]. We have also studied this oxidation and detected perylene in comparable amounts.

Received: July 6th, 1965 [Z 15/852 IE]
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[1] *A. Reiszert*, Ber. dtsch. chem. Ges. *55*, 858 (1922).

[2] *G. Wittig* and *R. W. Hoffmann*, Chem. Ber. *95*, 2718 (1962).

[3] *C. W. Rees* and *R. C. Storr*, Chem. Commun. *1965*, 193.

[4] Cf. *D. C. Dittmer* and *N. Takashina*, Tetrahedron Letters *1964*, 3809.

Formation of Cyclic Sulfones from Dialkylaminobutadienes and Methanesulfonyl Chloride

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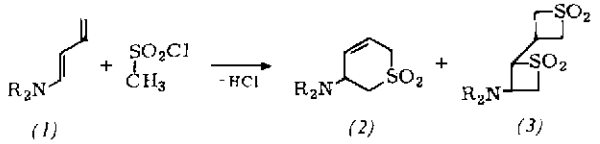
Treatment of 1-dialkylamino-1,3-butadienes *(1)* with methanesulfonyl chloride for 2 h at 15 °C in the presence of 3 moles of triethylamine yields 5-dialkylamino-1-thiacyclohex-3-ene-1,1-dioxide *(2)* plus 3-dialkylamino-2,3′-bithietane-

1,1,1',1'-tetroxide *(3)*. These products can be isolated from the dark brown reaction mixture by fractional crystallization from benzene or by column chromatography on alumina with acetone as eluting agent. The absence of an amino-olefinic grouping in *(2)* and *(3)* follows from their stability towards aqueous acids and excess methanesulfonyl chloride/triethylamine. This also excludes the possibility that the monoadduct is a precursor of the diadduct *(3)*.



(1) *(2)* *(3)*

R_2N	Yield [%]		M.p. [°C]	
	(2)	*(3)*	*(2)*	*(3)*
$(C_2H_5)_2N$	18	60	80–82	139–141
Piperidino	10	48	113–115	149–151
Morpholino	7	20	157–158	181–182

The monosulfones *(2)* have infrared absorptions at 1120, 1270, and 1315 cm^{-1} (SO_2) and at 700 and 1650 cm^{-1} (*cis*-olefin). Their NMR spectra exhibit signals for two olefinic protons at $\tau = 4.1-4.3$, a ring proton on the amino-substituted carbon at $\tau = 5.9-6.2$, and four protons adjacent to the SO_2 group at $\tau = 6.2-6.5$ and 6.8–6.9. The compounds absorb 1 mole of hydrogen over palladium, and afterwards no olefinic double bond can be detected. The chemical and spectroscopic properties of the disulfones *(3)* indicate that they contain no C=C double bond. We consider that the formation of the monosulfones *(2)* is due to a 1,4-cycloaddition of the amino diene *(1)* onto sulfene, $H_2C{=}SO_2$, formed *in situ*, and that the disulfones *(3)* arise by a 3,4-cycloaddition followed by a 1,2-cycloaddition.

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Synthesis of Hexachlorodihydrofuran

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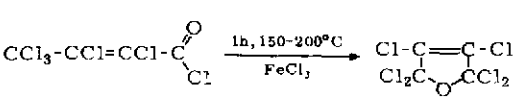
Hexachlorodihydrofuran *(2)* was hitherto only accessible with difficulty from furan by chlorination [1]. It has now been found that perchlorocrotonyl chloride *(1)*, which is readily obtainable by ethoxylation of hexachlorobutadiene and subsequent chlorination [2], rearranges smoothly to *(2)* on heating in the presence of catalytic amounts (0.01–1.0 %) of ferric chloride, ferric acetate, or aluminum trichloride.



(1) *(2)*

The conversion after 1 h at 175 °C lies between 85 and 95 % depending on the catalyst, and *(2)* is almost the only product formed. The course of the reaction can be followed by infrared spectroscopy: *(1)* has a characteristic absorption band at 8.93 μ, *(2)* at 8.30 μ. The product *(2)* is separated from the reaction mixture by distillation (b.p. 209–213 °C) and purified by fractional crystallization at −20 °C and reprecipitation with water from methanol; m.p. 38–39 °C.

Received: July 9th, 1965 [Z 20/842 IE]
German version: Angew. Chem. 77, 811 (1965)

[1] German Patent 921385 (May 6th, 1954), BASF; inventors: *H. Krzikalla, K. Merkel*, and *H. Linge*; U.S. Patent 2430667 (May 12th, 1945/November 11th 1947), Du Pont; inventors: *O. W. Cass* and *H. B. Copelin*; cf. Chem. Abstr. *42*, 2284 (1948).

[2] *A. Roedig* and *P. Bernemann*, Liebigs Ann. Chem. *600*, 9 (1956).

Synthesis of Benzaldehydes by Diazotization of Benzylamines in Dimethyl Sulfoxide

By Dr. K. H. Scheit and Dr. W. Kampe

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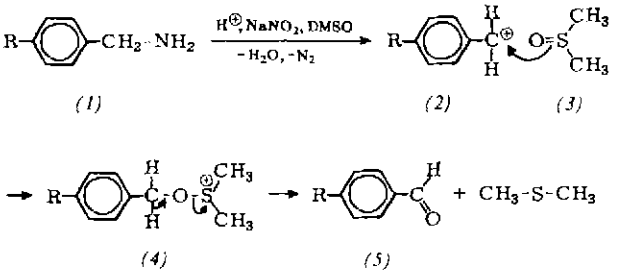
If benzylamines *(1)* are diazotized in dimethyl sulfoxide *(3)* in the absence of water, reaction of the carbonium ions *(2)* formed by the elimination of nitrogen with the dimethyl sulfoxide should lead to the intermediates *(4)*, from which the corresponding aldehydes should be obtained. When



(1) *(2)* *(3)* *(4)* *(5)*

benzylamines *(1)* were treated with sodium nitrite and trifluoroacetic acid in a molar ratio of 1:2:3 in dimethyl sulfoxide for 20 h at 100 °C, benzaldehyde derivatives *(5)* were in fact isolated in the form of their 2,4-dinitrophenylhydrazones (R = H, 82 % yield; R = CH_3, 60 %; R = OCH_3, 65 %). The use of isoamyl nitrite instead of sodium nitrite led to lower yields of aldehyde.

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German version: Angew. Chem. 77, 811 (1965)

Polar Reactions at Covalent Tin-Phosphorus Bonds

By Dr. H. Schumann, Dr. P. Jutzi, and Prof. Dr. Max Schmidt

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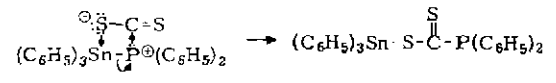
Straightforward reactions now enable synthesis of organostannylphosphines [1, 2] and thus the study of the covalent Sn–P bond. Diphenylphosphinotriphenyltin, for example, reacts with CS_2, $CSCl_2$, $CS(NH_2)_2$, $C_6H_5{-}NCO$, $C_6H_5{-}NCS$ (in boiling benzene), and COS (at 100 °C in a sealed tube), but not with CO_2. The products are the new compounds shown in the table below; they were crystallized from benzene/pentane.

$(C_6H_5)_3Sn\ P(C_6H_5)_2$	Product		M.p. [°C]	Yield [%]
CS_2	$R_3Sn{-}S{-}C(S){-}PR_2$	*(1)*	68	64
COS	$R_3Sn{-}O{-}C(S){-}PR_2$	*(2)*	97	63
$CSCl_2$	$R_3Sn{-}S{-}CCl_2{-}PR_2$	*(3)*	93	87
$CS(NH_2)_2$	$R_3Sn{-}S{-}C(NH_2)_2{-}PR_2$	*(4)*	115	22
C_6H_5NCO	$R_3Sn{-}N(C_6H_5){-}C(O){-}PR_2$	*(5)*	58	64
C_6H_5NCS	$R_3Sn{-}N(C_6H_5){-}(CS){-}PR_2$	*(6)*	(decomp.) 87	71

The reactions correspond to the formally analogous insertion reactions at Si–N and Sn–N bonds [3, 4] and probably proceed *via* a polar four-centered concerted mechanism.



Tetrakis(diphenylphosphino)tin [1] reacts with CS_2 or $C_6H_5{-}NCO$ with corresponding cleavage of all four Sn–P bonds in the molecule to give tin tetrakis(diphenylphosphinodithiocarbonate), m.p. 55 °C, or tin tetrakis-(*N*-diphenylphosphinocarbonyl-*N*-phenylamide), m.p. 50 °C. Tris(triphenylstannyl)phosphine [2], on the other hand, does not

undergo such cleavage reactions. This finding also provides support for the assumption of a polar mechanism for the reactions described here. The lone pair of electrons on the phosphorus which initiates the attack is rendered almost inactive in tris(triphenylstannyl)phosphine by interaction with the three tin atoms.

In the infrared spectra of compounds *(1)*–*(4)*, γ(Sn–S) was found at 349 cm^{-1} in *(1)*, at 351 cm^{-1} in *(3)*, and at 352 cm^{-1} in *(4)*, while γ(Sn–O) was found at 541 cm^{-1} in *(2)*. The structures of compounds *(5)* and *(6)* follow from the absence of P–N vibration bands.

Received: July 12th, 1965 [Z 22/844 IE]
German version: Angew. Chem. 77, 812 (1965)

[1] *H. Schumann, H. Köpf*, and *M. Schmidt*, J. organometallic Chem. *2*, 159 (1964).

[2] *H. Schumann, H. Köpf*, and *M. Schmidt*, Chem. Ber. *97*, 2395 (1964).

[3] *H. Brederveld*, Recueil Trav. chim. Pays-Bas *81*, 276 (1962).

[4] *K. Jones* and *M. F. Lappert*, Proc. chem. Soc. (London) *1962*, 358.

Formation of 2-Morpholino-5-phenylthiophene in the Willgerodt-Kindler Reaction of 1-Phenylbutanones

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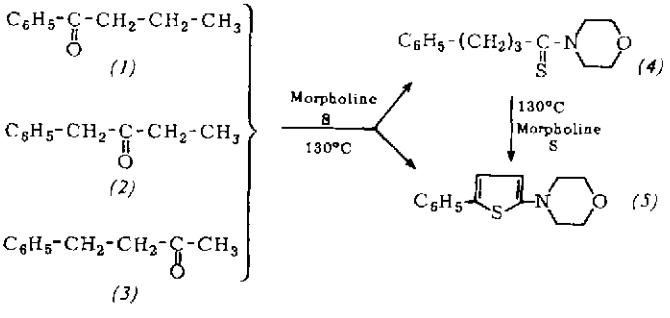
If the 1-phenylbutanones *(1)*–*(3)* are treated with 2 moles of morpholine and 2 g-atoms of sulfur per mole of ketone at the boiling point of morpholine (*ca.* 130 °C), 2-morpholino-5-phenylthiophene *(5)* [1], m.p. 134 °C, λ_{max} = 210 mμ, 226 mμ, and 328 mμ in ethanol, is obtained in each case in addition to the expected 4-phenylbutyrothiomorpholide *(4)*, m.p. 57 °C. Compound *(5)* is also formed when *(4)* is subjected to the same treatment.



The structure of *(5)* was established by hydrolysis with 50 % sulfuric acid, which gave 4-oxo-4-phenylbutyric acid, and by its synthesis from 4-oxo-4-phenylbutyromorpholide with P_2S_5.

Received: July 12th, 1965 [Z 23/845 IE]
German version: Angew. Chem. 77, 812 (1965)

[1] *T. Bacchetti, A. Alemagna*, and *B. Danieli*, Tetrahedron Letters *1965*, 2001, recently reported the formation of morpholinothiophenes during the Willgerodt-Kindler reaction of alkynyl ketones and β-diketones.

Synthesis of Methyl α-Nitro-β-methoxypropionate, a Protected α-Nitracrylic Ester

By Prof. Dr. K.-D. Gundermann and Dipl.-Chem. H.-U. Alles [1]

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α-Nitracrylic esters should be among the most reactive acrylic acid derivatives owing to the electron-attracting effects of both the nitro and ester groups. Earlier attempts to prepare α-nitro-β-alkoxypropionic esters, *i.e.* compounds of type *(3)*, as precursors of α-nitracrylic esters invariably led to α,α'-dinitro-α-alkoxymethylglutaric esters, the products of a Michael addition of the α-nitracrylic ester onto *(3)* [2].

Methyl α-nitro-β-methoxypropionate *(3)* has now been obtained by dehalogenation of methyl α-bromo-α-nitro-β-methoxypropionate *(2)* with sodium borohydride. A 10 % aqueous solution of $NaBH_4$ is added in 50 % excess to a 5 % solution of *(2)* in methanol at room temperature, the pH being maintained at 4–5 by simultaneous addition of 30 % sulfuric acid. After evaporation of the methanol in vacuum, the solution is extracted with ether. The ether extract is neutralized with sodium hydrogen carbonate and fractionated. The product, b.p. 69 °C/0.3 mm, n_D^{20} = 1.4313, is obtained in 70 % yield. Compound *(2)* can also be dehalogenated with potassium iodide in 10 % aqueous methanolic solution at 0–5 °C. The methanol is removed as above, the solution is shaken with ether, and the ether extract is freed from iodine by shaking it with sodium thiosulfate solution and then fractionated; the yield is again 70 %. The starting material *(2)*, b.p. 73–75 °C/0.3 mm, n_D^{20} = 1.4655 is made from methyl α-bromo-α-nitro-β-hydroxypropionate [3] by treatment for 4 days with trimethyloxonium fluoroborate, or less readily by bromination of methyl α-hydroximino-β-methoxypropionate [2] with *N*-bromosuccinimide and oxidation of the resultant α-bromo-α-nitroso ester with $KMnO_4$.

(1), R = H, R' = Br *(4)*, R = NO_2, R' = CO_2CH_3

(2), R = CH_3, R' = Br

(3), R = CH_3, R' = H

It was shown by trapping reactions that methanol is readily eliminated from *(3)* to give methyl α-nitracrylate. For example, the potassium salt of the aci-form of *(3)* yields the Michael adduct methyl α,α'-dinitro-α-alkoxymethylglutarate on gradual addition of 0.5 equivalent of sulfuric acid to its aqueous solution. When anthracene is heated with *(3)*, 9,10-dihydro-9,10-(1-nitro-1-methoxycarbonylethano)anthracene *(4)* is formed.

Compound *(3)* can be kept unchanged for months at room temperature in contrast to the recently described ethyl α-nitro-β-hydroxypropionate [4], which can also be regarded as a protected α-nitroacrylic ester.

Received: July 12th, 1965 [Z 24/846 IE]
German version: Angew. Chem. 77, 812 (1965)

[1] From a lecture in Clausthal (Germany), June 18th, 1965.

[2] *K.-D. Gundermann, W. Cohnen*, and *H.-U. Alles*, Chem. Ber. *97*, 647 (1964).

[3] *A. Dornow* and *A. Müller*, Chem. Ber. *93*, 27 (1960).

[4] *K. K. Babiewskii, W. M. Belikow*, and *N. A. Tichonowa*, Dokl. Akad. Nauk SSSR *160*, 103 (1965).

Uncoupling of the Oxidative Phosphorylation in Mitochondria by NH-Acidic Benzimidazoles

By Dr. K. H. Büchel and Prof. Dr. F. Korte

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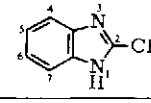
Some electronegatively substituted benzimidazoles [1] have a strong herbicidal and in some cases also insecticidal activity. They have pK_a values between 4 and 8 and behave like weak

acids: they dissolve in aqueous sodium carbonate and are reprecipitated by acidification with HCl but do not form hydrochlorides. Their biological activity is related to their pK_a value.

We have studied the action of such compounds on oxidative phosphorylation in isolated mitochondria from rat heart. It was found that the benzimidazoles listed in the table have an uncoupling effect similar to that of 2,4-dinitrophenol. They inhibit the regulation of the mitochondrial respiration by adenosine diphosphate (ADP) and stimulate the respiration beyond the state 3 rate [2]. They also counteract the inhibition of the respiration caused by oligomycin and octylguanidine, and stimulate ATPase as well as or even better than 2,4-dinitrophenol. The reduction of NAD in the electron transport of the mitochondria, which is dependent upon ATP and linked to succinate, is inhibited.

As shown in the table, the uncoupling activity increases exponentially with the N—H acidity of the benzimidazoles. *N*-Methylation leads to a complete loss of their action on the respiratory chain. Tetrachloro-2-trifluoromethylbenzimidazole effects complete uncoupling of oxidative phosphorylation at a concentration as low as 3×10^{-8} M. It is thus the strongest uncoupler known to date.

(1) 	pK_a [a]	Uncoupling concentration [μM/l] [b]
(1) TFB	9.6	500
(2) 5-Chloro-TFB	8.9	14
(3) 5,6-Dichloro-TFB	7.6	0.8
(4) 4,5,6-Trichloro-TFB	6.6	0.2
(5) 4,5,6,7-Tetrachloro-TFB	5.6	0.03
(6) *N*-Methyl-4,5,6-trichloro-TFB	–	inactive

[a] In 50 vol-% aqueous ethanol.

[b] The course of the respiration of rat heart mitochondria was measured at 25 °C [3] using an oxygen electrode [4]. The mitochondria (2—3 mg of protein) were suspended in 0.25 M sucrose/1.0 mM ethylenediaminetetraacetic acid and then added to 3.7 ml of a mixture containing the following components: 9.3 mmole of sucrose, 50 μmole of dipotassium glutamate, and 20 μmole of $MgCl_2$. When state 4 respiration started, 0.4 μmole of ADP was added in order to obtain state 3 respiration. On reattainment of state 4, a solution of the benzimidazole in ethanol was added; an increase in respiratory activity was immediately observed. More ADP was then added. When the second addition of ADP exhibits no further effect on the respiratory activity, the phosphorylation system is uncoupled.

4,5,6,7-Tetrachloro-2-trifluoromethylbenzimidazole

A solution of 93 g (0.5 mole) of 2-trifluoromethylbenzimidazole in dichlorobenzene is heated at 120 °C. The solution is stirred and chlorine is passed through for about 36 h at a rate of 4–5 l/h. The solvent is removed in vacuum and the crude crystalline residue is suspended in boiling water. More chlorine is passed in until the conversion to the tetrachloro derivative is complete (after approx. 24 h). The end point of the chlorination is determined by analysing a sample of the reaction mixture by gas chromatography on Apiezon L at 250 °C with helium in a column 96 cm long. The product is then filtered off and recrystallized from xylene. The yield of colorless crystals, m.p. 269 °C, $\lambda_{max} = 223$, 273, 290, and 301 mμ (log ε = 4.92, 3.94, 3.85, and 3.81), is above 95 %.

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German version: Angew. Chem. 77, 814 (1965)

[1] *K. H. Büchel, F. Korte, A. Trebst*, and *E. Pistorius*, Angew. Chem. 77, in press; Angew. Chem. internat. Edit. 4, 789 (1965).

[2] *J. B. Chappell*, Biochem. J. 90, 237 (1964).

[3] *B. Chance* and *B. Hagihara*: Proc. Vth Intern. Congr. Biochem., Moscow 1961. Pergamon Press, London 1963. Vol. 5, p. 3.

[4] *J. B. Chappell*, Biochem. J. 90, 225 (1964).

Inhibition of Photosynthesis Reactions by NH-Acidic Imidazoles and Benzimidazoles

By Dr. K. H. Büchel and Prof. Dr. F. Korte

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Prof. Dr. A. Trebst and E. Pistorius

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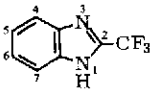
Imidazoles and benzimidazoles containing strongly electronegative substituents, *e.g.* halogens or trifluoromethyl or nitro groups, are strongly acidic at the NH group and sometimes exhibit good herbicidal properties. Since some herbicides, *e.g.* urea derivatives, aminotriazines, and uracils, inhibit the fixation of carbon and release of oxygen by photosynthesis, we have examined the effects of our herbicidal heterocycles on photosynthesis reactions in isolated chloroplasts.

The table shows that these substances inhibit the electron transport in photosynthesis. The compounds with the highest activity have a high NH-acidity [1]. *N*-Alkylation of the acidic secondary amino group, *e.g.* to give *(10)*, causes a reduction in the inhibitory effect. The imidazole anion is probably the species responsible for the effect. Since the release of oxygen is inhibited at concentrations which are insufficient to affect cyclic photophosphorylation, the blockage

Table 1. Relationships between the pK_a (in 50 % aqueous ethanol) of some substituted imidazoles and benzimidazoles and their inhibitory action (pI_{50} = minus the logarithm of the molar concentration which produces a 50 % inhibition) on the release of oxygen and the cyclic photophosphorylation during photosynthesis in isolated chloroplasts [3].

Compound	pK_a	Liberation of oxygen (Hill reaction with $K_3[Fe(CN)_6]$)		Formn. of ATP (cyclic photophosphorylation with vitamin K_3)	
		50 % inhibn. at [γ/ml]	pI_{50}	50 % inhibn. at [γ/ml]	pI_{50}
(1)  TFB	9.6	28	3.28	198	2.97
(2) 4-ChloroTFB	8.2	10	4.34	87	3.40
(3) 5,6-DichloroTFB	7.6	0.34	5.88	4.8	4.73
(4) 4,5,6-TrichloroTFB	6.6	0.44	5.82	3.3	4.93
(5) 4,5,6,7-TetrachloroTFB	5.6	0.9	5.56	2.9	5.05
(6) 4,5,6,7-TetrabromoTFB	5.5	1.7	5.47	2.9	5.24
(7) 5,6-DinitroTFB	4.1	0.3	5.96	3.4	4.91
(8) 2,4,5-Tribromoimidazole	6.9	0.5	5.79	24	4.11
(9) 2,4,5-Triiodoimidazole	8.0	0.4	6.05 [5]	7.8	4.76
(10) *N*-Methyl-4,5,6-trichloroTFB	–	10	4.48	No inhibition up to 2×10^{-4} M	

occurs in the region of the second light reaction of photosynthesis (photo-oxidation of water), for this is not required for cyclic phosphorylation. Higher concentrations – generally about ten times greater – cause inhibition of the cyclic photophosphorylation, *i.e.* formation of ATP, as well (see Table). In this respect, the imidazoles and benzimidazoles described here differ from the herbicides of the urea and triazine types, which only affect the cyclic phosphorylation at extremely high concentrations, if at all. The inhibition of the formation of ATP by the benzimidazoles is due to an uncoupling and not to a disturbance of the cyclic electron transport, because photosynthetic reduction of NADP by an artificial electron donor (diaminodurol/ascorbate [2]) is not inhibited even by much higher concentrations of herbicide. Hence the electron transport in the region of the first light reaction is unaffected.

The benzimidazole derivatives listed in the table were prepared by condensation of the correspondingly substituted *o*-phenylenediamines with excess trifluoroacetic acid at 80–100 °C or by substitution of 2-trifluoromethylbenzimidazole *(1)* [6]. Compound *(6)* was made by bromination of *(1)* with a twofold molar excess of bromine in boiling water. Compound *(7)* is obtained in 60 % yield by nitrating *(1)* with HNO_3 (sp. gr. = 1.52) at 60–70 °C and recrystallization from xylene. The *N*-methyl derivative *(10)* is formed by treating the sodium salt of *(4)* with methyl iodide in acetonitrile at 50 °C. The trihaloimidazoles *(8)* and *(9)* were made according to [7].

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German version: Angew. Chem. 77, in press.

[1] A similar relationship between the half-neutralization potential of substituted *N*-phenyl amides and the inhibition of the Hill reaction was recently observed: *N. D. Camper* and *D. E. Moreland*, Biochem. biophysica Acta *94*, 383 (1965).

[2] *A. Trebst* and *E. Pistorius*, Z. Naturforsch. *20b*, 143 (1965).

[3] Duplicate experiments were carried out on 3 ml samples containing chloroplast fragments (P_{151} from spinach [4], 0.2 mg of chlorophyll), 80 µmole of tris buffer at pH 8.0, 5 µmole of $MgCl_2$, 10 µmole of potassium phosphate, 10 µmole of ADP, and either 20 µmole of $K_3[Fe(CN)_6]$ or 0.3 µmole of vitamin K_3. The mixtures were exposed to 35000 lux for 15 min under nitrogen. The oxygen produced was determined manometrically and the amount of ATP formed was determined enzymatically with phosphoglycerokinase, triose phosphate dehydrogenase, phosphoglyceric acid, and $NADH_2$. The control value for the oxygen production without addition of inhibitor was 1300 mm^3 per mg of chlorophyll per h.

[4] *M. B. Allen, F. R. Whatley*, and *D. I. Arnon*, Biochim. biophysica Acta *32*, 32 (1959).

[5] The pI_{50} of *(9)* is relatively high in consideration of its pK_a, but this is because *(9)* is more lipophilic than *(8)*. Better correlations between the pK_a and pI_{50} are generally obtained by inclusion of partition coefficients.

[6] Synthesis of *(5)*: *K. H. Büchel, F. Korte*, and *R. B. Beechey*, Angew. Chem. *77*, 814 (1965); Angew. Chem. internat. Edit. *4*, 788 (1965).

[7] *J. E. Balaban* and *F. L. Pyman*, J. Chem. Soc. (London) *121*, 947 (1922); *H. Punly* and *K. Gundermann*, Ber. dtsch. chem. Ges. *41*, 3999 (1908).

Photo-initiated Hydrocarboxylation of Mono-olefins

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During hydrocarboxylation [1] of higher n-alkynes under normal pressure to give α,β-unsaturated carboxylic acids, the length of the inhibition time and the rate of the reaction depend on the intensity of the incident light [2]. We have found that if the reaction is carried out in ultraviolet light, open-chain or cyclic mono-olefins can also be converted into the corresponding carboxylic acids in good conversions and high yields, although these compounds can otherwise seldom be hydrocarboxylated. The results obtained are shown in the table. Each charge comprised 0.25 mole of olefin, 0.15 mole of nickel carbonyl, 5 moles of water, 0.5 mole of HCl (added in the form of concentrated hydrochloric acid), and 200 ml of acetone. The ultraviolet radiation source was a 70 watt Q 81 immersion lamp from Messrs. Quarzlampen GmbH, Hanau (Germany); the reaction temperature was 55–60 °C.

Olefin	Light	Duration of reaction [h]	Product	Conversion [%]	Yield [%]
Cyclohexene	Darkness	6	Cyclohexane-carboxylic acid	9.1	83
	Daylight	6		24	58
	Ultraviolet	6		64	84
	Ultraviolet	9		96	83
n-1-Octene	Darkness	6	No reaction		
	Daylight	6	A mixture of isomeric nonanoic acids [a]	9.1	55
	Ultraviolet	6		86.5	70
	Ultraviolet	9		98	70
cis-n-4-Octene	Daylight	6	No reaction		
	Ultraviolet	6	A mixture of isomeric nonanoic acids [b]	68	17
	Ultraviolet	9		91	17

[a] 37 % 1-nonanoic acid, 61 % 2-nonanoic acid, 1 % 3-nonanoic acid, and 1 % 4-nonanoic acid.

[b] 2 % 2-nonanoic acid, 3.5 % 3-nonanoic acid, and 94.5 % 4-nonanoic acid.

The unconverted olefin is partly isomerized. For example, after hydrocarboxylation of 1-octene in daylight, the unconverted olefin consists of 87.1 % starting material, 2.8 % *cis*-2-octene, and 10.1 % *trans*-2-octene. After irradiation with ultraviolet light, however, the percentages are 28.8, 13.6, and 57.6 %, respectively. After the reaction with *cis*-4-octene, the unchanged olefin comprises 92 % starting material, 5 % *trans*-n-4-octene, and 3 % *trans*-n-3-octene.

Received: July 19th, 1965 [Z 26/850 IE]
German version: Angew. Chem. 77, 813 (1965)

[1] *W. Reppe et al.*, Liebigs Ann. Chem. *582*, 1 (1963); *E. R. H. Jones, T. Y. Shen*, and *M. C. Whiting*, J. chem. Soc. (London) *1951*, 766.

[2] *J. M. J. Tetteroo*, Doctorate Thesis, Technische Hochschule Aachen, 1965.

N-(2,4-Dinitrophenyloxycarbonyl)amino Esters – New N-Activated Amino-Acid Derivatives

By Dr. J. Gante

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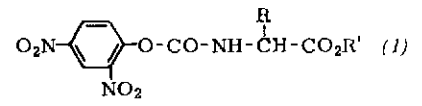
Reaction of amino esters with bis-(2,4-dinitrophenyl) carbonate [1] in a molar ratio of 1 : 1 in anhydrous ethyl acetate or ethyl acetate/ether (1 : 2 v/v) at room temperature followed by precipitation with petroleum ether gives the *N*-(2,4-dinitrophenyloxycarbonyl)amino esters *(1a)–(1d)*.

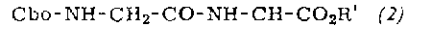
Compounds *(1a)–(1d)* are colorless to pale yellow crystalline solids which as *N*-activated amino esters are suitable for peptide syntheses. For example, reaction of *(1a)–(1d)* with an equimolar amount of Cbo-glycine led to the formation



(1)

	R	R'	Yield [%]	M.p. [°C]	Specific rotation
(1a)	$-H$	$-C_2H_5$	77	85–86	
(1b) DL-Form	$-CH_3$	$-C_2H_5$	45	80–81	
(1c) L-Form	$-CH_3$	$-CH_2-C_6H_5$	54	83–84	$[\alpha]_D^{20} = -53.9°$
(1d) L-Form	$-CH_2-S-CH_2-C_6H_5$	$-CH_2-C_6H_5$	72	87–88	$[\alpha]_D^{21} = -43.4°$ (c = 1, Ethyl acetate)

of the dipeptides *(2a)–(2d)* with liberation of 2,4-dinitrophenol and carbon dioxide. The condensation is carried out



(2)

	R	R'	Yield [%]	M.p. [°C]	Specific rotation
(2a)	$-H$	$-C_2H_5$	64	79–80	
(2b) DL-Form	$-CH_3$	$-C_2H_5$	35	Oil	
(2c) L-Form	$-CH_3$	$-CH_2-C_6H_5$	36	77–78	$[\alpha]_D^{20} = -13.3°$ (c = 0.47, Acetone)
(2d) L-Form	$-CH_2-S-CH_2-C_6H_5$	$-CH_2-C_6H_5$	41	97	$[\alpha]_D^{25} = -38.6°$ (c = 1, Ethanol)

either by melting a mixture of the reactants at 110 °C or leaving it standing in pyridine or chloroform/pyridine (5:1 v/v) at room temperature for 3 days.

Received: July 22nd, 1965 [Z 28/853 IE]
German version: Angew. Chem. 77, 813 (1965)

[1] *R. Glatthard* and *M. Matter*, Helv. chim. Acta *46*, 795 (1963).

CONFERENCE REPORTS

The Kinetics of Proton Transfer Processes

A discussion meeting was held by the Faraday Society on "The kinetics of proton transfer processes" in Newcastle-upon-Tyne (England) from April 12 to 14, 1965, at which 20 papers were read.

From the lectures:

In his introductory lecture, *M. Eigen* (Göttingen, Germany) outlined the general aspects of proton transfer processes. The rate of proton transfer is determined essentially by the distance between the proton donor and the proton acceptor at the moment of reaction; therefore, formation of hydrogen bonds between the two participants favors fast proton exchange. The rate constants of the recombinations

$H_3O^+ +$ base

and

$HO^- +$ acid

have been determined for numerous systems in aqueous solution. They approach the value characteristic of a diffusion-controlled reaction ($k = 10^{10}-10^{11}$ mole^{-1}·sec^{-1}). If the basicity of the acceptor is greater than that of the donor, the reaction is diffusion-controlled and is independent of the (positive) pK_a difference. If, on the other hand, $\Delta pK_a \leq 0$, log k will be a linear function of ΔpK_a. When log k is plotted against ΔpK_a, the gradient α decreases from 1 to 0 as ΔpK_a becomes more positive. The width of the ΔpK_a region for $0 \leq \alpha \leq 1$ depends on the nature of the reactants [1].

[1] Cf. *M. Eigen*, Angew. Chem. *75*, 489 (1963).

Brønsted's equation for acid and base catalysis stipulates a linear relationship between log k and the pK_a value of a catalytically active acid or base:

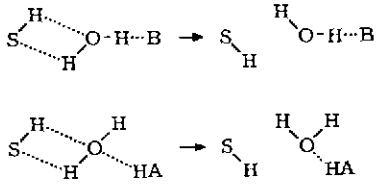
$$\log k = \alpha pK_a + c$$

where α and c are constants.

As long as the branches of the potential curves closely approximate to straight lines, α remains approximately constant. With increasing deviation from a linear shape, α must decrease and eventually become zero. Relaxation measurements carried out on numerous systems (*e.g.* the halogenation of acetylacetone, acetone, and bromoacetylacetone) indeed reveal a continuous change in the value of α between 1 and 0, when pK_a of the catalysing species varies. However, many reactions (*e.g.* mutarotation of glucose, hydration or dehydration of carbonyl compounds, hydrolysis of esters) behave differently. These reactions are governed by general acid-base catalysis:

$$HS + HA \rightleftharpoons HSH^+ + B$$
$$B + HSH^+ \rightleftharpoons HA + SH$$

The plot of log k against ΔpK_a often gives apparently too high rate constants. This finding is explained by simultaneous attack of the acid HA and the base B at the substrate SH, which is aided by the amphoteric nature of water. *Eigen* proposes the following transition complex formed by a concerted mechanism:



This concept of "concerted mechanism" was developed by *Swain* and *Brown* [2] in connection with studies involving amphoteric catalysts in aprotic solvents.

C. Challis and *F. A. Long* (Ithaca, U.S.A.) investigated the kinetics of the protonation of azulene (a weak base) using flow measurements. After making allowance for the solvent effect and a statistical correction, the results were found to be in complete agreement with the data for the acid-catalysed tritium-exchange of [1-T]-azulene and of substituted azulenes. The protonation of azulene can be analogously postulated to proceed in two steps *via* an A–SE2 mechanism [*]. The rate constants for protonation (k_f) and deprotonation (k_r) were determined independently. At perchloric acid concentrations between 1.5 M and 5 M,

$$k_f = 1.52 \times h_0^{1.26}$$

and $$k_r = 110 \times h_0^{-0.68},$$

where h_0 is *Hammett*'s acidity function. It follows from the temperature dependence of the acidity constant $K_{AzH_2^+}$ of the azulenium cation that $\Delta G^\circ = -2.4$ kcal, $\Delta S^\circ = -11$ cal·deg^{-1}, and $\Delta H^\circ = -5.8$ kcal. The small value of ΔG° indicates that azulene and the azulenium cation are of comparable stability.

On the basis of kinetic and equilibrium measurements, *A. J. Kresge et al.* (Chicago, U.S.A.) have refuted the earlier view [3] that proton exchanges in aromatic systems proceed *via* two basically different routes depending on whether they are catalysed by strong or weak acids. The proton exchange of aromatic systems was studied on [4-T]-1,3-dimethoxybenzene in fairly concentrated acid solutions. For the same value of h_0, proton transfer in sulfuric acid proceeds faster by a factor of 2.5 to 3 than in perchloric acid. The equilibrium concentration of protonated azulene in solutions of H_2SO_4 and $HClO_4$ was determined spectroscopically. When the rate of the reactions

$$HAr + H^+ \rightleftharpoons HArH^+$$

is plotted against the concentration ratio c_{HArH^+}/c_{HAr}, the reaction is seen to proceed 5.5 times as fast in sulfuric acid as in perchloric acid. It follows from the variation of the "excess rate" in sulfuric acid with the stoichiometric composition of the solution that HSO_4^- and H_2SO_4 are present as catalytically active species in addition to H_3O^+.

This demonstrates a general acid-base catalysis for the proton exchange in aromatic systems.

E. Grunwald (Waltham, U.S.A.) reported on the kinetics of proton transfer between various amines and solvents of different dielectric constants, *viz.* water, methanol, t-butanol, and glacial acetic acid. Nuclear magnetic resonance measurements allow the determination of reaction rates, and, occasionally, of the number of participating solvent molecules. In solvents of high dielectric constant, the following reactions involve proton exchange:

Acid dissociation of BH^+

$$BH^+ + ROH \underset{k_{-1}}{\overset{k_{+1}}{\rightleftharpoons}} B + ROH_2^+ \qquad (1)$$

Direct proton transfer from BH^+ to B

$$BH^+ + B \xrightarrow{k_2} B + HB^+ \qquad (2)$$

Proton transfer from BH^+ to B *via* a solvent molecule

$$BH^+ + \underset{R}{\overset{|}{O}}H + B \xrightarrow{k_3} B + \underset{R}{\overset{|}{HO}} + HB^+ \qquad (3)$$

Reactions (1) to (3) were investigated with ammonium, methylammonium and sarcosinium ($H_3C-\overset{\oplus}{N}H_2-CH_2-COOH$) ions in water. In these cases, at least two molecules of water are involved in the acid dissociation. The value obtained for k_{-1} indicates that the reaction is governed by diffusion [this does not apply to $(CH_3)_3PH^\oplus$]. Because of increasing steric hindrance and/or increasing energy of desolvation, k_2 rapidly falls with increasing degree of methylation, whereas k_3 is only slightly dependent on the number of substituents present. The involvement of one molecule of water in Reaction (3) has been confirmed.

The behavior of *p*-toluidinium, trimethylammonium, and phenyldimethylphosphonium ions in methanol has been investigated and the results agree with those obtained in water. The value of k_3 for the reaction of the phenyldimethylphosphonium ion is very much smaller than for the ammonium ions ($k_3 < 10^4$ mole^{-1} sec^{-1}). In t-butanol ($\varepsilon = 12.47$), the ammonium salts are present mostly as ion pairs, and proton transfer proceeds predominantly *via* Reaction (4):

$$BH^+X^- + \underset{t\text{-}Bu}{\overset{|}{O}}H \rightarrow B + H^+X^- + \underset{t\text{-}Bu}{\overset{|}{HO}} \qquad (4)$$

The ratio $k_3(H_2O)/k_4(t\text{-}Bu)$ for the trimethylammonium ion is strongly dependent on the nature of the anion, that for the methylammonium ion hardly so. In the latter, two protons are available for hydrogen bond formation with the solvent, without any inhibition of the reaction. The third proton is engaged in forming an ion pair with the anion, as in the case of the single proton of the trimethylammonium ion.

The proton exchange between aliphatic amines B and glacial acetic acid is a first order reaction with respect to BH^+OAc^-, and takes place according to Equations (5) and (6), the latter being the rate-determining step:

$$BH^+OAc^- \rightleftharpoons B{\cdot}HOAc \qquad (5)$$

$$AcOH^* + B{\cdot}HOAc \xrightarrow{k_H} B{\cdot}{}^*HOAc + AcOH \qquad (6)$$

H. Strehlow (Göttingen) reported that the H_3O^+-catalysed hydration of acetylaldehyde in a solution acidified with HCl is accompanied by a broadening of the NMR signals of both the hydrated and the unhydrated aldehyde species. The rate of the reaction was determined from the width of the lines. In solutions containing up to about 10 mole-% of acetaldehyde, hydration results mainly in $CH_3-CH(OH)_2$, whereas in more concentrated solutions the hemihydrate $(CH_3CHOH)_2O$ is formed increasingly. The first step in both reactions is the protonation of the weakly basic acetaldehyde. The variation in the rate constant with *Hammett*'s acidity function indicates that protonation is the rate-determining step or that its rate is at least comparable with that of hydration. Similar experiments in dimethylsulfoxide/water and acetone/water, lead to an estimated pK_a value of the protonated aldehyde of $-8.5 < pK_a < -7.5$. An amphoteric mechanism involving one or more molecules of water cannot be ruled out.

Regarding the intramolecular proton transfer between the positively charged carbon atom and adjacent positions, *D. M. Brouwer* (Amsterdam, Holland) discussed the kinetic inferences that can be drawn from the NMR spectra of the 2,3-dimethylbutyl cation and of several protonated aromatic systems (*i.e.* the cations of hexamethylbenzene, 1,2,3,4-tetramethylbenzene, 5,8-dimethyltetralin, *o*-dimethoxybenzene, and 1,4-benzodioxane). For the aromatic carbonium ions investigated, the rates of the proton transfer differ by more

[2] *C. G. Swain* and *J. F. Brown*, J. Amer. chem. Soc. *74*, 2534, 2538 (1952).

[*] A–SE2 denotes Aromatic substitution, electrophilic, bimolecular.

[3] *V. Gold*, Proc. chem. Soc. (London) *1961*, 453.

than 10^8, and show no correlation with the basicity of the aromatic systems. The rate of transfer is determined to a large extent by the proportion of the positive charge carried by the acceptor carbon atom. In the transition state, the positive charge remains on the carbon atom and a σ-bond is formed between carbon and hydrogen.

According to *A. H. Weller* (Amsterdam, Holland), the fluorescence spectra of β-naphthol and 3-hydroxypyrene vary according to whether the molecules are present in forms *(1)*, *(2)*, or *(3)*:

$$\underset{(1)}{A^*H + B} \rightleftharpoons \underset{(2)}{A^*H \cdots B} \rightleftharpoons \underset{(3)}{A^{*-} \cdots HB^+}$$

(AH and B are an acid and base, respectively, and the asterisk denotes an excited species). If intermolecular hydrogen bonds are formed, then the close dependence on solvent and temperature indicates that proton transfer is favored by highly polar solvents. Solvent orientation may be rate-determining, particularly at low temperatures. In intramolecular proton transfer, on the other hand, the solvent effect is small and operates in the opposite direction. This behavior is due to intramolecular electron displacement, which can partially compensate for the dipole moment of *(3)*. An upper limit of 0.12 kcal/mole is given for the activation energy of the intramolecular proton transfer.

E. U. Franck (Karlsruhe, Germany) has investigated the conductivity of aqueous solutions of KCl, HCl, and H_2SO_4 between 45 and 220 °C and at pressures of up to 8000 bars. According to *Walden*'s rule, the conductivity of such solutions should vary inversely with viscosity as the pressure increases. However, the decrease in conductivity of KCl solutions is less than expected. This is explained by assuming that the effective radius of the hydrated ions is smaller at higher pressures. The conductivity of HCl solutions decreases still less, and at temperatures below 130 °C even shows an initial increase with pressure. This behavior is due to the anomalous mobility of protons. Dilute solutions of H_2SO_4 show a strongly temperature-dependent increase in conductivity with pressure. In this case, the pressure-dependence of the viscosity of water, the anomalous proton mobility, and the dissociation of the HSO_4^- ion all act in the same direction. The values for the dissociation constant K_2 of HSO_4^- for various temperatures and pressures are given in the Table.

Pressure [bars]	K_2 [10^{-3} mole/l] 45 °C	100 °C	160 °C	190 °C
1	6.840	0.821	0.161	0.086
4000	55.93	10.19	1.97	0.72
8000	79.14	47.59	10.36	4.70

G. J. Hills (Southampton, England) reported on the variation in proton transfer in aqueous solutions with temperature and pressure. The structural orientation of the water molecules can be detected even at pressures in excess of 2500 atm, but decreases rapidly with increasing temperature. Ionic transport is related to this orientation and is more highly pressure-dependent than is the fluidity of water. *Hills* illustrated his lecture with numerous diagrams showing the variation in the equivalent conductivity of HCl with temperature and pressure, and gave some data concerning transport numbers and ionic conductivities. He concluded from these data that proton transfer consists essentially of a charge transfer and of a reorientation of the water molecules, the latter process being rate-determining. The Grotthuss mechanism therefore remains valid despite the hydrogen bond structure of water.

[VB 933/249 IE]

German version: Angew. Chem. 77, 814 (1965)

SELECTED ABSTRACTS

Regularities in the field-ion mass spectra of organic molecules are discussed by *H. D. Beckey* and *G. Wagner* with illustrations from amines containing 2–10 carbon atoms in branched or unbranched chains. In conventional mass spectrometers, the ions are created by bombarding the sample with electrons, but in field-ion mass spectrometry they are formed on thin metal wires or needle points in a strong electric field (10^7–10^8 volts/cm). The most striking phenomenon here is that straight chain amines give rise to ions with mass numbers 29 and 30 ($C_2H_5^{\oplus}$ and $CH_2NH_2^{\oplus}$) as the most frequently recurrent fragments; hence two members are split off of the chain at a time. / Z. Naturforsch. *20a*, 169 (1965) / –Hz. [Rd 309/518 IE]

A new method for resolving D,L-amino acids using stereoselective ligand exchange is described by *K. Harada*. For example, if the complex obtained from L-alanine and copper carbonate is left standing for 30 h with D,L-aspartic acid in aqueous solution, the D-aspartic acid/copper carbonate complex is obtained and can be filtered off and decomposed with H_2S in acidic solution. D-Aspartic acid is thus obtained in 95–100 % optical purity (0.54 g from 2.66 g of D,L-aspartic acid) and completely free from alanine. L-Aspartic acid is obtained analogously using D-alanine. Similar reactions occur between the copper carbonate complexes of L-glutamic acid, D-glutamic acid, and L-proline on the one hand, and D,L-aspartic acid on the other. This stereoselective reaction is also of interest in view of the development of optical activity of amino acids in prebiological systems. spontaneously acquired optical activity of one amino acid could have been transferred *via* metal chelates to other amino acids. / Nature (London) *205*, 590 (1965) / –Ma. [Rd 257/466 IE]

The isolation of some aquo and hydroxochloro complexes of Rh(III), Ir(III), and Pt(IV) has been achieved by *E. Blasius* and *W. Preetz*. In contrast to the current opinion that these elements (Rh, Ir, and Pt) occur essentially as hexachloro complexes in HCl solution, stepwise formation of mixed ligand complexes was now observed. The solutions could be separated into their individual metastable components by high-tension ionophoresis. In this way, $[IrCl_2(H_2O)_4]^{\oplus}$, $[IrCl_3(H_2O)_3]$, $[IrCl_4(H_2O)_2]^{\ominus}$, and $[IrCl_5(H_2O)]^{2\ominus}$, for example, were found. A weak zone close to that of $[IrCl_4(H_2O)_2]^{\ominus}$ is probably due to $[Ir(OH)Cl_3(H_2O)_2]^{\ominus}$. / Z. anorg. allg. Chem. *335*, 1 (1965) / –La. [Rd 341/550 IE]

Free dithioperoxodiphosphoric acid $H_4[O_3PSSPO_3]$ was obtained in a concentration of up to 75% in methanol by *F. Fehér* and *F. Vial* by oxidation of a suspension of potassium dihydrogen monothiophosphate KH_2PO_3S in ether with bromine.

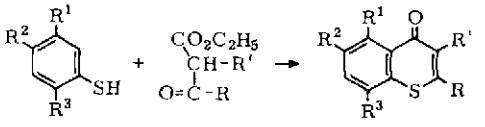
$$2\ H_2O_3PS^{\ominus} + Br_2 \rightleftharpoons (HO)_2(O)PS{-}SP(O)(OH)_2 + 2\ Br^{\ominus}$$

The new compound is a strong acid. The differences in the dissociation constants – particularly for the first two steps – are small. The salt KH_2PO_3S was also described for the first

$$PSCl_3 + 6\ KOH \rightarrow K_3PO_3S + 3\ KCl + 3\ H_2O$$
$$K_3PO_3S + 2\ CH_3COOH \rightarrow KH_2PO_3S + 2\ CH_3COOK$$

time and can be readily obtained by hydrolysis of phosphorus thiochloride with KOH and subsequent acidification with acetic acid. / Z. anorg. allg. Chem. *335*, 113 (1965) / –La. [Rd 342/551 IE]

A new synthesis of 1-thiochromones is described by *F. Bossert*. 1-Thiochromones *(1)* could be prepared hitherto only with difficulty and in yields of less than 20 % from *(2)* and *(3)*. However, they can now be obtained easily and in good yields

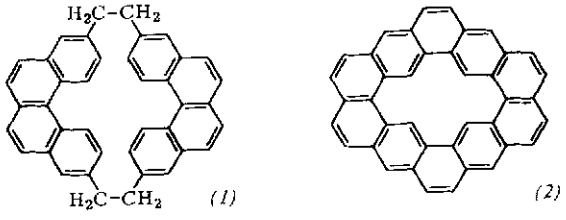


(2) *(3)* *(1)*

R	R'	R^1	R^2	R^3	M.p. [°C]
CH_3	H	H	H	H	105
CH_3	H	NH_2	H	Cl	179–180
CO_2H	H	H	Cl	H	253
γ-Pyridyl	H	H	Cl	H	207
C_6H_5	H	H	H	NH_2	139–140
$-(CH_2)_3-$		H	H	OCH_3	131

by condensation of thiophenols *(2)* and β-keto esters *(3)* by brief warming with polyphosphoric acid. / Liebigs Ann. Chem. *680*, 40 (1965) / –Ma. [Rd 260/469 IE]

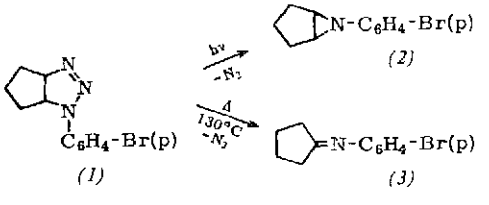
A cyclic hydrocarbon of the benzo[*c*]phenanthrene series *(1)* was synthesized by *R. Peter* and *W. Jenny* during attempts to build up cyclic *kata*-condensed hydrocarbons with a "hollow" in the middle, *e.g. (2)*. Starting from diethyl bis-*p*-tolylmethylmalonate, 3,10-bisbromomethylbenzo[*c*]phenanthrene was prepared *via* a number of steps and then converted with phenyl-lithium into *(1)* in 10 % yield. Bis-(3,10-dimethylene-



(1) *(2)*

henzo[*c*]phenanthrene) *(1)*, $C_{40}H_{28}$, m.p. 400 °C, exhibits a blue fluorescence in the solid state and can probably be aromatized to give *(2)*. / Chimia *19*, 45 (1965) / –Ma. [Rd 252/461 IE]

Aziridines were obtained by photolysis of 1,2,3-triazolines by *P. Scheiner*, nitrogen being eliminated smoothly and quantitatively. Thermal elimination of the nitrogen, on the other hand, leads to the isomeric anilines or to mixtures of both isomers. For example, the triazoline *(1)*, m.p. 122 °C, affords 59 % of the aziridine *(2)*, m.p. 73–74 °C, by the photochemical reaction or 67 % of the anil *(3)*, b.p. 110 to 111 °C/0.4 mm, by thermolysis; *(3)* is not formed by thermal rearrangement from *(2)*, for the latter is completely stable under the conditions of the pyrolysis (130 °C).



(1) *(2)* *(3)*

In practice, 0.08–0.60 M solutions of the triazolines in inert solvents such as acetone, toluene, or dioxane are irradiated with ultraviolet light until the evolution of nitrogen ceases, the temperature being maintained below 35 °C. 1,2,3-Triazolines are easy to prepare, *e.g.* by 1,3-dipolar addition of diazomethane onto anils. / J. org. Chemistry *30*, 7 (1965) / –Bi. [Rd 301/510 IE]

The mode of action of penicillin was investigated by *U. Schwarz* and *W. Weidel* with *Escherichia coli* B. It is known that penicillin inhibits the synthesis of mureine – the polymer that occurs in the cell walls of almost all species of bacteria and which encloses the bacterial cell as a rigid sac. The cell walls of bacteria that are sensitive towards penicillin are burst by it. Materials identified among the degradation products formed from mureine were oligosaccharides containing 2,6-diaminopimelic acid and parts of the muropeptide side chains and their enzymatic degradation products. The penicillin spheroplasts from *E. coli*. contain uridine phosphate-muramyl peptides, which can be regarded as precursors of mureine. It could be shown with [^{14}C]diaminopimelic acid that this amino acid is liberated in the form of oligopeptides under the influence of penicillin both from mureine itself and from its precursors. Penicillin upsets the balance of the enzymes which synthesize and degrade mureine – partial dissolution of the rigid cell sac is necessary for the cell to grow – so that the bacteria are destroyed by their own enzymes. / Z. Naturforschg. *20b*, 147, 153 (1965) / –De. [Rd 294/503 IE]

A "living" polymer was prepared from tetrahydrofuran by *M. P. Dreyfuss* and *P. Dreyfuss* by cationic initiation. Tetrahydrofuran reacts at 25 °C with benzenediazonium hexafluorophosphate $C_6H_5N_2PF_6$ to give a polymer which remains "living". Log [η] varies in a linear manner characteristic for living polymers with log [$C_6H_5N_2PF_6$]. The limited solubility of the initiator in tetrahydrofuran sets a lower limit to the molecular weight of the living polymer. The chain initiation is due either to a phenylcarbonium ion according to Equation (a)

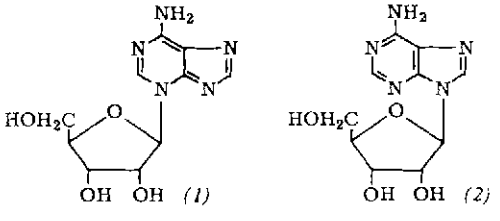
$$C_6H_5N_2^{\oplus}PF_6^{\ominus} \rightarrow C_6H_5^{\oplus} + N_2 + PF_6^{\ominus} \qquad (a)$$

or to phosphorus pentafluoride according to Equation (b).

$$C_6H_5N_2^{\oplus}PF_6^{\ominus} \rightarrow C_6H_5F + N_2 + PF_5 \qquad (b)$$

/ Polymer *6*, 93 (1965) / –Hl. [Rd 295/504 IE]

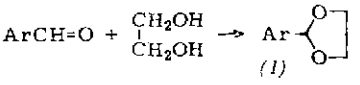
3-Isoadenosine derivatives were synthesized by *N. J. Leonard* and *R. A. Laursen*. Starting from P^1-diphenyl-P^2-[(3-β-D-ribofuranosyladenine)-5']-pyrophosphate, the isoanalogues of adenosine monophosphate (AMP), adenosine diphosphate (ADP), adenosine triphosphate (ATP), and nicotinamide adenine dinucleotide (NAD) were prepared.

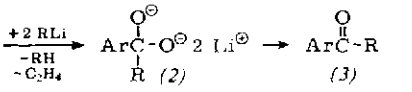


(1) *(2)*

It was investigated whether the derivatives of isoadenosine *(1)* could replace derivatives of natural adenosine *(2)* in biological reactions. Myokinase (adenylic kinase) converts iso-ATP and iso-AMP into iso-ADP. Hexokinase phosphorylates glucose about half as fast with iso-ATP as with ATP to give glucose-6-phosphate. Dehydrogenases reduce iso-NAD at various rates depending on the enzyme concerned. The alcohol dehydrogenase from horse liver reacts with iso-NAD faster (relative rate 140) than with NAD (100), but the alcohol dehydrogenase from yeast reacts much more slowly (6). Assays of iso-ATP with luciferase leads to lower yields than with ATP. Iso-ADP is polymerized by the polynucleotide phosphorylase from *Azotobacter vinelandii* to the corresponding polynucleotide. / Biochemistry *4*, 365 (1965) / –Hö. [Rd 307/516 IE]

The conversion of aromatic aldehydes into alkyl aryl ketones has been achieved by *K. D. Berlin, B. S. Rathore*, and *M. Peterson*. When the 1,3-dioxolanes *(1)* obtained from the aldehydes by condensation with ethylene glycol are treated at 60 °C under nitrogen with an excess of alkyl-lithium (molar ratio about 1:3) in cyclohexane/ether, the ketone derivatives *(2)* are obtained *via* several intermediates;

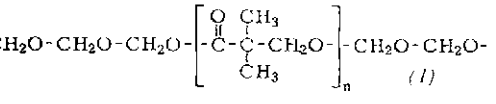




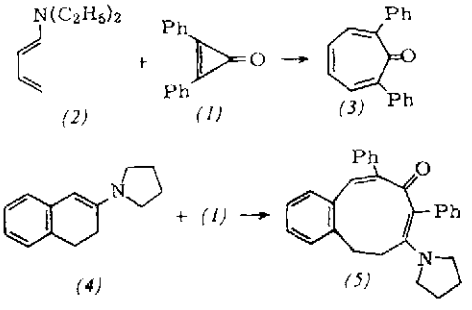
(a) Ar = C_6H_5, R = C_4H_9 (87,5%)
(b) Ar = p-$CH_3C_6H_4$, R = C_6H_{11} (66,5%)
(c) Ar = p-$CH_3OC_6H_4$, R = C_4H_9 (78%)
(d) Ar = p-$CH_3C_6H_4$, R = C_4H_9 (80%)

hydrolysis of *(2)* affords the ketones *(3)* in yields of 66.5 to 80 %, together with equivalent amounts of alkane and ethylene. / J. org. Chemistry *30*, 226 (1965) / –Bi. [Rd 300/509 IE]

A new thermostable copolymer of formaldehyde *(1)* is described by *G. Natta, G. F. Pregaglia, G. Mazzanti, V. Zamboni*, and *M. Binaghi*. It is produced by copolymerization of HCHO with dimethylketene catalysed by tertiary amines. The amount of dimethylketene incorporated depends largely upon the polymerization temperature: 80 % is built in at 0 °C and progressively lesser amounts at higher temperatures, where side reactions also occur. By varying the reaction conditions, copolymers with irregular monomer sequences, block copolymers, or copolymers with alternating structures can be produced. The softening points depend on the composition: 168–174 °C for a polymer with little dimethylketene and 150–155 °C for one containing 10 % dimethylketene. The rate of decomposition at temperatures above 220 °C lies between that of the acetylated homopolymer and that of the trioxane copolymer, which is more stable than *(1)*. / European Polymer J. *1*, 25 (1965) / –Hl. [Rd 323/532 IE]



A cycloaddition of diphenylcyclopropenone onto aminoalkenes has been observed by *J. Ciabattoni* and *G. A. Berchtold*. 1-Diethylamino-1,3-butadiene *(2)* and diphenylcyclopropenone *(1)* react in refluxing benzene to form 2,7-diphenyltropone *(3)* as yellow platelets, m.p. 132–133 °C, in 68 % yield. Similarly, *(1)* and 2-(*N*-pyrrolidino)-3,4-dihydronaphthalene *(4)* afford 2,9-diphenyl-8-(*N*-pyrrolidino)benzo[*d*]cyclonona-2,4,8-trien-1-one *(5)*, m.p. 136–137 °C, in 62 % yield. The reaction involves 1,2- and 1,4-additions, but it is still unknown



whether its mechanism is a one-step cycloaddition or a Michael addition with subsequent cyclization. / J. Amer. chem. Soc. *87*, 1404 (1965) / –Ma. [Rd 331/540 IE]

BOOK REVIEWS

Carbene Chemistry. By *W. Kirmse*, in collaboration with *H. M. Frey, P. P. Gaspar*, and *G. S. Hammond*. Organic Chemistry, a Series of Monographs, edited by *A. T. Blomquist*. Academic Press, New-York-London 1964. 1st edit., VIII + 302 pp., numerous tables, several illustrs., linen $ 9.50.

Prolific developments have taken place in the field of carbene chemistry over the past ten years. Hundreds of publications have appeared, and anyone not working in this field could hardly have read even only the most important of these. The appearance of this monograph – incidentally the first in the series "Organic Chemistry" edited by *A. T. Blomquist* – is therefore highly welcome.

The book deals mainly with the reactions of carbenes and their mechanistic aspects. Following a short introduction, there are nine short but pregnant chapters of the nature of review articles which give a practically flawless survey of the preparation, reactivities, and preparative applications of all the carbenes known to date. There is a carefully compiled bibliography covering literature sometimes until the start of 1964. A welcome feature of the book is that topics on the fringe of carbene chemistry are also dealt with, *e.g.* the synthesis of diazirines or the preparatively important compounds chloromethylzinc and iodomethylzinc, which although not true carbenes, behave as if they were.

Two chapters by competent authors examine theoretical aspects of the subject. In one, *H. M. Frey* relates why it must be assumed that methylene made by photolysis or thermolysis from diazomethane or ketene has excess translational and/or vibrational energy. In the other, *P. P. Gaspar* and *G. S. Hammond* discuss the spin state of carbenes. Here, among other things, the chemist is carefully shown the pitfalls into which he can stumble if he attempts to deduce the electronic state of a carbene from its chemical reactions.

The reviewer found this book a pleasure to read. Since he is convinced that any other scientist interested in the chemistry of short-lived intermediates will enjoy the same experience, he can recommend the book most highly. It is unfortunate that monographs on modern trends become outdated rather rapidly. It would therefore be a commendable undertaking for the author and publisher to produce a translation into German of the work with inclusion of any new material that has appeared.

U. Schöllkopf [NB 394/252 IE]

Handbook of Chemistry and Physics. Edited by *C. D. Hodgman, R. C. Weast*, and *S. M. Selby*. A Ready-Reference Book of Chemical and Physical Data. The Chemical Rubber Company, Cleveland, Ohio, U.S.A., 1964. 45th edit., XXI + 1472 pp., imitation leather, about $ 15.–.

The fact that a reference book has appeared in 45 editions in 45 years is an outstanding proof of its quality, which cannot be diminished or augmented by any review. However, the 45th edition of the "Handbook of Chemistry and Physics" has undergone so many changes in comparison with its predecessors that some appraisal seems justified.

The format of the book has been doubled; this agreeable feature makes the volume handier and easier to peruse.

The sections of the book of greatest interest to chemists have been reorganized. There is a section on "Elements and Inorganic Compounds", another on "Organic Compounds", and a section with data which are of general interest to chemists, including for example, a list of over seven hundred azeotropic mixtures (new), dissociation constants, specific heats and enthalpies of some metals at low temperatures (new), vapor pressures of organic and inorganic compounds, *etc.*

The table of the "Physical Constants of Organic Compounds" (525 pp.) is the most extensive. Here data are listed for over 13500 substances, separate columns being devoted for each to the name, formula, synonyms, molecular weight, crystal form, color and specific rotation, melting point, boiling point, density, index of refraction, solubility in water, alcohol, ether, acetone, benzene, and other solvents, and a literature reference. This table has been extended by about 5000 entries in this edition, and is probably the largest of its kind anywhere.

It would take too long to characterize the variety and abundance of the other tables of chemical, physical, and mathematical content in turn. However, it may be mentioned here that a newly revised table of all known stable and radioactive isotopes is given, that the physical properties of inorganic compounds are given as fully as those of organic substances, and that a short portion of text is devoted to each element – an unusual feature for a handbook – describing its properties, discovery, occurrence, and chemical behavior. The reviewer would find it hard to pose a question within the scope of this book which it would fail to answer.

A few items could be improved in later editions. The table on buffers is too short and does not do justice to the importance of these solutions – especially in biochemistry. The section on the nomenclature of organic compounds contains the IUPAC rules of 1957 and a list of carbocyclic and heterocyclic rings. The reviewer considers this to be insufficient, even though the long table on the physical properties of organic compounds that follows alleviates this situation a little by giving examples. It might be worthwhile to include a short introduction to the nomenclature of functional organic compounds and derivatives. The structural formulae in the large table (particularly on p. C-75) are neither attractive nor clear; in the formula of coniferyl alcohol on p. C-259, the positions of OCH_3 and OH have been interchanged; sometimes, *e.g.* with steroids, one has difficulty in recognizing the compounds portrayed. Here there is definitely room for improvement; the structural formulae should be set by a printer who has the necessary type available. Uniform use of the designations D, L, d, l, (–), and (+) would also be preferred. *H. Grünewald* [NB 395/253 IE]

Organic Experiments. By *L. F. Fieser.* D. S. Heath and Co., Boston 1964. 1st edit., 325 pp., numerous figs., linen about $ 7.00.

The main aim of this new book by *Louis F. Fieser* is the experimental training of students.

Practical experiments, described in every detail, form the mainstay of the book. In addition, particular emphasis is placed upon the identification and characterization of the compounds prepared using chemical and physicochemical methods. Less attention is intentionally paid to reaction mechanisms.

The book starts with descriptions of the equipment required for preparative work in organic chemistry. This is followed by an introduction to elementary practical techniques such as the handling of wash bottles, filter flasks, suction filters, and burners, distillation, crystallization, extraction, *etc.* Even during this introduction to practical techniques exercises are given, *e.g.* the isolation of citral from lemon grass oil during the discussion of steam distillation. In the course of the practical preparations that follow, any new apparatus or methods that are required for the synthesis or separation of the compounds to be made are described separately (*e.g.* chromatography).

There are no old-fashioned, hackneyed procedures, *e.g.* that for the preparation of bromobenzene, included among the selection of examples and instructions given; instead, interesting preparative work applying the most modern methods is described. For example, directions are given for the synthesis of diacetylene, on how to reduce double bonds with $NaBH_4$ or HCl/Pt, for the preparation of hydrazobenzene from azobenzene with diimine, the addition of dichlorocarbene onto *cis,cis*-1,5-cyclooctadiene, the synthesis of tropylium bromide, and the production of trypticene *via* dehydrobenzene. Even an enzymatic reaction has been incorporated, *viz.* the isolation of L-alanine from the racemate of the acetyl derivative, as well as analysis of peptides by chromatography.

In order to introduce the student to the applications of spectroscopic methods, there is a chapter on 1,2-diphenylethane derivatives, which skilfully and instructively combines preparative and spectroscopic methods.

An interesting feature is a chapter on the calculation of costs, for the attention of the student should occasionally be called to such matters too.

The subject matter in each individual chapter is presented with extraordinary clarity; on the margins there are keywords and suggestions and even warnings whenever a reaction could become dangerous. Practical exercises are added at the ends of some chapters. It must be said that every chapter is a success. However, there is no continuous didactic development from chapter to chapter such as is normally encountered in practical textbooks of organic chemistry. It is therefore up to demonstrator or supervisor – who will himself find many instructive exercises in the book – to select a series of preparations to be carried out by the student.

Fieser's "Organic Experiments" should definitely be present in every organic undergraduate laboratory.

H.-J. Bestmann [NB 407/265 IE]

Physikalische Chemie (Physical Chemistry). By *Klaus Schäfer.* Ein Vorlesungskurs (A Lecture Course). Springer-Verlag, Berlin-Göttingen-Heidelberg-New York 1964. 2nd improved and extended edition, XII + 432 pp., 81 figs., linen DM 36.– (about $ 9.00).

The alterations introduced in this new edition of *Schäfer*'s book [*] affect mainly the chapter on the structure of matter, which has been extended and modernized.

The book is divided up as follows: I. States of aggregation and their equations of state (46 pp.); II. Energy content of matter (55 pp.); III. Chemical and thermodynamic equilibria (91 pp.); IV. Electrochemistry (49 pp.); V. Chemical kinetics (21 pp.); and VI. The structure of matter (148 pp.). The book closes with two tables and a subject index. There is no need for an author index since there is only one reference given in the whole book.

In its structure and organization, the book is closely allied to the textbooks by *Eucken*, to which *Schäfer* did of course make many contributions. However, a novel feature of this work is the detailed treatment given to the fundamentals of quantum mechanics and to the theory of the chemical bond. Here the discussion goes into the most recent developments, whereas thermodynamics and electrochemistry, for instance, are dealt with in the conventional way. Kinetics receives only brief treatment on 21 pages, and interfacial phenomena are only briefly touched upon.

The presentation and appearance of the book are attractive.

R. Haase [NB 389/247 IE]

[*] Cf. Chemie-Ing.-Techn. *24*, 471 (1952).

Vanadium. Toxicology and Biological Significance. By *T. G. Faulkner-Hudson*. Elsevier Monographs on Toxic Agents. Edited by *E. Browning*. Elsevier Publishing Co., Amsterdam-London-New York 1964. 1st edit., X + 140 pp., 11 figs., 6 tables, linen DM 19.50 (about $ 3.90).

This small work by a medical advisor in the British vanadium-processing industry will be greeted by all engaged with the functions of vanadium as a trace element or with vanadium poisoning. Topics dealt with include 1. the occurrence in soils, plants, animals, and humans; 2. all the effects of V known so far on metabolism processes (sulfur, cholesterol, lipid, and calcium metabolism, serotonin oxidation, and hemopoesis); 3. questions of vanadium resorption, distribution in the organism, and excretion; 4. experimental production of vanadium poisoning, toxicity phenomena observed in industry, and the pertinent therapy and precautions. Descriptions which go beyond the limits suggested by the title of the book are given of the mineral sources and industrial extraction of the metal and of its compounds and their technical uses. Tables are also given of the world production and export figures for various countries. On the other hand, the chemical properties of vanadium, *e.g.* its great tendency to form complexes, which are undoubtedly important for its biological effects, receive insufficient attention. Although all details cannot be included in view of the broad spectrum of aspects considered, brevity can be no excuse for impreciseness. In addition to incorrect structural formulae (*e.g.* coenzyme A, lipothiamide, p. 25), the work of *Lynen* and *Bloch* is overlooked in the section on the biosynthesis of isoprenoids, a C_5 intermediate of unknown structure in the isoprene series appears as a metabolite of mevalonic acid, *etc.* The latest publications on the specificity of the vanadium uptake by marine invertebrates (tunicates) are not mentioned, although the situation here is probably interesting as a model for that in vertebrates as well. Otherwise the literature is evaluated until 1961. The book can be recommended only to critical readers, but offers these many incentives.

H.-J. Bielig and *W. Rüdiger* [NB 366/224 IE]

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On the Analysis of Photosynthesis by Flashlight Techniques [*]

BY H. T. WITT, B. RUMBERG, P. SCHMIDT-MENDE, U. SIGGEL, B. SKERRA, J. VATER, AND J. WEIKARD

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Direct information regarding the primary process in photosynthesis is obtained by measurement of the very short-lived primary and intermediate products with the aid of (1) flash photometry, (2) periodic flash photometry, and (3) flash manometry. The analysis of the primary process using these methods on normal plant cells and chloroplasts and on those which have been chemically or physically modified has led to the formulation of a reaction scheme for the transport of electrons in photosynthesis.

I. Survey [**]

1. Overall Process

Of all the reactions that take place on earth, photosynthesis in green plant cells is the most frequent. When the plants are exposed to light, sugar and other energy-rich substances are synthesized from CO_2 and H_2O. The reaction path from CO_2 to sugar (the Calvin cycle) is well known [5]. However, detailed ideas regarding the primary processes that provide the driving force for this reaction have only recently been obtained, and this is the subject of the present paper.

2. Cleavage of Water

The primary processes take place in highly organized cell components known as the chloroplasts, and consist in the conversion of electromagnetic energy into chemical free energy. Thus water is broken down by the energy of visible light into hydrogen and oxygen [6]. The oxygen escapes into the atmosphere, while the hydrogen is transferred to triphosphopyridine nucleotide (TPN) [***] [7]. *Hill* [8] found that the cleavage of water also occurs in isolated chloroplasts suspended in water, if artificial hydrogen acceptors such as potassium hexacyanoferrate(III) are added instead of the natural acceptor, TPN.

3. Phosphorylation

According to *Arnon et al.* [9], the cleavage of water in the primary process is accompanied by the synthesis of the energy-rich ATP from ADP and phosphate. TPNH and ATP then reduce CO_2 to sugar in dark reactions.

[*] From a lecture delivered to the General Meeting of the Gesellschaft Deutscher Chemiker in Heidelberg on September 10, 1963, and to the 63rd Annual Meeting of the Deutsche Bunsen-Gesellschaft für Physikalische Chemie in Berlin on May 8, 1964.

[**] This survey gives only the results that are essential to an understanding of what follows. For general reviews on the primary process in photosynthesis, see *e.g.* [1–4].

[1] *M. D. Kamen*, Primary Processes in Photosynthesis. Academic Press, New York, London 1963.

[2] *J. A. Bassham*, in *F. F. Nord*: Advances in Enzymology. Interscience, New York 1963, Vol. 25, p. 39.

[3] *G. W. Robinson*, Annual Rev. physic. Chem. *15*, 311 (1964).

[4] *A. Trebst*, Ber. dtsch. botan. Ges. *77*, 123 (1964).

[5] *M. Calvin*, Angew. Chem. *74*, 165 (1962).

[6] *S. Ruben, M. Randall, M. D. Kamen*, and *J. L. Hyde*, J. Amer. chem. Soc. *63*, 877 (1941).

[***] The following abbreviations are used: ADP = adenosine diphosphate; ATP = adenosine triphosphate; Asc = ascorbate; Chl = chlorophyll; CMU = *N*-*p*-chlorophenyl-*N'*-dimethylurea; Cyt = cytochrome; DPIP = 2,6-dichlorophenolindophenol (2,6-dichloroquinone-4-*p*-hydroxyanil); Fd = ferredoxin; PMS = N-methylphenazonium methyl sulfate; Q = plastoquinone; TPN = triphosphopyridinenucleotide (=NADP); TPNH = reduced triphosphopyridinenucleotide (=$NADPH_2$).

[7] *W. Vishniac* and *S. Ochoa*, Nature (London) *167*, 768 (1951); *L. J. Tolmach*, ibid. *167*, 946 (1951); *D. I. Arnon*, ibid. *167*, 1008 (1951); *A. San Pietro* and *H. M. Lang*, Science (Washington) *124*, 118 (1956).

[8] *R. Hill*, Proc. Roy. Soc. (London), Ser. B *127*, 192 (1939).

[9] *D. I. Arnon, M. B. Allen*, and *F. R. Whatley*, Nature (London) *174*, 394 (1954); Science (Washington) *127*, 1026 (1958); *A. W. Frenkel*, J. Amer. chem. Soc. *76*, 3568 (1954).

4. The Structure of Chloroplasts

The fact that photosynthesis occurs is due to the special arrangement of the molecules in the chloroplasts. The structure and composition of chloroplasts has therefore been studied in detail [10]. They were found to contain, *inter alia*, cytochrome-f and cytochrome-b [11], plastoquinone [12], ferredoxin [13], flavin [14], manganese [15], and plastocyanine [15a].

5. Active Chlorophyll and Energy Transfer

Rather surprisingly, only about 0.1 % of the total chlorophyll is photochemically active [16]. The remaining 99.9 %, as well as the carotenoids present in the chloroplasts, are so arranged that the light, which they absorb, is led to the active chlorophyll molecules by energy migration [17].

6. Quantum Yield

The values found for the quantum yield are between 3 [18] and 12 quanta per molecule of oxygen formed. The most probable value is 8 to 10 quanta [19].

7. Participation of Two Pigment Systems

Emerson et al. [20–23] studied the oxygen yield as a function of the wavelength of the light, and concluded that probably two pigment systems are involved in the primary processes. The same conclusion was reached later on the basis of fluorescence measurements [24]. Various theories were advanced to explain the Emerson phenomenon [25,26], but no experimental interpretation was at first possible.

In recent years, methods have been developed which permit the direct observation of the primary processes in the chloroplasts (fluorescence [24], phosphorescence [27], electron resonance [28], and absorption measurements). A technique which has proved very succesful is the measurement of absorption changes using static (continous light) [29,30] or dynamic (flashlight) [31,32] methods.

8. Two Coupled Photochemical Reactions

Thus *Kok* [33], *Duysens* [34], and *Witt et al.* [35–37] first showed directly by measurements of absorption changes that two pigment systems with two coupled photochemical reactions take part in the primary processes (Section VII). This conclusion was also reached indirectly on the basis of biochemical studies [38].

9. Primary and Intermediate Products

By means of static measurements of absorption changes, and above all by dynamic measurements using flashlight excitation, nine primary and intermediate products of photosynthesis were identified (Section III).

10. Reaction Scheme

It has been possible, using flashlight methods, to determine some properties of the primary and intermediate products, the order in which they occur, and the kinetics of the reactions. On the basis of these results, a reaction scheme has been formulated, which describes in detail the formation of TPNH, ATP, and O_2 (Section XIII).

[10] *W. Menke*, Annual Rev. Plant Physiol. *13*, 27 (1962).

[11] *R. Hill* and *R. Scarisbrick*, New Phytologist *50*, 98 (1951).

[12] *R. L. Lester* and *F. L. Crane*, J. biol. Chemistry *234*, 2169 (1959).

[13] a) *A. San Pietro* and *H. M. Lang*, Science (Washington) *124*, 118 (1956); b) *H. E. Davenport* and *R. Hill*, Proc. Roy. Soc. (London) Ser. B *139*, 346 (1952); c) *K. Tagawa* and *D. I. Arnon*, Nature (London) *195*, 537 (1962).

[14] *D. L. Keister*, *A. San Pietro*, and *F. E. Stolzenbach*, Arch. Biochem. Biophysics *98*, 235 (1962); *M. Shin*, *K. Tagawa*, and *D. I. Arnon*, Biochem. Z. *338*, 84 (1963).

[15] *E. Kessler*, Planta *49*, 435 (1957).

[15a] *S. Katho*, Nature (London) *186*, 533 (1960).

[16] *R. Emerson* and *W. Arnold*, J. gen. Physiol. *16*, 191 (1932).

[17] *H. Gaffron* and *K. Wohl*, Naturwissenschaften *24*, 81 (1936); *H. J. Dutton*, *W. M. Manning*, and *B. M. Duggar*, J. physic. Chem. *47*, 308 (1943); *Th. Förster*, Z. Naturforsch. *2b*, 174; (1947); *C. S. French* and *V. K. Young*, J. gen. Physiol. *35*, 873 (1952); *L. N. M. Duysens*, Thesis, Utrecht 1952.

[18] *O. Warburg* and *G. Krippahl*, Z. Naturforsch. *13b*, 509 (1958).

[19] *B. Kok*: Handbuch der Pflanzenphysiologie. Springer, Berlin 1960, Vol. 5, p. 566.

[20] *R. Emerson*, Annual Rev. Plant Physiol. *9*, 1 (1958); *R. Emerson*, *R. Chalmers*, *C. Cederstrand*, and *M. Brody*, Science (Washington) *123*, 673 (1956); *R. Emerson*, *R. Chalmers*, and *C. Cederstrand*, Proc. nat. Acad. Sci. U.S.A. *43*, 133 (1957).

[21] *L. R. Blinks*, Plant Physiol. *34*, 200 (1959); Proc. nat. Acad. Sci. U.S.A. *46*, 327 (1960).

[22] *J. Myers* and *C. S. French*, J. gen. Physiol. *43*, 723 (1960).

[23] *R. Govindjee*, *J. B. Thomas*, and *E. Rabinowitch*, Science (Washington) *132*, 421 (1960); *R. Govindjee* and *E. Rabinowitch*, ibid. *132*, 355 (1960); Biophysic. J. *1*, 73 (1960); *2*, 377 (1961).

[24] *H. Kautsky*, *W. Appel*, and *H. Amann*, Biochem. Z. *332*, 277 (1960).

[25] *J. Franck*, Proc. nat. Acad. Sci. USA *44*, 941 (1958).

[26] *R. Hill* and *F. Bendall*, Nature (London) *186*, 136 (1960).

[27] *B. L. Strehler* and *W. Arnold*, J. gen. Physiol. *34*, 809 (1952).

[28] *B. Commoner*, *J. Heise*, and *J. Townsend*, Proc. nat. Acad. Sci. USA *42*, 710 (1956); *M. Calvin*. J. theoretical Biol. *1*, 258 (1961).

[29] *L. N. M. Duysens*, Thesis, Utrecht 1952.

[30] *B. Chance*, J. biol. Chemistry *202*, 383 (1953).

[31] *H. T. Witt*, Naturwissenschaften *42*, 72 (1955); Z. Elektrochem. *59*, 981 (1955); *H. T. Witt*, *R. Moraw*, and *A. Müller*, Z. physikal. Chem., N.F. *20*, 193 (1959).

[32] *H. Rüppel*, *V. Bültemann*, and *H. T. Witt*, Ber. Bunsenges. physikal. Chem. *68*, 340 (1964); *66*, 760 (1962); *H. Rüppel*, Doctorate Dissertation, Universitat Marburg, 1962; *H. T. Witt*, Ber. Bunsenges. physikal. Chem. *64*, 87 (1960).

[33] *B. Kok* and *G. Hoch*, in: *W. D. McElroy* and *B. Glass*: Light and Life. The Johns Hopkins Press, Baltimore 1961, p. 397.

[34] *L. N. M. Duysens*, *J. Amesz*, and *B. M. Kamp*, Nature (London) *190*, 510 (1961).

[35] *H. T. Witt*, *A. Müller*, and *B. Rumberg*, Nature (London) *191*, 194 (1961).

[36] *H. T. Witt*, *A. Müller*, and *B. Rumberg*, Angew. Chem. *73*, 507 (1961).

[37] *H. T. Witt*, *A. Müller*, and *B. Rumberg*, Nature (London) *192*, 967 (1961).

[38] *M. Losada*, *F. R. Whatley*, and *D. I. Arnon*, Nature (London) *190*, 606 (1961).

II. Flashlight Methods

The direct analysis of the primary processes in photosynthesis requires the use of fast and extremely sensitive techniques, since only 0.1 % of all the chlorophyll molecules are photochemically active, and since the half-lives of the reaction steps are only of the order of $< 10^{-5}$ to 10^{-1} sec.

1. Flash Photometry

This method, which was developed by *Porter* and *Norrish* [39] for inorganic reactions, was first introduced for the study of photosynthesis in 1955 [31]. The highly sensitive apparatus specially developed for this work can record processes lasting from 10^{-5} to 10 sec. Transmission changes of 0.1 % can be recorded in 10^{-5} sec, and the sensitivity is correspondingly greater in the case of slower processes (*e.g.* transmission changes of 0.01 % in 10^{-3} sec). The sensitivity of the measurements increases with the intensity of the measuring light, but the latter must be limited so that the photochemical reaction caused by it is negligible. The intensities used were between about 4 and 200 erg cm^{-2} sec^{-1}, depending on the duration of the processes to be recorded (between 10^{-1} and 10^{-5} sec). The optical bandwidth of the measuring light was 3 mμ (grating, prism) or 10 mμ (interference filter).

2. Periodic Flash Photometry

The technique of periodic relaxation was proposed and developed in 1960 for the study of fast chemical reactions [32]. One such measuring technique is periodic flash photometry [32, 40], which can be used to analyse processes lasting from 10^{-6} to 1 sec. The sensitivity is more than 100 times greater than that of flash photometry: in 10^{-6} sec it is possible to record transmission changes of 10^{-3} %. The time resolution of this method depends only on the duration of the flash.

Whereas in flash photometry the entire sequence of absorption changes following a flash is recorded, only one absorption change at a definite instant (between t and t + Δt) is recorded in the periodic technique, and this measurement can be repeated many times by periodic excitation. Since the accuracy of the measurement increases with the square root of the number of measurements, the absorption change at a given time can be found with very great accuracy. The absorption change at another instant is then measured, and so on until the entire sequence of absorption changes with time has been covered. All operations are carried out electronically and automatically.

3. Flash Manometry

With the aid of flash manometry, which was introduced by *Emerson et al.* [16] in 1932, it is possible to scan reaction steps in photosynthesis indirectly. This technique involves the manometric measurement of the quantity of oxygen formed per flash as a function of the flash frequency. We have used this method under different experimental conditions [41] to obtain information about the kinetics of the cleavage of water (see Section X). The measuring range extends to processes lasting between 10^{-4} and 1 sec.

The efficiencies of the flashlight methods in comparison with other measuring techniques are shown diagrammatically in Fig. 1.

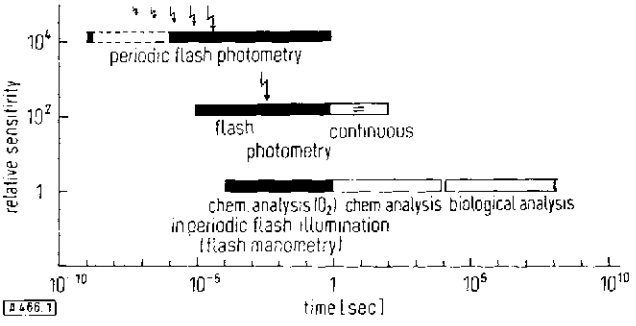


Fig. 1. Sensitivity and time resolution of various methods used in the investigation of photosynthesis.

III. Absorption Changes during Photosynthesis in Green Plant Cells

Using a static method, *Duysens* has demonstrated the participation of a cytochrome in photosynthesis in red algae. He also has observed absorption changes at about 420, 475, and 520 mμ in green cells, but these were not identified [42]. *Kok* [43] discovered absorption changes at about 700 mμ in various plant cells and in chloroplasts, due to the oxidation of a pigment P 700.

With the aid of flashlight methods, we have observed short-lived absorption changes (all lasting less than about 10^{-1} sec at 20 °C) between 240 and 800 mμ in normal green cells *(Chlorella)* and in fully active chloroplasts (spinach). By varying the external parameters and by chemically or physically altering the cell processes, we were able to separate the absorption changes into different types, and to analyse the reactions associated with these types:

1. Formation of the derivate of a particular chlorophyll-a molecule, Chl-a_1-430-520 (Fig. 2b) [44, 45].

2. Oxidation of a particular chlorophyll-a molecule, Chl-a_1-430-703, established by absorption changes at 430 mμ, which are accurately coupled with those of the pigment P 700 at 703 mμ (Fig. 2c) [46–48].

[39] *R. G. W. Norrish* and *G. Porter*, Nature (London) *164*, 658 (1949).

[40] *H. Rüppel, V. Bültemann*, and *H. T. Witt*, Ber. Bunsenges. physikal. Chem. *68*, 752 (1964).

[41] *V. Bültemann, H. Rüppel*, and *H. T. Witt*, Nature (London) *204*, 646 (1964).

[42] *N. M. Duysens*, Nature (London) *173*, 692 (1954).

[43] *B. Kok* and *W. Gott*, Plant Physiol. *35*, 802 (1960); *B. Kok*, Acta bot. neerl. *6*, 316 (1957).

[44] *R. Moraw* and *H. T. Witt*, Z. physikal. Chem., N.F. *29*, 1 (1961).

[45] *G. Zieger, A. Müller*, and *H. T. Witt*, Z. physikal. Chem., N.F. *29*, 13 (1961).

[46] *H. T. Witt, A. Müller*, and *B. Rumberg*, Nature (London) *192*, 967 (1961).

[47] *B. Rumberg* and *H. T. Witt*, Z. Naturforsch. *19b*, 693 (1964).

[48] *B. Rumberg*, Z. Naturforsch. *19b*, 707 (1964).

3. Reaction of a particular chlorophyll-b molecule, Chl-b-478-513-648 (Fig. 2d) [49–52].

4. Oxidation of a cytochrome-f, Cyt-f-407-424-555 (Fig. 2f) [46, 53–55].

5. Reduction of a cytochrome-b^+, Cyt-b-412-435-563 (Fig. 2e) [56].

6. Reduction of plastoquinone Q-254 (Fig. 2g) [57 to 61].

7. Reduction of a substance Z, established indirectly from the kinetics of the absorption changes of Chl-a_I [48, 62].

8. Oxidation of a substance Y, established indirectly from the kinetics of the absorption changes of Chl-b and from the O_2 yield with periodic flashes [41].

9. Reaction of a special chlorophyll-a molecule, Chl-a_{II}, established from the action spectra of the absorption changes [63]. This result confirms measurements reported by *Govindjee et al.* [23], who deduced the existence of a chlorophyll-a_{II} molecule from the Emerson effect.

10. Formation of the π-π^* triplet state in the majority of the chlorophyll-a and chlorophyll-b molecules, Chl-a_0-435-675 and Chl-b_0-475-650, with a change in the chloroplast structure and with deactivated photosynthesis respectively (Fig. 2a) [64].

The following cytochrome reactions occur under abnormal conditions: *Chance et al.* [65] have observed slow ($\geqslant$ 1 sec) changes in the absorption of cytochrome-f in low-chlorophyll and low-carotene mutants under aerobic conditions, and changes in the absorption of cytochrome-b under anaerobic conditions. *Olson et al.* [66] discovered slow ($>$ 10 sec) absorption changes due to cytochrome-b in fragments of *Euglena* chloroplasts which contained no cytochrome-f. *Bonner* and *Hill* [67] have observed changes of this type only in etiolated green cells, but not in normal cells. Changes in the cytochrome absorption measured by *Lundegard* [68] are so slow ($>$10 sec) that they cannot be connected with the primary process [65]. *Kouchkovski et al.* [69] have observed absorption changes at 590 mμ due to a reaction of plastocyanin. It is not yet known to what extent this relatively slow reaction ($>$ 1 sec) is connected with the primary processes.

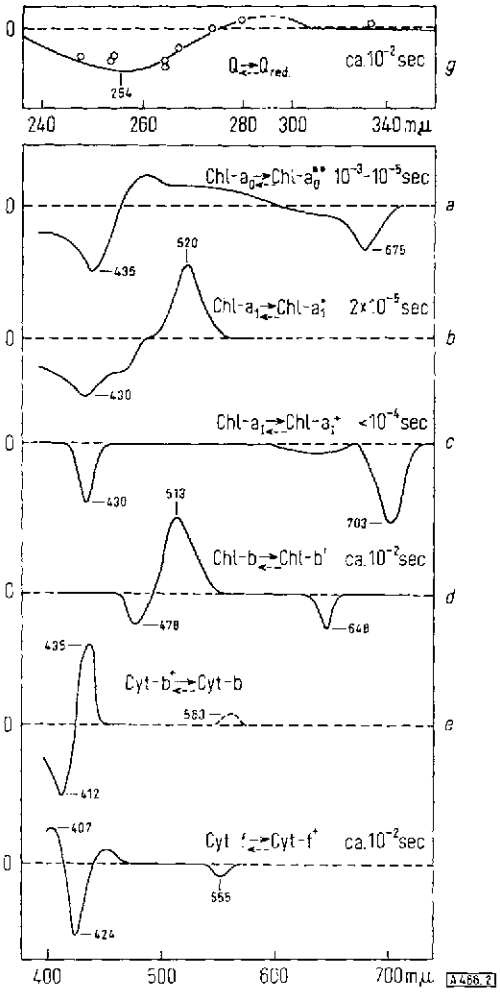


Fig. 2. Difference spectra for green cells (*Chlorella* cells or spinach chloroplasts) irradiated with flash illumination [47]. The spectra were isolated from a complex mixture of absorption changes. The order of magnitude of the absorption changes is about 0.1 %. The figures indicate the absorption-change maxima, and the times are those of the reverse reactions, indicated by the broken arrows. The method of isolation and the meanings of the symbols are described in the text.

Ordinate: Absorption change.
Abscissa: Wavelength.

IV. The Isolated Reaction Cycle I

1. Isolation of the Difference Spectrum of Chlorophyll-a_I-430-703

The triplet state of Chl-a_0 and Chl-b_0 (Fig. 2a) does not occur under „normal" conditions [*] [64]. The derivative formed from chlorophyll-a_1 (Fig. 2b) has a half-life

[49] *H. T. Witt* and *R. Moraw*, Z. physikal. Chem., N.F. *20*, 253 (1959).

[50] *H. T. Witt* and *R. Moraw*, Z. physikal. Chem., N.F. *20*, 283 (1959).

[51] *H. T. Witt* and *A. Müller*, Z. physikal. Chem., N.F. *21*, 1 (1959).

[52] *B. Rumberg*, Nature (London) *204*, 860 (1964).

[53] *H. T. Witt*, *A. Müller*, and *B. Rumberg*, Nature (London) *191*, 194 (1961).

[54] *A. Müller*, *B. Rumberg*, and *H. T. Witt*, Proc. Roy. Soc. (London), Ser. B, *157*, 313 (1963).

[55] *H. T. Witt*, *A. Müller*, and *B. Rumberg*: Colloques Internationaux No. 119 "La Photosynthèse". Editions du Centre National de la Recherche Scientifique, Paris 1963, p. 43.

[56] *B. Rumberg*, Biochim. biophysica Acta *102*, 354 (1965); Recent Progress in Photobiology. Blackwell Scientific Publications, Oxford 1965, p. 269.

[57] *M. Klingenberg*, *A. Müller*, *P. Schmidt-Mende*, and *H. T. Witt*, Nature (London) *194*, 379 (1962).

[58] *J. Weikard*, *A. Müller*, and *H. T. Witt*, Z. Naturforsch. *18b*, 139 (1963).

[59] *B. Rumberg*, *P. Schmidt-Mende*, *J. Weikard*, and *H. T. Witt* in: Photosynthetic Mechanisms of Green Plants. Publ. 1145, Nat. Acad. Sci. – Nat. Res. Council, Washington 1963, p. 18.

[60] *B. Rumberg*, *P. Schmidt-Mende*, and *H. T. Witt*, Nature (London) *201*, 466 (1964).

[61] *B. Rumberg*, *P. Schmidt-Mende*, *B. Skerra*, *J. Weikard*, and *H. T. Witt*, Z. Naturforsch., in the press.

[62] *B. Rumberg*, *A. Müller*, and *H. T. Witt*, Nature (London) *194*, 854 (1962).

[63] *A. Müller*, *D. C. Fork*, and *H. T. Witt*, Z. Naturforsch. *18b*, 142 (1963).

[64] *R. Moraw* and *H. T. Witt*, Z. physikal. Chem., N.F. *29*, 25 (1961).

[65] *B. Chance* and *R. Sager*, Plant Physiol. *32*, 548 (1957).

[66] *J. M. Olson* and *R. M. Smillie*: Photosynthetic Mechanisms of Green Plants. Publ. 1145, Nat. Acad. Sci. – Nat. Res. Council, Washington 1963, p. 56.

[67] *W. Bonner* and *R. Hill*, [66], p. 82.

[68] *H. Lundegardh*, Physiol. Plantarum *7*, 375 (1954).

[69] *Y. de Kouchkovski* and *D. C. Fork*, Proc. nat. Acad. Sci. USA *52*, 232 (1964).

[*] Normal conditions: *Chlorella* cells or spinach chloroplasts with electron acceptors I. Oxygen production: 1000–3000 mm³ of O_2 per mg of chlorophyll per hour. Irradiation with blue (380 to 480 mμ) or red (620–720 mμ) light.

of only 2×10^{-5} sec [44]. The absorption changes of plastoquinone Q-254 (Fig. 2g) occur only in the ultraviolet region of the spectrum [57]. If we confine ourselves to the visible region (400–800 mμ) and disregard the very fast Chl-a_1 absorption changes, we find under normal conditions a simplified but still complex mixture of absorption changes (Fig. 3a). Four partial reactions can be detected in this spectrum, and these will be discussed *inter alia* in this paper.

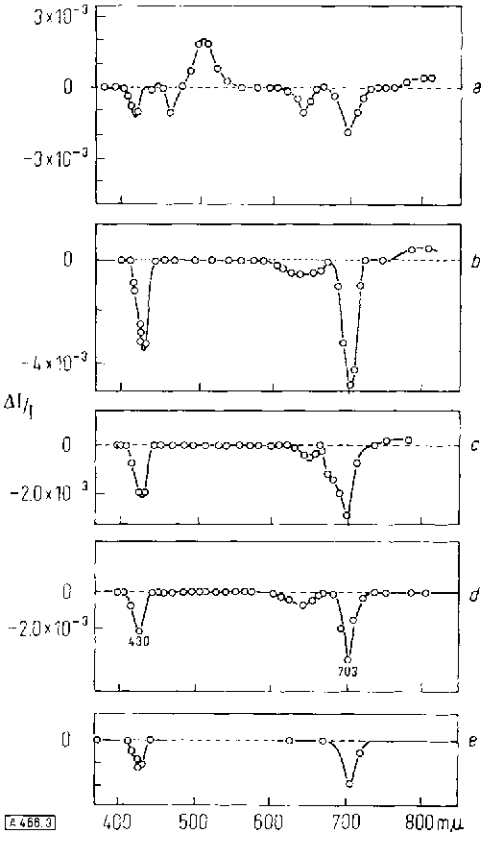


Fig. 3. Difference spectra of illuminated spinach chloroplasts [47].

a) Normal conditions. Addition of benzyl viologen as electron acceptor.

b) After aging and addition of *N*-methylphenazonium methyl sulfate + ascorbate.

c) After treatment with digitonin and addition of *N*-methylphenazonium methyl sulfate + ascorbate.

d) After extraction with petroleum ether.

e) At −150 °C with addition of *N*-methylphenazonium methyl sulfate + ascorbate.

The curves (b)–(e) represent the isolated difference spectrum of the oxidation of chlorophyll-a$_1$–430–703.

Ordinate: Absorption change ΔI/I.
Abscissa: Wavelength [mμ].

The absorption changes at about 700 mμ in Fig. 3a were discovered by *Kok et al.* [70–72], and were attributed to the oxidation of a pigment P 700 (redox potential $E_0 = 0.43$ volt). On the basis of measurements at 430 mμ on acetone-extracted inactive chloroplasts, it was assumed that the pigment P 700 is a chlorophyll-a. However, no direct evidence was offered [47]. In order to identify P 700, we have isolated the reaction characterized by the absorption change at 703 mμ, *inter alia* in active chloroplasts. This was achieved in various ways [47]: (a) Isolated chloroplasts become photosynthetically inactive after a few hours. *Vernon* and *Zaugg* [73] showed that this loss of activity applies only to the cleavage of water. If electron donors are added to aged chloroplasts, they reduce TPN on exposure to light. Using this system (addition of 2,6-dichlorophenolindophenol or *N*-methylphenazonium methyl sulfate with excess ascorbate), we obtained a difference spectrum with changes at about 430 and 703 mμ (Fig. 3b). Similar difference spectra were observed (b) on breaking down the chloroplasts into finely divided particles with the aid of surface active substances (digitonin) (Fig. 3c), (c) in chloroplasts from which plastoquinone had been extracted with petroleum ether (Fig. 3d), (d) in chloroplasts at −150 °C, (e) in chloroplasts after blockage of the cleavage of water by the addition of *N*-*p*-chlorophenyl-*N*-'dimethylurea [47], and (f) in normal chloroplasts on additional continuous exposure to light of wavelength 700–730 mμ [47,48].

The extent to which the simplified difference spectrum is due to the reaction of *one* substance can be ascertained by comparison of the magnitudes and the time variation of the changes at 430 and 703 mμ under various conditions.

2. Time Variation of the Absorption Changes

When a normal chloroplast suspension is illuminated with a flash lasting 3×10^{-6} sec, the absorption at 703 mμ falls off in $< 10^{-5}$ sec (Fig. 4), then returns to the original value in $>10^{-2}$ sec at 20 °C [47,55].

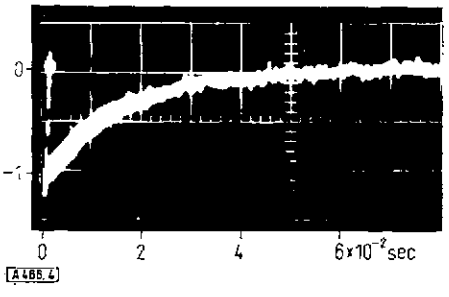


Fig. 4. Time variation of the change in the absorption of chlorophyll-a$_1$ at 703 mμ in spinach chloroplasts. At time t = 0, the sample was illuminated with a flash lasting 3×10^{-6} sec. 20 °C.

Ordinate: Relative absorption change.
Abscissa: Time [sec].

This value for the time taken by the reverse reaction is found only when the sample is also exposed to continuous long-wave illumination (700–730 mμ), such as the measuring light. With very weak additional illumination (intensity of measuring light → 0), the absorption returns to its original value in less than 10^{-4} sec [52] (cf. Section XII).

[70] a) *B. Kok*, Plant Physiol. *34*, 184 (1959); b) *B. Kok* and *W. Gott*, ibid. *35*, 802 (1960); c) *B. Kok*, *B. Cooper*, and *I. Yang*: Studies on Microalgae and Photosynthetic Bacteria. The University of Tokyo Press 1963, p. 373.

[71] *B. Kok*, Biochim. biophysica Acta *48*, 527 (1961).

[72] *H. Beinert*, *B. Kok*, and *G. Hoch*, Biochem. biophys. Res. Commun. *7*, 109 (1962); *B. Kok* and *H. Beinert*, ibid. *9*, 349 (1962).

[73] *L. P. Vernon* and *W. S. Zaugg*, J. biol. Chemistry *235*, 2728 (1960).

3. Assignment of the Absorption Changes to a Reaction of Chlorophyll-a_I

The magnitudes and half-lives of the absorption changes at 430 and 703 mμ change in the same manner when the external conditions are altered [47]. For example, Fig. 5

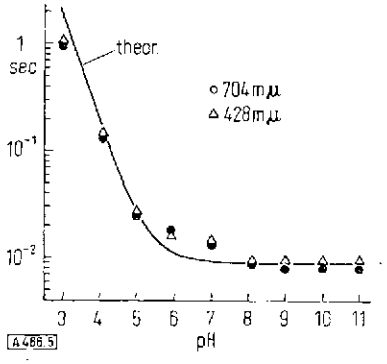


Fig. 5. Half-lives of the absorption changes of chlorophyll-a_I at 428 and 704 mμ for spinach chloroplasts, as a function of the pH. Addition of *N*-methylphenazonium methyl sulfate + ascorbate as electron donor [47].

Ordinate: Half-life [sec].
Abscissa: pH.

shows the half-lives of the two absorption changes as a function of the pH. It can be concluded, therefore, that both absorption changes result from the reaction of *one* substance. Since chlorophyll-a in vivo has absorption maxima at about 430 and 700 mμ, the difference spectra reproduced in Fig. 3b–e must correspond to a photochemically active chlorophyll-a, Chl a_I-430-703 [46,47]. The fall in absorption on flash illumination therefore indicates the formation of a derivative Chl-a'_I, whilst the subsequent increase in absorption is caused by the reverse reaction leading back to the original state Chl-a_I.

4. Oxidation of Chlorophyll-a_I

If *N*-methylphenazonium methyl sulfate and excess ascorbate are added to aged chloroplasts, the reverse reaction is found to be strongly dependent on the concentration of the phenazonium salt (Fig. 6) [47,74].

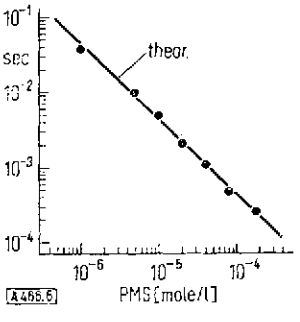


Fig. 6. Half-life of the changes in the absorption of chlorophyll-a_I at 705 mμ in spinach chloroplasts, as a function of the concentration of *N*-methylphenazonium methyl sulfate (PMS) + ascorbate [47,74].

Ordinate: Half-life
Abscissa: Concentration

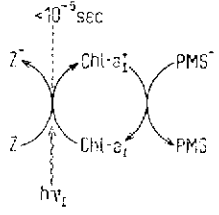
[74] *H.T. Witt, A. Müller*, and *B. Rumberg*, Nature (London) *197*, 987 (1963).

The analysis indicates a first-order reverse reaction, which may be interpreted as a reaction of the derivative Chl-a'_I with reduced phenazonium salt, *i.e.* the derivative Chl-a'_I formed on illumination must be an oxidized product. The pH-dependence of the redox potential (Fig. 8) shows that Chl-a'_I is a cation Chl-a_I^+ (cf. Section V.7). The pH-dependence of the half-live shows that the reduced *N*-methylphenazonium methyl sulfate reacts with Chl-a_I^+ as PMS^-:

$$\text{Chl-a}_I^+ + \text{PMS}^- \rightarrow \text{Chl-a}_I + \text{PMS}$$

The rate constant for this reactions is $k = 1.5 \times 10^7$ l mole^{-1} sec^{-1}. The temperature-dependence gives an activation energy of $E_A = 3.8$ kcal/mole [47].

The electron acceptor involved in the oxidation of Chl-a_I to Chl-a_I^+ is unknown. We shall refer to it as Z. Since the absorption of the Chl-a_I falls off in $< 10^{-5}$ sec on flash illumination ($h\nu_I$), the transfer of the electron from Chl-a_I to Z must take place within this period. These findings are summarized in Scheme 1.



Scheme 1. Oxidation of chlorophyll-a_I on flash illumination ($h\nu_I$) and reduction by reduced *N*-methylphenazonium methyl sulfate.

5. Oxidation of Chlorophyll-a_I as a Primary Process

Chlorophyll-a_I is also oxidized at low temperatures, but the reduction is inhibited under these conditions. This is shown by the irreversibility of the absorption change at −150 °C (Fig. 7).

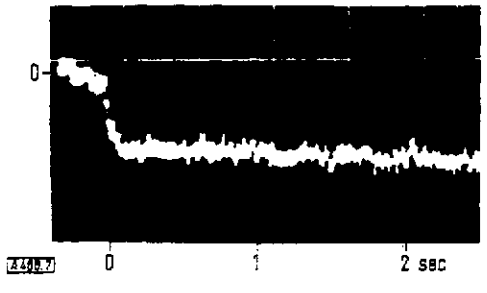


Fig. 7. Time variation of the change in the absorption of chlorophyll-a_I at 426 mμ in spinach chloroplasts at −150 °C [47,75]. Illuminated for 0.2 sec at time t = 0.

Ordinate: Relative absorption change.
Abscissa: Time [sec].

The difference spectrum of the irreversible absorption change at −150 °C (Fig. 3e) is the same as the difference spectra of the reversible absorption changes at 20 °C (Fig. 3b–d). The fact that the oxidation of chlorophyll-a_I is not inhibited at −150 °C shows that it must be a primary act of photosynthesis [46,47].

6. Redox Potential of Chlorophyll-a_I

The oxidation of Chl-a_I *in vivo* can be brought about not only photochemically, but also chemically, with the aid of potassium hexacyanoferrate(III). When $K_3Fe(CN)_6$/$K_4Fe(CN)_6$ is added, the ratio Chl-a_I^+/Chl-a_I changes in favor of Chl-a_I^+ as the concentration of $K_3Fe(CN)_6$ increases. This leads to a decrease in the absorption change brought about by light, since less Chl-a_I is available to the incident light. The redox potential found from the magnitude of the absorption change as a function of the ratio $K_3Fe(CN)_6/K_4Fe(CN)_6$ (Fig. 8) [46,48, 59] is:

$E^0_{Chl\text{-}a_I^+/Chl\text{-}a_I} = 0.46 \pm 0.01$ volt

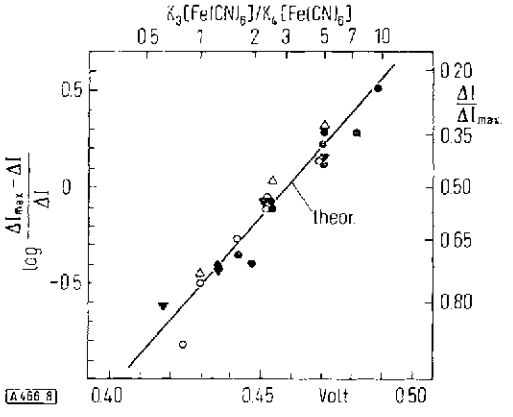


Fig. 8. Changes in the absorption of chlorophyll-a_I at 705 mμ in spinach chloroplasts, as a function of the redox potential of a mixture of $K_3Fe(CN)_6/K_4Fe(CN)_6$ [48, 59].

○ pH 6.0; △ pH 6.7; ● pH 7.2; ▲ pH 7.8.

Ordinate: Relative absorption change.

Abscissa: Top: Concentration ratio.
Bottom: Redox potential [volt].

The independence of the redox potential on the pH points to a pure electron transfer. Using a similar method, *Kok* [71] first found the redox potential of P 700$^+$/P 700 in acetone-extracted chloroplasts to be 0.43 volt.

7. The Natural Electron Donor for the Reduction of Chl-a_I^+

In the isolated reaction of Chl-a_I (Scheme 1), reduced *N*-methylphenazonium methyl sulfate (PMS) acts as the artificial electron donor. Since the absorption changes observed in the isolated system also occur in normal chloroplasts [47,48], the Chl-a^+ in this case must be reduced by a natural electron donor. The time indicated for this reduction at 20 °C by the time variation of the absorption changes is about 10^{-2} sec (Fig. 4).

If the Chl-a_I reaction is isolated from the natural electron donor (by aging of the chloroplasts, extraction with petroleum ether, or addition of digitonin or *N*-*p*-chlorophenyl-*N*-'dimethylurea, Section IV.1), no reduction of the Chl-a_I^+ should occur unless an artificial electron donor is added. This, however, is not the case (Fig. 9b). Instead, absorption changes lasting 10^{-2} sec occur evidently because the electron initially transferred to the natural electron acceptor Z can reduce the Chl-a_I^+ in a reverse reaction lasting about 10^{-2} sec (curved arrow in Scheme 2) [48,62,74].

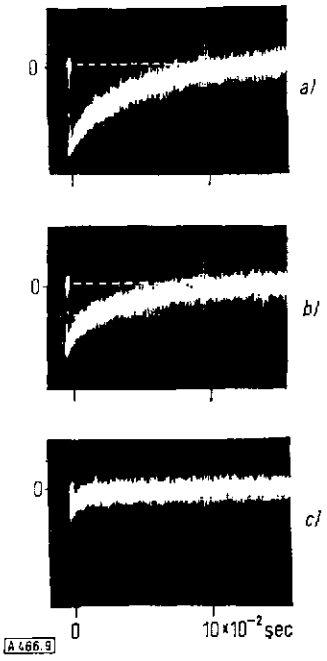


Fig. 9. Time variation of the change in the absorption of chlorophyll-a_I at 705 mμ in spinach chloroplasts (a) without and (b) with added *N*-*p*-chlorophenyl-*N'*-dimethylurea (6×10^{-5} M), and (c) with *N*-*p*-chlorophenyl-*N'*-dimethylurea (6×10^{-5} M) plus benzyl viologen (10^{-4} M). Flash illumination lasting 2×10^{-4} sec at time t = 0 [48].

Ordinate: Relative absorption changes.

Abscissa: Time [sec].

8. Artificial Electron Acceptors for Z$^-$ and the Redox Potential of Z

This reduction of Chl-a_I^+ can be prevented if the electron transferred to Z is intercepted by artificial electron acceptors. Thus the Chl-a_I reaction isolated from the natural electron donor by *N*-*p*-chlorophenyl-*N'*-dimethylurea disappears if *e.g.* benzyl viologen is added to the system as an electron acceptor (Fig. 9c). It is possible in this way, and particularly with the aid of the method described in Section XII.2, to establish which substances attack Z$^-$. These are listed in Table 1, and are referred to as "artificial electron acceptors I" (cf. Scheme 2) [48,62,74].

Table 1. Artificial electron acceptors I which can remove electrons from Z$^-$ [48,74].

	Redox potential (pH 7) [volt]
Potassium hexacyanoferrate(III)	+0.43
p-Benzoquinone	+0.28
m-Cresolindophenol	+0.21
Vitamin K_3	*ca.* 0
Indigosulfonates	−0.05 to −0.16
Riboflavin	−0.21
Flavin mononucleotide	−0.22
Safranine T	−0.29
Neutral red	−0.33
Benzyl viologen	−0.36
Methyl viologen	−0.44

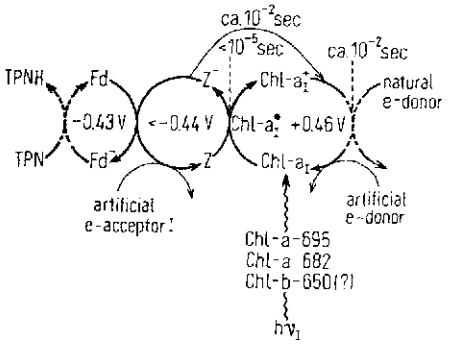
The data in Table 1 indicate that the redox potential of Z is less than −0.44 volt [48,62].

9. TPN and Ferredoxin as Natural Electron Acceptors for Z^-

Using the method described in Section XII.2, it was found that, of the natural electron acceptors present in plant cells, TPN alone cannot act as a natural electron acceptor for Z^-, whereas TPN together with TPN reductase can [74]. Thus TPN reductase contains a redox system which operates between Z and TPN (Scheme 2) [74]. *Tagawa et al.* [13c] had previously shown that TPN reductase [13a, b] is identical with ferredoxin, and that a flavoprotein acts as the carrier between ferredoxin and TPN [14].

10. Scheme of Reaction Cycle I

If we summarize the observations described so far, we obtain the picture shown in Scheme 2 for reaction cycle I.



Scheme 2. Electron flow in reaction cycle I [48, 54, 55, 62, 74]. PMS^- or DPIP + ascorbate can act as artificial electron donors.

Chl-a_I-430-703 is first converted into the excited state Chl-a_I^* by the absorption of light ($h\nu_I$). An electron is transferred from Chl-a_I^* to Z in $< 10^{-5}$ sec. The redox potential of Chl-a_I^* must be lower than −0.44 volt, since the redox potential of $Z/Z^- < -0.44$ volt. The redox potential of Chl-a^+/Chl-a_I is +0.46 volt. The electron is transferred from Z^-, *via* ferredoxin, to TPN. If there is no natural electron acceptor (TPN) available in isolated chloroplasts, the electron can be returned from Z^- to Chl-a_I^+ in about 10^{-2} sec or can be consumed by an artificial electron acceptor I (Table 1). Normally, Chl-a_I^+ is reduced within 10^{-2} sec by an (unknown) natural electron donor. If the cycle I is isolated from the natural electron donor (by aging, extraction with petroleum ether, treatment with digitonin, addition of *N-p*-chlorophenyl-*N'*-dimethylurea, or the use of low temperatures), the function of the latter can be taken over by an artificial electron donor (2,6-dichlorophenolindophenol or *N*-methylphenazonium methyl sulfate + excess ascorbate) [47, 54, 55, 59, 74].

The characteristics of the isolated reaction cycle I are summarized in Table 2 and Fig. 19 (left) [48, 74, 82].

Table 2. Characteristics of the isolated reaction cycles I and II [48, 61, 74, 82].

Property	Reaction cycle I	Reaction cycle II
Change of absorption	Chl-a_I: 430, 703 mμ	(Chl-b): 478, 513, 648 mμ Q: 254 mμ
Concentration	$[\text{Chl-a}_I] = 10^{-3} \times$ [chlorophyll]	$[(\text{Chl-b})] = 10^{-3} \times$ [chlorophyll]
Extinction	$\varepsilon_{\text{Chl-a}_I}(703) = 10^5$ l mole^{-1} cm^{-1}	$\varepsilon(\text{Chl-b})(478) = 10^5$ l mole^{-1} cm^{-1}
Redox potential — donor	+ 0.46 volt Chl-a_I^+/Chl-a_I	$\gtrsim$ + 0.81 volt Y^+/Y
Redox potential — acceptor	< -0.44 volt Z/Z^-	*ca.* 0 volt (Chl-b)/(Chl-b)$^-$
Supplied by energy transfer *via*	Chl-b-650?, Chl-a-682, Chl-a-695	Chl-b-650, Chl-a-674
Range of excitation	$\lambda < 730$ mμ	$\lambda < 700$ mμ
Rate constant	$k = 1.5 \times 10^7$ l mole^{-1} sec^{-1} (Chl-a_I with PMS^-)	$k = 1.6 \times 10^6$ l mole^{-1} sec^{-1} [(Chl-b)$^-$ with DPIP at pH 6.5]
Energy of activation	$E_A = 3.8$ kcal/mole (Chl-a_I with PMS^-)	$E_A = 7.4$ kcal/mole [(Chl-b)$^-$ with DPIP]
pH range	3–11	5–8
Temperature of inactivation (5 min)	65 °C	40 °C
Sensitive to ageing	no	yes
Sensitive to *N-p*-chlorophenyl-*N'*-dimethylurea (CMU)	no	yes

V. The Isolated Reaction Cycle II

1. Isolation of the Difference Spectrum of Chlorophyll-b-478-513-648

When cycle I is isolated, the absorption changes at 478 and 513 mμ are no longer observed (Fig. 3). It is also possible, by physical or chemical interference with the cell process, to deactivate cycle I and isolate the absorption changes at 478 and 513 mμ, which are associated with cycle II.

a) Physical Isolation

If the cell system is largely screened from continous illumination of wavelength $\lambda > 700$ mμ (this even includes the measuring light) the resulting difference spectrum has maxima at 478, 513, and 648 mμ (Fig. 10b) [52]. The change in the Chl-a_I absorption at 700 mμ (Fig. 10a) has practically disappeared. (For the cause of isolation, see Section XII.1).

b) Chemical Isolation

A similar result is obtained if *e.g.* dichlorophenolindophenol (with $K_3Fe(CN)_6$ as a redox buffer) is added to chloroplasts. The difference spectrum is again characterized by maxima at 478 and 513 mμ (Fig. 10c) [54, 59, 61]. The absorption change at 648 mμ (Fig. 10b) cannot be measured under these conditions, since dichlorophenolindophenol absorbs strongly between 550 and 660 mμ. (For the cause of this chemical isolation, see Section V.10).

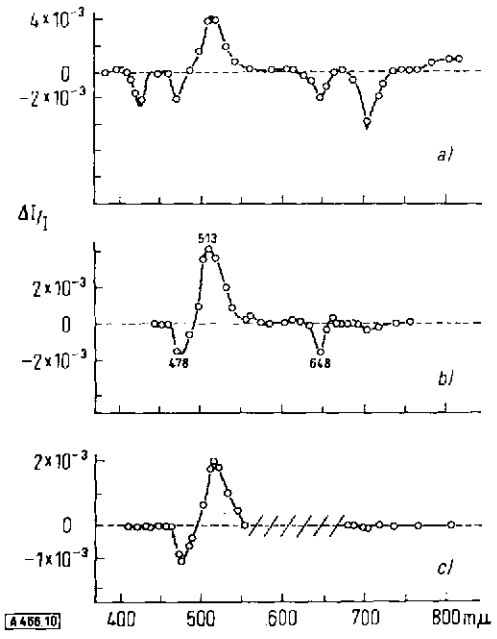


Fig. 10. Difference spectra for illuminated *Chlorella* cells (b) and spinach chloroplasts (a, c) [52, 59]

a) Normal conditions. Addition of benzyl viologen as electron acceptor. Not screened from continuous light of wavelength $\lambda > 700$ mμ.
b) Screened from continuous light of wavelength $\lambda > 703$ mμ [52].
c) With addition of dichlorophenolindophenol + $K_3Fe(CN)_6$ [59, 61].

Curves (b) and (c) represent the isolated difference spectrum of the reaction of chlorophyll-b-478-513-648.

Ordinate: Absorption change ΔI/I.
Abscissa: Wavelength [mμ].

2. Time Variation of the Absorption Changes

On flash illumination, the absorption at 515 mμ increases in $< 10^{-5}$ sec (Fig. 11). The system returns to its original state in about 10^{-2} sec in the dark at 20 °C [76–78].

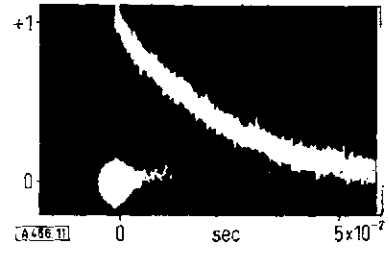


Fig. 11. Time variation of the change in the chlorophyll-b absorption at 515 mμ in *Chlorella* cells. Flash illumination lasting 10^{-5} sec at time t = 0. 20 °C [49].

Ordinate: Relative absorption change.
Abscissa: Time [sec].

3. Assignment of the Absorption Changes to a Reaction of Chlorophyll-b

The magnitudes and half-lives of the absorption changes at 478, 513, and 648 mμ are strongly dependent on the external conditions. Their quantitative relationships, however, are always the same [49–52]. It follows that they must all be due to *one* substance. Two examples are shown in Fig. 12.

The decrease in the absorption at 478 and 648 mμ (Fig. 10) corresponds to the fading of a pigment which absorbs at these wavelengths. Chlorophyll-b *in vivo* has bands at about 478 and 648 mμ. The absorption change is therefore due to the reaction of a chlorophyll-b, Chl-b-478-513-648 [52], leading to the formation of a derivative which absorbs at 513 mμ. The difference spectrum shown in Fig. 10b and 10c can be observed only in plant cells which contain chlorophyll-b (green plant cells). Blue and red algae, which do not contain chlorophyll-b, do not give this spectrum.

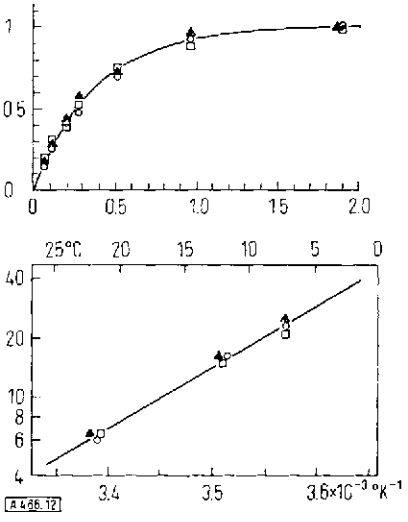


Fig. 12. Changes in the absorption of chlorophyll-b at 473 (o), 515 (□), and 648 (▲) mμ in *Chlorella*, as a function of the light intensity (top) and of the temperature (bottom) [52].

Ordinates: Top: Relative absorption change;
Bottom: Half-life [10^{-3} sec].
Abscissas: Top: Irradiation intensity [10^5 erg cm^{-2} sec^{-1}].
Bottom: Temperature [°C] and reciprocal of the absolute temperature [°K^{-1}].

4. The Chlorophyll-b Reaction as an Indicator Reaction

Chlorophyll-b is not directly involved in the electron flow during photosynthesis. The changes in the absorption of chlorophyll-b can be almost eliminated chemically without appreciably affecting either the change in the absorption of chlorophyll-a_I or the oxygen yield (Fig. 13) [61, 79], *i.e.* the elementary reaction of photosynthesis continues to occur. Chlorophyll-b is therefore simply an indicator for a substance X which is involved in the transfer of electrons. Alcohol dissociates the Chl-b from this substance, without affecting the functioning of the latter. Under normal conditions a reaction of X probably causes a change in the optical properties of the chlorophyll-b in the vicinity. The resulting absorption changes then correspond quantitatively to the reaction

[75] *A. Müller*, Doctorate Dissertation, Universität Marburg, 1962.
[76] *H. T. Witt*, Naturwissenschaften *42*, 72 (1955).
[77] *H. T. Witt*, Z. Elektrochem. *59*, 981 (1955).
[78] *H. T. Witt*, *R. Moraw*, and *A. Müller*, Z. Elektrochem. *60*, 1148 (1956).
[79] *B. Rumberg*, unpublished work.

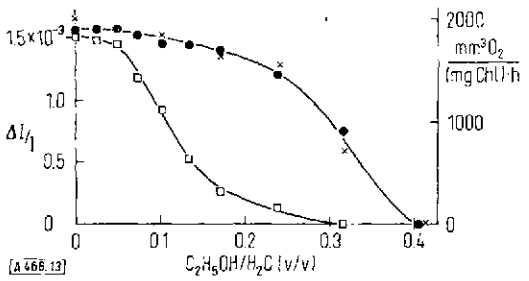


Fig. 13. Oxygen yield (×) and changes in the absorption of chlorophyll-a1 at 704 mμ (●) and of chlorophyll-b at 515 mμ (□) in spinach chloroplasts in aqueous ethanol [61, 79].

Ordinates: Left: Absorption change ΔI/I.
Right: Oxygen yield [mm³ O_2/(mg Chl) h].
Abscissa: Volume ratio ethanol/water.

of X. Since Chl-b acts as an indicator for X. we denote the latter by the symbol (Chl-b).

The absorption increase in $< 10^{-5}$ sec corresponds to the formation of a derivative (Chl-b)′, while the absorption decrease in the dark in about 10^{-2} sec corresponds to the regeneration of (Chl-b).

5. Reduction of (Chl-b)

The difference spectrum of Chl-b can be isolated chemically by the addition of dichlorophenolindophenol + excess $K_3Fe(CN)_6$. The $K_3Fe(CN)_6$ is only of minor importance. It acts as an electron acceptor I to suppress Cycle I (see Section IV.8), and it maintains the dichlorophenolindophenol in the oxidized state. As the concentration of dichlorophenolindophenol is increased, the rate of the regeneration of (Chl-b) from (Chl-b)′ also increases very rapidly [51, 78] (Fig. 14).

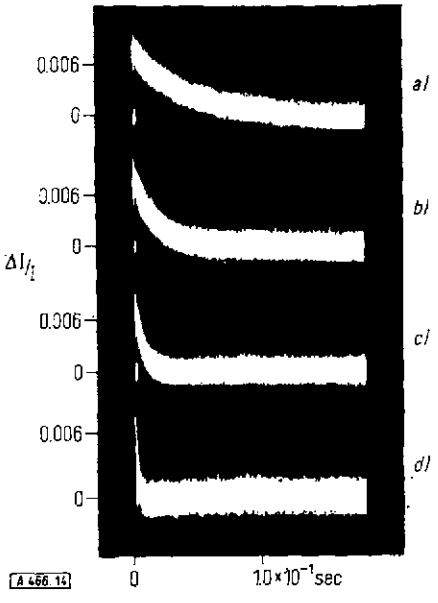


Fig. 14. Time variation of the change in the absorption of chlorophyll-b at 515 mμ in spinach chloroplasts, as a function of the concentration of 2,6-dichlorophenolindophenol [51, 78] [(a) 3.75×10^{-5} M, (b) 5.1×10^{-5}M, (c) 7.8×10^{-5} M, (d) 1.6×10^{-4} M].

The half-lives of the reverse reaction are:

(a) 24 msec, (b) 11 msec, (c) 4 msec, (d) 1 msec [51, 78].

Ordinate: Absorption change ΔI/I.
Abscissa: Time (sec).

It can be shown that dichlorophenolindophenol is reduced in the course of the reverse reaction. (Chl-b)′ must therefore be a reduced form of (Chl-b) formed on exposure to light, which is oxidized by dichlorophenolindophenol (DPIP) in the dark [51].

$$\text{(Chl-b)}^- + \text{DPIP} \rightarrow \text{(Chl-b)} + \text{red. DPIP}$$

The time variation of the dark reaction indicates that it is pseudofirst order, and gives a rate constant of $k = 1.62\times10^6$ lmole^{-1} sec^{-1} [*] and an activation energy of $E_A = 7.4$ kcal/mole [51].

6. Artificial Electron Acceptors II for (Chl-b)⁻

Of various substances with redox potentials between −0.44 and +0.43 volt which were investigated only those listed in Table 3 have been found to act as electron acceptors for (Chl-b)⁻. They are referred to as "artificial electron acceptors II".

Table 3. Artificial electron acceptors which can remove electrons from (Chl-b)⁻ [51].

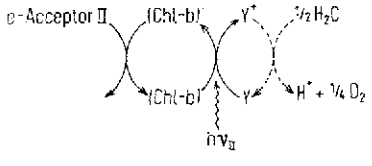
	Redox potential (pH 6.5) [volt]
Methylene blue	+0.03
Thionine	+0.08
Toluylene blue	+0.14
Thymolindophenol	+0.20
2,6,3′-Trichlorophenolindophenol	+0.26
2,6-Dichlorophennlindophenol	+0.26
Phenolindophenol	+0.26

7. The Redox Potential of (Chl-b)

Since only substances with a redox potential $\gtrsim 0$ volt react with (Chl-b)⁻ (Table 3), the redox potential of (Chl-b) must be about 0 volt [51].

8. Water as the Natural Electron Donor for (Chl-b)

From the above it can be seen that exposure to light causes the transfer of an electron from an unknown substance Y to (Chl-b). (Chl-b)⁻ can then give up the electron to one of the electron acceptors II. The ultimate electron donor is water (Scheme 3), as is shown by the following observations:



Scheme 3. Water as the natural electron donor for (Chl-b).

a) *N-p*-Chlorophenyl-*N′*-dimethylurea blocks the cleavage of water, *i.e.* the O_2 production [80]. The addition of increasing quantities of this poison leads also to the

[*] This value was obtained by recent measurements and differs a little from that published in [51].

[80] *N. I. Bishop*, Biochim. Biophysica Acta *27*, 205 (1958).

suppression of the absorption change associated with the isolated (Chl-b) reaction (Fig. 19, right) [46, 53].

b) In the chemically isolated (Chl-b) reaction, under various conditions, there is a quantitative relationship between the reduction of (Chl-b) and the oxygen yield [61].

c) There is also a quantitative relationship between the oxygen and the reduction of dichlorophenolindophenol (electron acceptor II).

9. The Electron Carrier Y

Since the transfer of an electron to (Chl-b) takes place in $< 10^{-5}$ sec (Fig. 11), whereas the liberation of the electron from water takes about 10^{-3} sec [81] (see Section X), there must be at least one carrier Y with a reaction time of 10^{-3} between (Chl-b) and the water. Chlorophyll-a_{II} (see Section V.11) cannot be identical with Y, since no absorption changes lasting 10^{-3} sec have so far been observed for Chl-a_{II}.

10. The Natural Electron Acceptor for $(Chl\text{-}b)^-$

In order to isolate the (Chl-b) reaction chemically from the remainder of the cell processes, we blocked the flow of electrons to the natural electron acceptor by means of the electron acceptors II. The isolated process is referred to as "Reaction Cycle II". The natural electron acceptor is unknown at present. From the time variation of the absorption changes (Fig. 11) it can be concluded that the transfer of electrons to this acceptor takes about 10^{-2} sec at 20 °C.

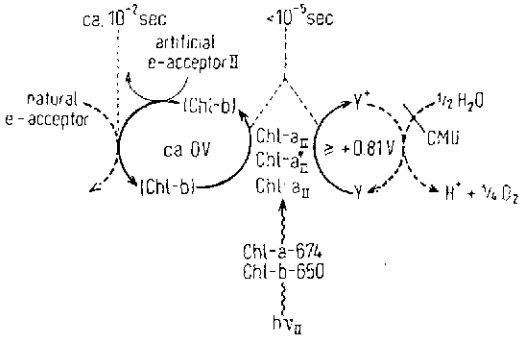
11. Chlorophyll-a_{II} as the Sensitizer for Reaction Cycle II

What photochemically active pigment sensitizes reaction cycle II? Chlorophyll-b is an indicator molecule and can be ruled out for this reason. Some information can be obtained from the action spectrum of reaction cycle II (see Section VI), which shows that the reaction must be sensitized by a chlorophyll-a molecule, which we refer to as Chl-a_{II} [63]. The excited Chl-a_{II} molecule evidently transfers an electron from Y to (Chl-b) so fast that the reaction of Chl-a_{II} has not so far been detected by absorption changes.

12. Scheme of Reaction Cycle II

If we summarize all the observations described so far, we obtain the picture shown in Scheme 4 for reaction cycle II.

On exposure to light ($h\nu_{II}$), the excited Chl-a_{II}^* causes the transfer of an electron from Y to (Chl-b) in $< 10^{-5}$ sec. (Chl-b) has a redox potential of about 0 volt. The electron transfer from $(Chl\text{-}b)^-$ to the natural acceptor takes about 10^{-2} sec at 20 °C. Water is the ultimate electron donor, *i.e.* Y^+ is reduced by water with liberation of $^1/_4$ O_2 and H^+. The



Scheme 4. Flow of electrons in reaction cycle II [54, 55, 61, 62, 74].

redox potential of water is +0.81 volt (pH 7). The redox potential of Y^+/Y must therefore be $\geq$ 0.81 volt [46]. By intercepting the electron from $(Chl\text{-}b)^-$ by one of the artificial electron acceptors II listed in Table 3, cycle II can be isolated from the remainder of the cell processes. The quantitative isolation of cycle II depends on the illumination time, the flash frequency, and the concentration of $K_3Fe(CN)_6$, as well as on the concentration of the electron acceptor II [82]. It has been shown by *Kessler* [15] that manganese ions are involved in the cleavage of water.

The isolated cycle II must be responsible for the system described by *Losada et al.* [38], *i.e.* O_2-producing chloroplasts with added dichlorophenolindophenol and $K_3Fe(CN)_6$ which are incapable of producing ATP.

The characteristics of the isolated reaction cycle II are summarized in Table 2 and Fig. 19 (right) [61, 74, 82].

13. Relationship between (Chl-b) and Plastoquinone

Bishop [83] has shown that on extraction with petroleum ether, chloroplasts lose the ability to cleave water, but they regain their photochemical activity on subsequent recondensation of plastoquinone. It was concluded, therefore, that plastoquinone plays some part in photosynthesis. The redox potential of plastoquinone is about 0 volt, and that of (Chl-b) is also about 0 volt [51].

This agreement, together with the following experiment, led to the conclusion that the two substances must be related. When plastoquinone is extracted, the difference spectrum of Chl-b disappears but reappears in full on condensation of synthetic plastoquinone (Fig. 15) [58, 75, 84]. We have therefore attempted to detect directly the participation of plastoquinone in the electron transport.

14. The Difference Spectrum of Plastoquinone (Q-254)

The reduction of plastoquinone *in vitro* is characterized by absorption changes in the ultraviolet region (maximum at 254 mμ) [90]. A similar difference spectrum is found when spinach chloroplasts [57] or *Chlorella* cells [60] are exposed to light (Fig. 2g). Thus plastoquinone (Q-254), like (Chl-b), is reduced *in vivo* on exposure to light.

[81] *J. Vater, H. Rüppel,* and *H. T. Witt,* unpublished work.

[82] *B. Rumberg, U. Siggel, B. Skerra,* and *H. T. Witt,* Z. Naturforsch., in the press.

[83] *N. I. Bishop,* Proc. nat. Acad. Sci. USA *45,* 1696 (1959).

[84] *H. T. Witt* in *W. Ruhland:* Handbuch der Pflanzenphysiologie. Springer, Berlin 1960, Vol. V/1, p. 634.

15. The Reaction of Plastoquinone in Reaction Cycle II

The changes in the absorption of Q-254 are also observed in the chemically isolated reaction cycle II (Fig. 19, right) [59]. Since, according to Scheme 4, the evolution of oxygen and the reduction of (Chl-b) are connected with each other, the evolution of oxygen and the changes in the absorption of Chl-b and of plastoquinone should be suppressed when plastoquinone is extracted, and should reappear on recondensation of plastoquinone, if plastoquinone is involved in cycle II [53, 85]. The changes in the absorption of Chl-a_I in cycle I must be unaffected by these measures. This is confirmed by the results reproduced in Fig. 15 [59, 61].

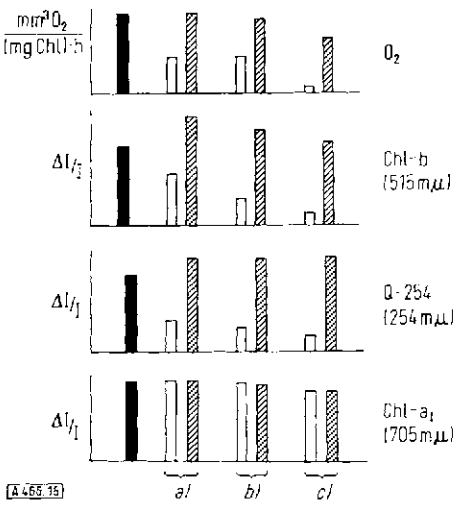


Fig. 15. Relative oxygen production and changes in the absorption of chlorophyll-b, plastoquinone, and chlorophyll-a$_I$ in spinach chloroplasts under normal conditions (black rectangles), after extraction of plastoquinone with petroleum ether (white rectangles), and after subsequent condensation of synthetic plastoquinone (cross-hatched rectangles). The groups marked a), b), and c) differ in the extent of extraction with petroleum ether [59, 61].

16. The Characteristics of the Plastoquinone Reaction

The characteristics of the plastoquinone reaction agree quantitatively with those of the (Chl-b) reaction (Fig. 19, right): pH range 5–8, temperature range $< 40\,^{\circ}C$, sensitive to *N*-*p*-chlorophenyl-*N'*-dimethylurea [61]. The magnitude of the changes in the absorption of plastoquinone depends on the O_2 content of the chloroplast suspension. This indicates that Q^{-}-254 is oxidized by O_2 [59, 60]. This electron transfer is slow (seconds), and is indicated by an arrow in Scheme 8.

17. Chlorophyll-b as an Indicator for the Plastoquinone Reaction

(Chl-b) and Q-254 have roughly the same redox potential, the changes in the absorption of both disappear when plastoquinone is extracted, both are reduced when the isolated cycle II is induced, and their reactions have the same characteristics. It may be assumed, therefore, that (Chl-b) and Q-254 are identical, *i.e.* that the changes in the absorption of chlorophyll-b are indicative of the plastoquinone reaction [58, 61]. Moreover, the time variation of the absorption changes at 515 and 254 mμ under various conditions also agree [59, 61]. This is shown in Fig. 16 for the excitation times. The magnitudes of the changes in the absorption of chlorophyll-b and plastoquinone show the same dependence on flash duration. In the case of prolonged flashes (10^{-1} sec), the quantity of plastoquinone that takes part in the reaction is about four times as great as when the flashes last only $\lesssim 10^{-3}$ sec (Fig. 16) [59–61].

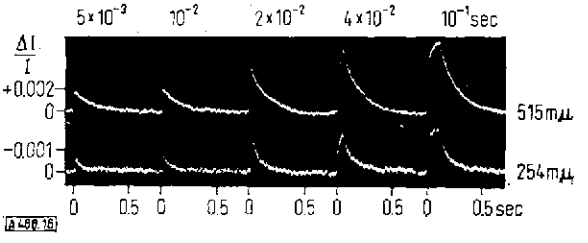


Fig. 16. Time variation of the absorption changes at 515 mμ (chlorophyll-b) and 254 mμ (plastoquinone) in *Chlorella* cells, as a function of the duration of the flash (numbers above the diagram) [61].

Ordinate: Absorption change ΔI/I.
Abscissa: Time [sec].

18. Plastosemiquinone

Under certain conditions, differences are observed in the time variations of the absorption changes at 515 and 254 mμ. These differences indicate the participation of plastosemiquinone and plastohydroquinone. It has not yet been proved which of the two reduced forms is indicated by chlorophyll-b.

VI. The Action Spectra of the Isolated Reaction Cycles I and II

The isolated cycle I can be optically measured by the change in the absorption of Chl-a_I, *e.g.* at 430 mμ and chemically by the rate of reduction of the electron acceptor I, *e.g.* benzyl viologen. The isolated cycle II can be optically measured by the change in the absorption of Chl-b, *e.g.* at 515 mμ, and chemically by the rate of production of oxygen. Fig. 17 shows the action spectra obtained by these methods for the isolated cycles I and II.

The optically measured action spectra are more accurate than those obtained by chemical methods. The shoulders and maxima of the spectra show which of the photochemically inactive chlorophyll types supply the reaction centers Chl-a_I and Chl-a_{II} with energy by energy transfer. Chl-a_I is supplied with energy *via* the chlorophylls Chl-a-682, Chl-a-695, and probably also Chl-b-650 (Scheme 2), and Chl-a_{II} is supplied by Chl-b-650 and Chl-a-674 (Scheme 4). Cycle I can be excited by light of wavelength < 730 mμ, and cycle II only by light of wavelength < 700 mμ (Fig. 17).

According to the laws of energy migration, the absorption maximum of the active chlorophyll in cycle II must be at longer wavelengths than the maximum of the chlorophyll molecules transporting the energy (674 mμ).

[85] *H. T. Witt, A. Müller*, and *B. Rumberg*, Angew. Chem. *73*, 507 (1961).

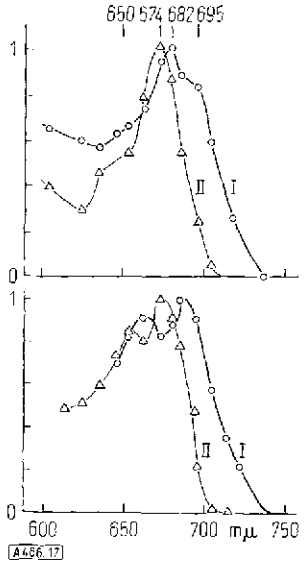


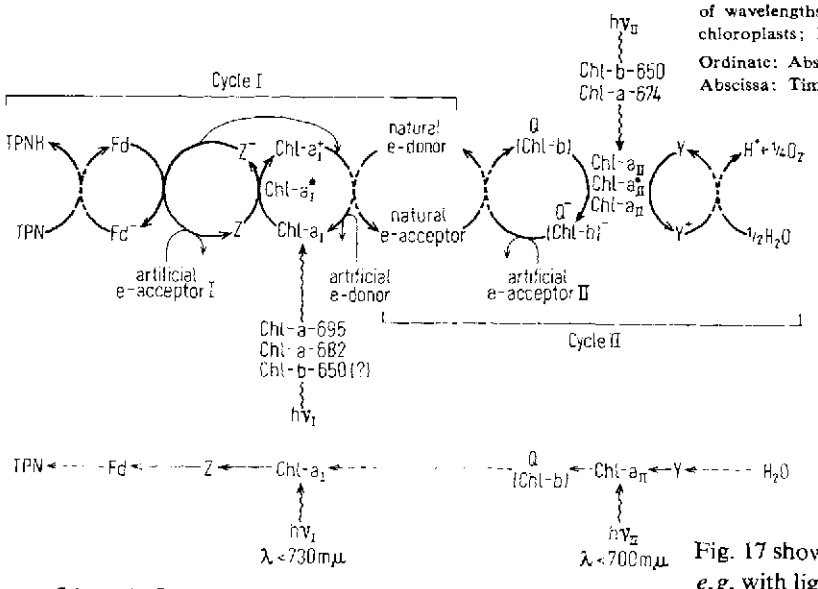
Fig. 17. Action spectra of the isolated reaction cycles I and II in spinach chloroplasts [59, 63].

Ordinates: Top: Relative change in the absorption of chlorophyll-a_I at 433 mμ (I) and of chlorophyll-b at 515 mμ (II).
Bottom: Relative reduction of benzyl viologen (I) and production of O_2 (II).
Abscissa: Wavelength of inducing light [mμ] (equal numbers of *incident quanta*).

Maxima above 674 mμ belong to the chlorophyll-a type, so that a chlorophyll-a must be the active molecule in cycle II [63]; this result has already been used in Section V.11, in which the active molecule was denoted by Chl-a_{II}. The same result had previously been deduced from the Emerson effect [23].

VII. Quantitative Coupling of Reaction Cycles I and II in the Complete System

The natural electron donor for cycle I (Scheme 2) and the natural electron acceptor for cycle II (Scheme 4) are unknown. It seems obvious to assume that cycle II acts as the natural electron donor for cycle I, and that cycle I acts as the natural electron acceptor for cycle II (Scheme 5). This coupling of the two cycles in the complete system can be demonstrated in four ways.



Scheme 5. Coupling of reaction cycles I and II in the complete system [46, 54, 55, 62, 74].
Below: simplified line diagram.

1. Demonstration through Chl-a_I

Fig. 17 shows that Chl-a_I can be oxidized *e.g.* with light of wavelength 720 mμ (only $h\nu_I$) (decrease in absorption at 703 mμ) without Chl-a_{II} being excited. On subsequent exposure to light of wavelength *e.g.* 638 mμ ($h\nu_I$ and $h\nu_{II}$), Chl-a_{II} should also be excited and should effect the transfer of an electron from the water to the plastoquinone. If cycles I and II are coupled, Q^- must reduce the Chl-a_I^+, *i.e.* the absorption at 703 mμ must increase. This is verified by Fig. 18, top [59, 60].

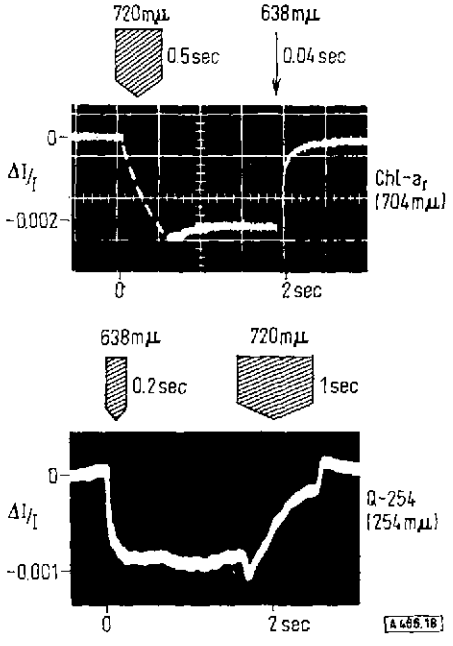


Fig. 18. Time variation of the changes in the absorption of chlorophyll-a_I (704 mμ) on excitation with light of wavelengths 720 mμ and 638 mμ (*top*), and of plastoquinone (254 mμ) on excitation with light of wavelengths 638 mμ and 720 mμ (bottom). Subject: top: spinach chloroplasts; bottom: *Chlorella* cells [59, 60].

Ordinate: Absorption change $\Delta I/I$.
Abscissa: Time [sec].

2. Demonstration through Plastoquinone

Fig. 17 shows that plastoquinone (Chl-b) can be reduced *e.g.* with light of wavelength 638 mμ ($h\nu_I$ and $h\nu_{II}$). This ligth also oxidizes Chl-a_I (Fig. 17). After a long period of darkness, however, it is mainly plastoquinone that is

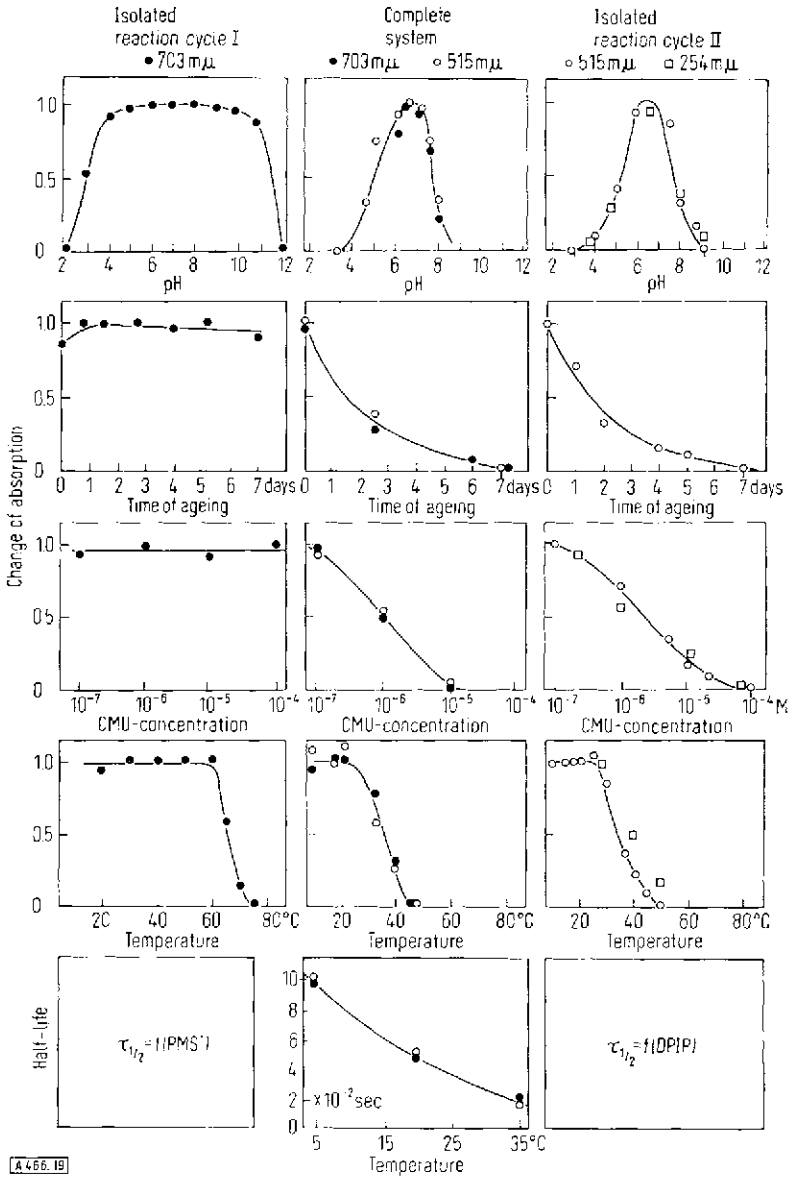


Fig. 19. *Left*: Dependence of the isolated reaction cycle I on various parameters, measured on the basis of the decrease in the absorption of chlorophyll-a_I at 703 mμ.

Right: Dependence of the isolated reaction cycle II on various parameters, measured on the basis of the change in the absorption of chlorophyll-b at 515 mμ and of plastoquinone at 254 mμ.

Center: Dependence of reaction cycles I and II in the complete system on various parameters, measured on the basis of the increase in the absorption of chlorophyll-a_I at 703 mμ and of chlorophyll-b at 515 mμ.

Subject: spinach chloroplasts; for the measurement of the half-lives: *Chlorella* cells [60, 82].

CMU = *N*-*p*-chlorophenyl-*N'*-dimethylurea;- DPIP = dichlorophenol-indophenol.

PMS^- = reduced *N*-methylphenazonium methyl sulfate.

reduced, as is shown by the fact that the absorption at 254 mμ decreases on exposure to light, and that reoxidation no longer takes place as soon as the light is switched off (Fig. 18, bottom). On subsequent exposure to light of wavelength 720 mμ ($h\nu_I$ only), only Chl-a_I is oxidized. If cycles I and II were coupled, Chl-a_I^+ should accept the electron from Q^-, and the absorption at 254 mμ should increase. It can be seen from Fig. 18, bottom, that this is in fact the case [59, 60].

3. Demonstration through Common Characteristics of Cycles I and II

The characteristics of the *isolated* cycles I and II are compared in Table 2 and in Fig. 19. They differ considerably. If the two cycles are coupled, however, they should depend in the same way on various parameters. To show this, Chl-a_I is first oxidized alone by exposure to continuous light of wavelength 720 mμ ($h\nu_I$ only) (decrease in absorption at 703 mμ). On further exposure to light *e.g.* of wavelength 638 mμ ($h\nu_I$ and $h\nu_{II}$), the reduction of Chl-a_I^+, *i.e.* the increase in absorption at 703 mμ, should be dependent on the reduction of plastoquinone [(Chl-b)] in cycle II, *i.e.* the increase in absorption at 703 mμ, and the change at 515 mμ in the *coupled* system should exhibit the same dependence as the change at 515 mμ in the *isolated* cycle II (Fig. 19, right). The good agreement (Fig. 19, center) shows that the coupling between cycles I and II is quantitative [60, 82].

Kinetic Demonstration

In the complete system of *Chlorella* the increase in absorption at 703 (reduction of Chl-a_I) and the decrease at 515 mμ [oxidation of (Chl-b)⁻] have equal half-lives at various temperatures (Fig. 19, bottom center). This provides kinetic evidence of the quantitative coupling between the two cycles [60, 62]. The half-lives are characteristic of the rate-determining step between cycles I and II. Depending on the conditions, half-lives between 1×10^{-2} and 4×10^{-2} sec at 25 °C have been found [60, 82].

5. Feed-Back between Cycles I and II; Reduction of (Chl-b) by Excitation of Chl-a_I and Chl-a_{II}

The difference spectrum of Chl-b is produced by excitation of Chl-a_{II}. It has not yet been pointed out, however, that this applies only for one half of the amplitude, the other half being produced by excitation of Chl-a_I. This is shown by the following observations:

a) If only Chl-a_{II} is excited [deactivation of cycle I with dichlorophenolindophenol + $K_3Fe(CN)_6$], the amplitude of the difference spectrum of Chl-b is only half as great as under normal conditions with excitation of Chl-a_I and Chl-a_{II} (Section V.1 and Fig. 10) [59].

b) If only Chl-a_I is excited (*e.g.* with light of wavelength 720 mμ $h\nu_I$ only), the difference spectrum of Chl-b does not disappear. It is simply reduced [53] to about half of its usual amplitude at the saturation intensity [63, 82, 95].

c) With increasing excitation of Chl-a_I with continuous light (*e.g.* λ = 728 mμ, $h\nu_I$ only), the changes in the absorption of Chl-b that can be stimulated by additional flash illumination (*e.g.* λ – 638 mμ, $h\nu_I$ and $h\nu_{II}$) are reduced to about half (Fig. 20). The continuous illumination evidently saturates the (Chl-b) component that can be stimulated by Chl-a_I [52].

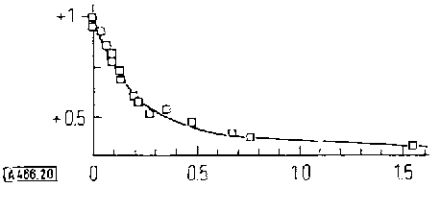


Fig. 20. Changes in the absorption of chlorophyll-b at 515 mμ on flash illumination as a function of the intensity of continuous illumination (λ = 728 mμ).
Subject: *Chlorella* cells [52].
Ordinate: Relative absorption change.
Abscissa: Intensity of illumination [10^5 erg cm^{-2} sec^{-1}].

This result shows that, as mentioned earlier, (Chl-b) is reduced on excitation of cycle II, but that (Chl-b) may also be reduced by the backward flow of electrons from Z^- to (Chl-b), *i.e.* to Q. This is indicated in Scheme 8 by a broken arrow.

If cycle II is deactivated by the addition of *N*-*p*-chlorophenyl-*N*-dimethylurea (Section V.8), the changes in the absorption of Chl b reappear on illumination when dichlorophenolindophenol + excess ascorbate are added to the chloroplast suspension [54]. These changes can be produced by excitation of Chl-a_I alone, *i.e.* with light of wavelength 720 mμ ($h\nu_I$ only) [82]. Thus instead of water, ascorbate can evidently act (*via* dichlorophenolindophenol) as an electron donor for plastoquinone (Scheme 8).

6. Unambiguity of the Representation of Cycle II by Chlorophyll-b [61]

1. The absorption changes at 478, 513, and 648 mμ that characterize cycle II are due to changes in chlorophyll-b (Section V, 3).

2. Chlorophyll-b is simply an indicator, the change in the absorption of which is brought about by the action of another substance, (Chl-b) or plastoquinone (Section V, 4).

3. Alterations of the chloroplasts can cause a breakdown of the coupling between chlorophyll-b and plastoquinone (Section V, 4).

4. (Chl-b) can be reduced by Chl-a_{II} and also by feed-back from cycle I (Section VII, 5).

5. It follows that the changes in the absorption of Chl-b exclusively and unambiguously represent cycle II only if the difference spectrum of Chl-b, which can be induced by cycle I, is suppressed. This is the case:

a) if cycle I is deactivated chemically [addition of an electron acceptor II + $K_3Fe(CN)_6$ (Section V, 1)] or

b) if the feed-back from cycle I is saturated by additional continuous illumination of wavelength 700–730 mμ ($h\nu_I$ only) (Section VII, 5).

These points were borne in mind in determining the characteristics of cycle II.

VIII. The Intermediates

There remains an as yet unexplained difference between the complex difference spectrum under normal conditions and that of Chl-a_I in the blue region of the spectrum between 400 and 460 mμ (cf. Fig. 22a and e). This difference is due to the superposition of the changes in the absorptions of a cytochrome-f and a cytochrome-b [56].

1. The Difference Spectrum of Cytochrome-f-407-424-555 and its Isolation

Fast ($< 10^{-1}$ sec) light-induced reactions of cytochrome-f cannot normally be detected in green cells. However, three methods of altering the cell system [62] can bring about absorption changes which are due to the well-known oxidation of Chl a_I and an oxidation of Cyt-f which cannot otherwise be detected (Fig. 21):

a) illumination at low temperatures (–150 °C) [46],

b) excitation of cycle I alone, *e.g.* with light of wavelength 710 mμ ($h\nu_I$ only) [53],

c) addition of dichlorophenolindophenol to chloroplasts [55].

The changes at about 700 mμ at –150 °C marked by a broken curve in Fig. 21a indicate that Chl-a_I is involved. If *N*-methylphenazonium methyl sulfate is added, only the difference spectrum of Chl-a_I at 150 °C is obtained (Fig. 3e) [46]. If this spectrum is subtracted from the spectrum shown in Fig. 21a or 21b, we obtain the same difference spectrum as is observed on chemical oxidation

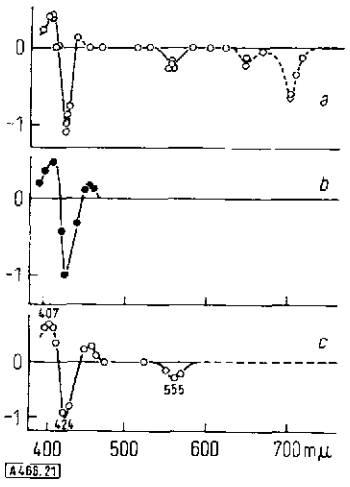


Fig. 21. Difference spectrum of illuminated spinach chloroplasts (a, c) and *Chlorella* cells (b).

a) −150 °C, no additives; broken curve: change in the absorption of Chl-a_I; continuous curve: changes in the absorption of Cyt-f and Chl-a_I [46].

b) 25 °C, excitation with light of wavelength 710 mμ [53].

c) 25 °C, addition of dichlorophenolindophenol [55].
Curve (c) represents the isolated difference spectrum for the oxidation of cytochrome-f-407-424-555.

Ordinate: Relative absorption change.
Abscissa: Wavelength [mμ].

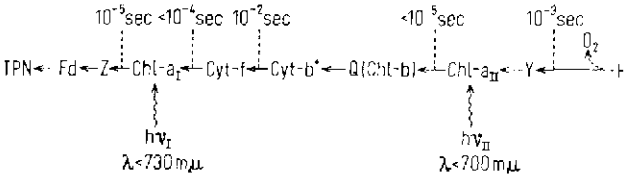
of a cytochrome-f *in vitro* [86]. After the addition of dichlorophenolindophenol the kinetics of the difference spectrum of Chl-a_I are sufficiently different from those of the difference spectrum of Cyt-f that the difference spectrum of the Cyt-f oxidation is obtained directly (Fig. 21c) [55]. The redox potential of Cyt-f *in vivo* was estimated to be about 0.4 volt [53], while the value *in vitro* is 0.37 volt [86].

2. The Chl-a_I-Cyt-f Complex

The difference between the difference spectra at −150 °C shown in Fig. 3e and in Fig. 21a can be explained by complex formation between Chl-a_I and Cyt-f [46,47]. On illumination, Chl-a_I is oxidized first. Cyt-f can then reduce Chl-a_I^+ within the complex, even at −150 °C. Further light quanta oxidize Chl-a_I a second time, so that Chl-a_I^+ and Cyt-f_I^+ are found (Fig. 21a). If at −150 °C an artificial electron donor (*e.g.* > 10^{-4} M reduced *N*-methylphenazonium methyl sulfate) is offered to the Chl-a_I^+, then Cyt-f can no longer act as the electron donor and cannot be oxidized; consequently, only the difference spectrum of Chl-a_I oxidation is observed (Fig. 3e) [47].

3. The Difference Spectrum of Cytochrome-b-412-435-563 and its Isolation

The three sets of conditions described in Section VIII,1 are not the only situations in which cytochrome-f takes part in the transfer of electrons; it is also involved under normal conditions, although in association with cytochrome-b. In the dark, cytochrome-f exists in a reduced form and cytochrome-b in an oxidized form. Cytochrome-b intervenes between Cyt-f and plastoquinone (Scheme 6) [56].



Scheme 6. Positions of cytochrome-b and cytochrome-f in the photosynthetic chain [47, 56].

This is shown by the following observation: if only Chl-a_I is excited, *e.g.* with light of wavelength 720 mμ ($h\nu_I$ only), Chl-a_I and subsequently Cyt-f are oxidized. The difference spectrum obtained must therefore be the sum of the difference spectra of these two substances (Fig. 22b).

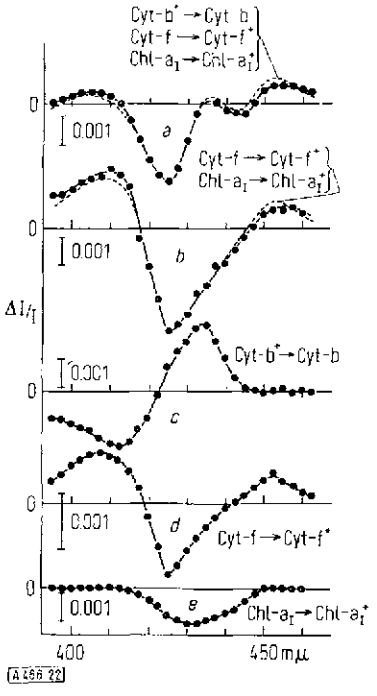


Fig. 22. a) Complex difference spectrum of illuminated spinach chloroplasts under normal conditions (continuous line); sum of the isolated difference spectra c-e (broken line) [56].

b) Difference spectrum on illumination with λ = 720 mμ (continuous curve); sum of the isolated difference spectra d and e (broken curve).

c) Difference spectrum of cytochrome-b on illumination with λ = 650 mμ after pre-illumination with λ = 720 mμ.

d) Difference spectrum of cytochrome-f with the addition of dichlorophenolindophenol (cf. Fig. 21c).

e) Difference spectrum of chlorophyll-a$_I$ on illumination of aged chloroplasts (cf. Fig. 3b).

Curve c represents the isolated difference spectrum for the reduction of cytochrome-b-412-435-563$^+$.

Ordinate: Absorption change $\Delta I/I$.
Abscissa: Wavelength [mμ].

On subsequent excitation of Chl-a_I and Chl-a_{II}, *e.g.* with light of wavelength 650 mμ ($h\nu_I$ and $h\nu_{II}$), the $h\nu_I$ illumination keeps Chl-a_I and Cyt-f in the oxidized state; according to Scheme 6, the $h\nu_{II}$ illumination should reduce Cyt-b$^+$ by an electron transfer from water, *via* Y and plastoquinone. Thus only the difference spectrum due to a reduction of Cyt-b$^+$ should be observed (Fig. 22c). This corresponds indeed to that obtained in the chemical reduction of Cyt-b$^+$ *in vitro*.

[86] *H. E. Davenport* and *R. Hill*, Proc. Roy. Soc. (London), Ser. B, *139*, 327 (1952).

The redox potential of Cyt-b *in vitro* is −0.03 volt [87]. Under normal conditions, the cytochromes cannot be observed directly, since the oxidation of Cyt-f and the reduction of Cyt-b^+ lead to an uncharacteristic interference of the associated absorption changes (Fig. 22c and d). Cytochrome-f, however, appears (Fig. 21) as a result of the alterations mentioned in Section VIII.1, since these suppress the Cyt b reaction and prevent the interference:

a) The electron transfer to Cyt-b^+ is blocked at low temperatures.

b) If only cyle I is stimulated with light of wavelength 710 mμ ($h\nu_I$ only), the reduction of Cyt-b^+ does not occur.

c) When dichlorophenolindophenol is added, the electrons are intercepted from the plastoquinone Q, so that the reduction of Cyt-b^+ is blocked. The electron donor for Cyt f in this case is the dichlorophenolindophenol reduced by Q^-.

IX. Quantitative Analysis of the Short-Lived Absorption Changes during Photosynthesis

The analysis of the absorption changes between 400 and 800 mμ is complete if the sum of the isolated difference spectra of Chl-a_I, Chl-b, Cyt-f, and Cyt-b gives the complex difference spectrum under normal conditions (Fig. 3a or 10a). The absorption changes at 703 mμ are entirely due to Chl-a_I (Fig. 3), those at 648 mμ to Chl-a_I and Chl-b, and those at 478 and 513 mμ entirely to Chl-b (Fig. 10). Between 400 and 450 mμ the absorption changes due to Chl-a_I, Cyt-f, and Cyt-b appear. Their isolated difference spectra are shown in Fig. 22c–e. The sum is indicated by the broken curve in Fig. 22a, which exhibits excellent agreement with the complex difference spectrum under normal conditions (continuous curve, Fig. 22a) [56].

X. Rate of Cleavage of Water

Emerson et al. have measured the oxygen yield of *Chlorella* cells which were illuminated by periodic flashes, as a function of the dark period between the flashes (flash manometry). The time required to obtain half of the maximum yield was taken as the half-live of the rate-determining step of the overall reaction (approximately 10^{-2} sec at 20 °C) [16,84]. We have also used this method, but in a considerably modified form: we determined the oxygen yield in the *isolated* reaction cycle II, and used such a high concentration of dichlorophenolindophenol that the electrons were very rapidly (5×10^{-4} sec) intercepted from $(Chl\text{-}b)^-$, so that this step was no longer rate-determining. Measurements under these conditions should yield direct information regarding the rate-determining step between H_2O and Chl-a_{II}.

[87] *R. Hill*, Nature (London) *174*, 501 (1954).

In order to obtain conclusive results, we used periodic flash illumination and groups of flashes.

The first observations made on excitation with groups of flashes indicated a two-phase formation of O_2, characterized by half-lives of about 10^{-1} and 10^{-3} sec [41]. Periodic flash illumination gave a half-life of 10^{-2} sec, which was explained as the resultant of the partial reactions taking 10^{-1} and 10^{-3} sec. Recent measurements [81] have shown, however, that the reaction with a half-life of 10^{-1} sec was simulated by a fall in the activity of the chloroplasts. Both illumination with groups of flashes and periodic flash illumination give a single-step formation of O_2, characterized only by a half-life of $\tau^A_{1/2} \approx 2\times10^{-3}$ sec (20 °C) (Fig. 23, curve A). This half-life corresponds to the rate of cleavage of water.

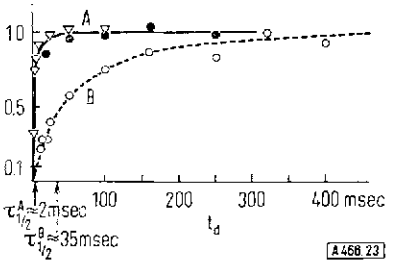


Fig. 23. Relative oxygen yield per flash as a function of the dark time t_d between flashes [81] Subject: spinach chloroplasts. 20 °C.

Curve A: Isolated reaction cycle II on excitation with double flashes (▽) and periodic flashes (●).

Curve B: Complete reaction system on excitation with periodic flashes (○).

Ordinate: (Quantity of O_2 per flash at t_d)/(Quantity of O_2 per flash at t_d = 320 msec).

Abscissa: Dark time t_d between flashes [msec].

XI. Rate of the Overall Reaction and Location of the Rate-Determining Reaction

In agreement with results obtained by *Clendenning et al.* [88], experiments with periodic flash illumination on the complete chloroplast system (cycles I and II) with added electron acceptor I [$K_3Fe(CN)_6$] gave a half-life of $\tau^B_{1/2} \approx 3.5\times10^{-2}$ sec at 20 °C (Fig. 23, curve B) for the rate-determining reaction. This value agrees closely with that deduced in Section VII,4 from absorption changes for the rate-determining step between cycles I and II in *Clorella* cells (1×10^{-2} to 4×10^{-2} sec at 25 °C). From this it follows that the rate-determining step of the overall reaction is located between the cycles I and II.

XII. The Anomalies on Continuous Illumination with Light in the Far Red

Far red light (λ = 700 to 730 mμ, $h\nu_I$ only) excites only Chl-a_I in cycle I (Fig. 17). If the changes in the absorption of Chl-a_I at 703 mμ caused by flashes *e.g.* of wavelength 638 mμ ($h\nu_I$ and $h\nu_{II}$) are measured as a function of the intensity of the additional continuous far red

[88] *K. A. Clendenning* and *H. C. Ehrmanntraut*, Arch. Biochem. *29*, 387 (1950).

illumination, the results obtained are as follows (Fig. 24): With continuous illumination at a *medium* intensity (b in Fig. 24), the absorption changes described earlier (Fig. 4) are observed in *Chlorella* on flash illumination (time t_3). With *weak* continuous illumination I (down to $I \rightarrow 0$), the absorption changes on flash illumination (time t_1) practically disappear completely (a in Fig. 24). With *more intense* continuous illumination (time t_5), the zero-point of the absorption changes moves; this gives rise to positive absorption changes (Fig. 24c) which have already been observed by *Kok* in pigment 700 [43].

1. The Chl-a_I-Cyt-f Complex

The interpretation of curves a and b in Fig. 24 is found in the existence of a Chl-a_I-Cyt-f complex [46] (cf. Section VIII.1). With *weak* additional continuous illumination (curve a), Chl-a_I and Cyt-f are present in the reduced form. On flash illumination (t_1), Chl-a_I is oxidized

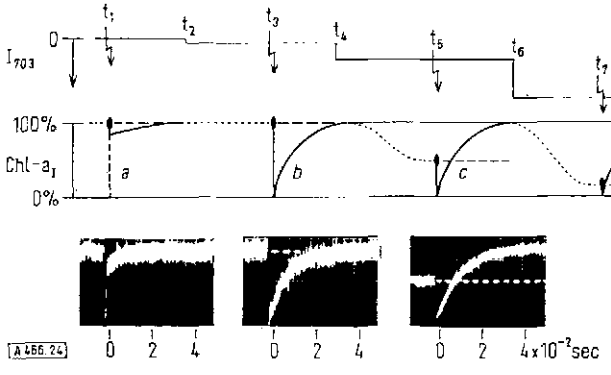


Fig. 24. Time variation of the change in the absorption of chlorophyll-a_I at 703 mμ (bottom) as a function of the intensity of additional continuous light (top) [89]. Wavelength of the continuous light: 703 mμ. Subject: *Chlorella* cells. A course as shown by curve d is not observed experimentally in *Chlorella* cells (see text, Section XII, 1).

Flash illumination lasting 10^{-5} sec at time t = 0.

Ordinate: Top: Intensity of continuous illumination at 703 mμ.
Bottom: Relative absorption change at 703 mμ.
Center: Absorption change converted to % Chl-a_I (left) and % Chl-a_I^+ (right).

Abscissa: Time [sec].

in $< 10^{-5}$ sec and is so rapidly reduced again in the complex by Cyt-f ($< 10^{-4}$ sec) that the associated absorption changes cannot be observed [52]. (This made possible the physical separation of the difference spetrum of Chl-b from that of Chl-a_I; Section V.1). At *medium* intensities of the continuous illumination (curve b) Cyt-f is permanently oxidized. On flash illumination (t_3), Chl-a_I is also oxidized. The reduction of Chl-a_I^+ cannot be faster than the transfer of an electron from cycle II *via* Cyt-f^+. The time required for this is about 10^{-2} sec (Section VII.4). With *more intense* continuous illumination (curve c), part of the Chl-a_I is permanently oxidized in addition to the Cyt-f. Flash illumination (t_5) can oxidize only the portion of the Chl-a_I that has remained in the reduced form. The negative absorption changes are therefore correspondingly weaker. The electrons supplied by cycle II reduce the Chl-a_I^+ which has been oxidized by the additional continuous illumination and the flash illumination, with consequent positive absorption changes rising above the zero line. All these observations agree with the reaction scheme outlined earlier. However, the fact that Chl-a_I is oxidized only to a maximum extent of 50% by continuous light of *high* intensity still remains unexplained. If oxidation were complete, curve d in Fig. 24 should be obtained. Since this is not the case, about 50% of the Chl-a_I behaves differently from the remainder.

2. The Electron Acceptor I for Z^-

Corresponding measurements on chloroplasts (Fig. 24 refers to *Chlorella* cells) show positive absorption changes only on addition of one of the electron acceptors I listed in Table 1 (Fig. 25a, b). This is understandable, since in the absence of the electron acceptor I, the electrons flow back from Z^- to Chl-a_I^+ (Scheme 2), so that the additional continuous light cannot cause an accumulation of Chl-a_I^+. Electron acceptors I suppress the reverse flow and so permit Chl-a_I^+ to accumulate. Flash illumination (t_2) then causes the oxidation of the remaining Chl-a_I. As in *Chlorella* the electron transfer from cycle II takes 10^{-2} sec; it brings about the reduc-

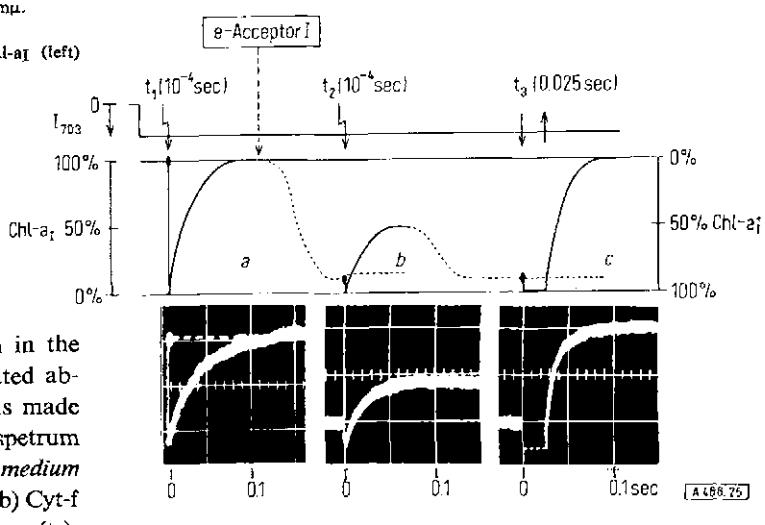


Fig. 25. Time variation of the change in the absorption of chlorophyll-aI at 703 mμ (bottom) as a function of the intensity of the additional continuous illumination (top) [89]. Wavelength of continuous illumination: 703 mμ. Subject: spinach chloroplasts.

Ordinates: Top: Intensity of continuous light at 703 mμ.
Bottom: Relative absorption change at 703 mμ.
Center: Absorption change converted to % Chl-a_I (left) and % Chl-a_I^+ (right).

Abscissa: Time [sec].

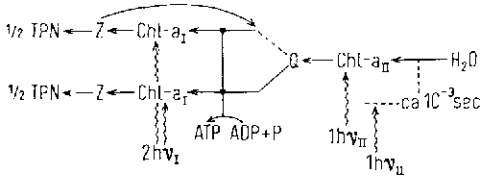
[89] *B. Rumberg*, Doctorate Dissertation, Technische Universität Berlin, 1965.

tion of the Chl-a_I^+ and gives rise to the absorption increase associated with this reduction (Fig. 25b). The transition from negative absorption changes (Fig. 25a) to positive (Fig. 25b) was used to find the electron acceptors I which react with Z^- (Section IV.8) [48,62].

In the presence of electron acceptors I, the total absorption change is halved (Fig. 25a, b); positive absorption changes which correspond in magnitude to the negative changes occur only on flash illumination for a period of $\geqslant 10^{-3}$ sec (t_3) (Fig. 25a,c). Thus approximately 50% of the Chl-a_I molecules in chloroplasts also behave differently from the remainder.

3. Two Reactions of Chl-a_I

50% of the Chl-a_I molecules evidently take part in a reaction which has not yet been detected. A second Chl-a_I cycle may run parallel to cycle I (Scheme 7). It must then be assumed that a cyclic flow of electrons (bent arrow in Scheme 7) takes place in one of the Chl-a_I cycles in *Chlorella*, since only 50% of the Chl-a_I can be accumulated as Chl-a_I^+ (Section XII.1). The fact that the positive absorption changes in chloroplasts are doubled at a flash period of $\geqslant 10^{-3}$ sec (Fig. 25c) is related to the rate of cleavage of water (10^{-3} sec, Section X). In $\geqslant 10^{-3}$ sec, at least two electrons can be transferred from the water to plastoquinone, and thence to Chl-a_I^+.

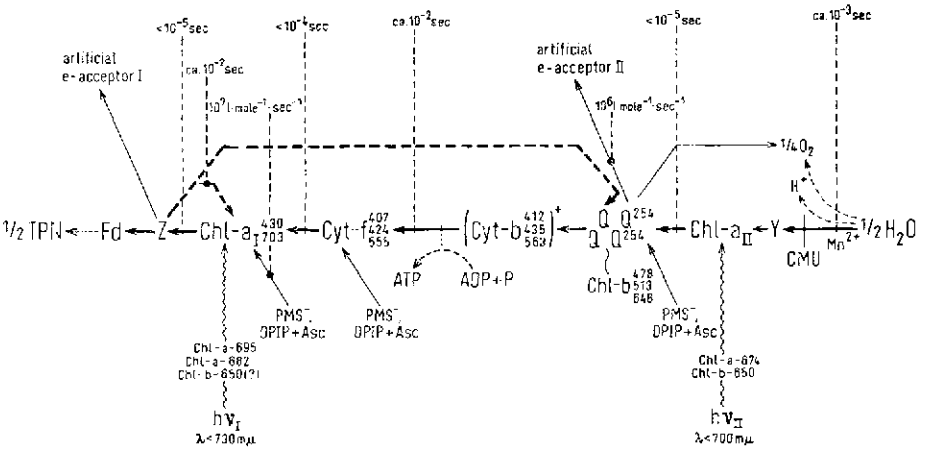


Scheme 7. Two parallel Chl-a_I cycles. (Concerning the reaction ADP + P → ATP, see Section XIII, 3).

XIII. The Overall Reaction

1. The Flow of Electrons

The facts established so far are summarized in Scheme 8, which shows the transfer of electrons from water, *via* intermediates, to TPN. The heavy continuous arrows indicate the direction of the electron flow, while the heavy broken arrows show the cyclic electron flow from Z^- to Chl-a_I^+ and Q. The thin arrows correspond to the flow of electrons in chloroplasts under artificial conditions: (a) interception of the electrons from Z^- by electron acceptors I (Section IV.8); (b) interception of electrons from $(Chl\text{-}b)^-$, *i.e.* plastoquinone Q^-, by electron acceptors II (Section V.6) and by oxygen (Section V.17). Electron donors such as PMS and DPIP (with ascorbate)



Scheme 8. Electron transfer in photosynthesis [74].

TPN = Triphosphopyridine nucleotide
Fd = Ferredoxin
Z = Experimentally detected but chemically unknown intermediate
Chl-a_I = Chlorophyll-a_I
Cyt-f = Cytochrome-f
Cyt-b = Cytochrome-b
Q = Plastoquinone
Chl-b = Chlorophyll-b
Chl-a_{II} = Chlorophyll-a_{II}
Y = Experimentally detected but chemically unknown intermediate
ATP = Adenosine triphosphate
ADP = Adenosine diphosphate
P = Phosphate
CMU = *N*-*p*-Chlorophenyl-*N'*-dimethylurea
PMS = *N*-Methylphenazonium methyl sulfate
DPIP = 2,6-Dichlorophenolindophenol
Asc = Ascorbate

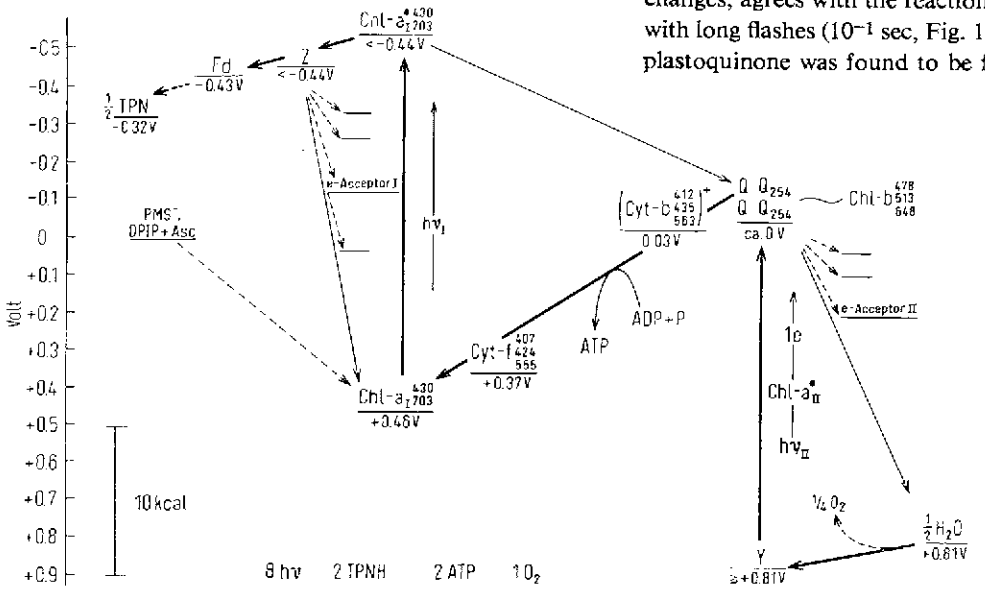
The figures beside the symbols Chl, Cyt, and Q indicate the maxima of the absorption changes. Also indicated are the times required for the various electron transfer processes.

can be coupled to (c) Chl-a_I (Section IV.4), (d) Cyt-f (Section VIII.3), and (e) plastoquinone (Section VII,5). The wavy lines represent the incident light quanta. The times are the durations of the electron transfers. The energy thresholds are overcome by the absorption of energy in Chl-a_I and Chl-a_{II}. The energy of the absorbed light is supplied to these molecules by energy transfer. The chlorophyll types Chl-a-695, Chl-a-682, and probably Chl-b-650 help to supply energy to Chl-a_I, while the types Chl-a-674 and Chl-b-650 help to supply Chl-a_{II}. Chl-a_I can be excited with light of wavelength < 730 mμ, and Chl-a_{II} with wavelengths < 700 mμ. Chl-a_I in the excited state Chl-a_I^* has such a low redox potential (< -0.44 volt) that it is capable of reducing Z (redox potential < -0.44 volt). Chl-a_{II}^* causes an electron transfer from Y to plastoquinone Q. The electron from Z^- is transferred to TPN *via* ferredoxin and flavoprotein. Y^+ is reduced by water, with formation of H^+ and $^1/_4O_2$. Chl-a_I^+ is reduced by Cyt-f, and Cyt-f^+ is reduced in turn by the transfer of an electron from Q^- (*via* Cyt-b^+). We

have placed Cyt-b$^+$ in brackets because its position in the chain is not yet accurately known.

2. The Energy Diagram

It is possible, on the basis of the redox potentials of the intermediates, to construct an energy diagram for the electron transfer (Scheme 9).



Scheme 9. Energy diagram for the electron transfer during photosynthesis, as represented in Scheme 8 [74].
Ordinate: Redox potential.

3. Phosphorylation

The redox potentials show that the transfer of electrons from Q to Cyt-f is accompanied by the liberation of approximately 10 kcal/mole, which may be used to form ATP from ADP and phosphate. For this reason, the phosphorylation step is inserted at this stage in Schemes 8 and 9 [46, 53].

4. Quantum Yields

It can be seen from Schemes 8 and 9 that the absorption of 8 light quanta ($4\ h\nu_I + 4\ h\nu_{II}$) is accompanied by the formation of 2 TPNH, 2 ATP, and 1 O_2. (The formation of 2 ATP is shown by the fact that 1 molecule of ATP is formed during the flow of two electrons [9]). A similar quantum yield is found by direct measurement: 8–10 quanta per molecule of O_2 (Section I.6). According to the Calvin cycle, however, the reduction of CO_2 requires 2 TPNH and 3 ATP [5]. The third molecule of ATP may be formed by the reverse flow of electrons from Z^- to Q (broken arrow in Scheme 8). This requires two further light quanta, so that the formation of 2 TPNH, 3 ATP, and 1 O_2 requires a total of ten light quanta.

5. Stoichiometry of the Primary and Intermediate Products

The extinction coefficients of the pigments *in vitro* and the magnitudes of the absorption changes *in vivo* give concentrations of Chl-a_I [47], Cyt-f, and Cyt-b [56] *in vivo* which are approximately 1000 times smaller than the total chlorophyll concentration. This agrees with the results obtained from oxygen measurements, *i.e.* that only one thousandth of all the chlorophyll molecules present are engaged in photosynthesis (Section I.5). On the other hand, the ratio Chl-a_f:Cyt-f:Cyt-b $\approx$ 1:1:1, as found from the extinction coefficients and absorption changes, agrees with the reaction scheme. On excitation with long flashes (10^{-1} sec, Fig. 16), the concentration of plastoquinone was found to be four times greater than that of Chl-a_I, Cyt-f, and Cyt-b [60] (the total quantity of plastoquinone is actually 40 times greater [90]). This agrees with the fact that extracted plastoquinone returns to its original position when it is recondensed with the system, and is possible only if a large quantity of plastoquinone is located between cycles I and II.

6. Concluding Remarks

The very fast reaction of chlorophyll-a_I [44,45] (see Section III) is not included in Scheme 8. It is perhaps related to the excited states of the Chl-a molecules.

The triplet states of chlorphyll-a_0 and chlorophyll-b_0 [64] (Section III) have so far been detected *in vivo* only after the chloroplast structure had been altered and the photosynthesis deactivated. If these states are involved in photosynthesis, their half-lives must be less than 10^{-5} sec [64].

Ke [91] has confirmed the results discussed in Sections IV, 2 and IV, 4.

Amesz [92] has carried out measurements on *Chlorella* cells and blue algae, and was able to verify the reduction of plastoquinone which we had detected optically in chloroplasts (Section V, 15) [57] and *Chlorella* cells (Section VII, 2) [60].

Chance et al. [93] deduced from kinetic investigation of the cytochrome reaction in bacteria that the primary processes take less than 10^{-5} sec. Thus they cast doubt on the Chl-a_I process in green cells (which according to our results has a half-life of $< 10^{-4}$ sec, but 10^{-2} sec with additional continuous illumination) as a primary process. This conclusion is invalid, however, since the oxidation of cytochrome-f on

[90] *F. I. Crane*, Plant Physiol. *34*, 128, 546 (1959).
[91] *B. Ke*, Biochim. biophysica Acta *90*, 289, 297 (1964).
[92] *I. Amesz*, Biochim. biophysica Acta *79*, 257 (1964).
[93] *B. Chance* and *D. Devault*, Ber. Bunsenges. physikal. Chem. *68*, 722 (1964).

additional continuous illumination (Section XII, 1) was not taken into account.

Duysens [42] obtained a difference spectrum of cytochrome caused by long-wave illumination in red algae. According to our results (Section VII, 1), the oxidation of Cyt-f and that of Chl-a_I occur together under these conditions. The difference spectrum observed by *Duysens* is therefore composed of the absorption changes due to the oxidation of Cyt-f and of Chl-a_I.

Measurements carried out by *Chance* [94], *Rubinstein* [95], *Fork* [96], and *Kok et al.* [70c] led to different views regarding the interpretation of the absorption changes at about 515 mμ. These are partly explained, however, if the results discussed in Section VII, 6 are taken into account.

Scheme 8 represents the present-day knowledge of electron transfer in photosynthesis as analysed by flashlight techniques. It explains the Emerson effect (Section I.8), as well as many phenomena that were not previously understood. It agrees with more recent results obtained by other methods [1–4]. However, it also brings to light a number of new problems (Section XII.3). The Scheme will have to be supplemented and refined by further measurements. It is of particular interest to obtain detailed information on the mechanism of the cleavage of water in reaction cycle II, on the mechanism of phosphorylation and on the structure of the electron transport system described.

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[94] *B. Chance* and *R. Sager*, Plant Physiol. *32*, 548 (1957).

[95] *D. Rubinstein* and *E. Rabinowitch*, Biophysic. J. *4*, 107 (1964).

[96] *D. C. Fork* and *Y. de Kouchkovsky*, Annual Rep. Carnegie Inst., Dept. Plant Biol. *63*, 441 (1964).

Structure Determination of Free Molecules by Electron Diffraction

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The intensity of electrons scattered by a gas can be calculated with classical as well as with quantum-mechanical methods. The range of validity of the equations obtained can be found experimentally. Comparison of the calculated and empirical intensity or radial distribution curves allows the determination of the structure and amplitudes of vibration of a molecule. – For example, it has been found that the two bromine atoms in cis-1,3-dibromocyclobutane occupy equatorial positions. The benzene rings in biphenyl derivatives are inclined at about 45° to each other. In biscyclopentadienylberyllium, the metal atom is not located midway between the two rings.

1. Introduction

In a survey article written in 1959 [1] a bright future for the electron diffraction method in the study of gas molecule structures was anticipated. The development during the last five years has shown that this optimism was justified. The established groups are growing, new groups are entering the field, and new and better equipment is being built. On the other hand, experience shows that design and construction of modern electron diffraction apparatuses are more time consuming than usually foreseen, considering the rather simple principles on which the method is based.

The theoretical basis for the method has recently been described in an up-to-date article by *Spiridonov, Rambidi*, and *Alekseev* [2]. We shall therefore confine ourselves to a short review of the theory, including only what is considered necessary for the application of the method. A comprehensive survey of the field will not be attempted; we shall rather outline what we consider to be the main features of the development by a few examples mostly taken from recent work of our own group.

[1] *O. Bastiansen* and *P. N. Skancke*, Adv. chem. Physics, Vol. III, 323 (1960).

[2] *V. P. Spiridonov, N. G. Rambidi*, and *N. V. Alekseev*, Zh. Strukturnoi Khim., *4*, 779 (1963); J. Struct. Chem. *4*, 717 (1963) (English transl.).

2. Theory

For a rigid molecule the electron diffraction intensity may be approximated by the following classical expression:

$$I_t(s) = \frac{K}{s^4}\left\{\sum_i [(Z_i - F_i)^2 + S_i] + \sum_{i,j}{}' \left[(Z_i - F_i)(Z_j - F_j)\frac{\sin R_{ij}s}{R_{ij}s}\right]\right\} = I_b(s) + I_m(s) \qquad (1)$$

where $s = (4\pi/\lambda)\sin\vartheta$;
λ = wavelength;
ϑ = Bragg angle;
K = a constant at constant electron velocity;
Z_i = atomic number of the ith atom;
F_i = scattering factor of the ith atom;
S_i = incoherent scattering factor of the ith atom;
R_{ij} = distance between the ith and jth atoms.

Only the second term in (1), *i.e.* $I_m(s)$, contains information about the molecular structure, and the discussion will therefore mainly concern this term. Apart from the obviously wrong assumption that the molecule is rigid (this will be discussed later), the expression for $I_m(s)$ given in (1) depends on the validity of the classical treatment of the scattering process. For a better approximation, the problem must be treated quantum mechanically.

In the following, the most important equations will be presented without proof, and the usual approximations will be discussed. Most of the theory can be found in textbooks [3–5] and in the review article [2].

Let the differential scattering cross section be defined by

$$\sigma(\vartheta,\varphi) = (I/I_0)r^2 \tag{2}$$

where I_0 is the electron intensity incident on the scattering center, and $I(\vartheta,\varphi)$ the electron intensity scattered in the directions ϑ, φ at a distance r from the scattering center. The scattering cross section is thus the quantity found by experiment.

The Schrödinger equation for a spherically symmetrical force field V(r) is

$$\left[-\frac{h^2}{8\pi^2 m}\nabla^2 + V(r)\right]\psi(\mathbf{r}) = E\psi(\mathbf{r}) \tag{3}$$

Let the incident wave be along the z-axis. The asymptotic expression ($r\to\infty$) for $\psi(\mathbf{r})$ is

$$\psi(\mathbf{r}) = e^{ikz} + (1/r)e^{ikr}f(\vartheta);\ k^2 = (8\pi^2 m/h^2)E \tag{4}$$

if the potential falls to zero faster than the Coulomb field. From Equation (4) it is seen that the asymptotic wave function is composed of the incident plane wave and a scattered wave; $f(\vartheta)$ is usually referred to as the scattering amplitude. The differential cross section is given by

$$\sigma(\vartheta) = |f(\vartheta)|^2 \tag{5}$$

The solution of (3) may be written

$$\psi(\mathbf{r}) = e^{ikz} - \frac{2\pi m}{h^2}\int \frac{e^{(ik|\mathbf{r}-\mathbf{r}'|)}}{|\mathbf{r}-\mathbf{r}'|}V(r')\psi(\mathbf{r}')d\tau' \tag{6}$$

By letting $r\to\infty$ in Equation (6) and comparing with (4) an expression for $f(\vartheta)$ is obtained.

$$f(\vartheta) = -\frac{2\pi m}{h^2}\int e^{-ik'\cdot r'}V(r')\psi(r')d\tau' \tag{7}$$

k' is a vector of length k in the direction of the scattered wave. An approximate expression for $f(\vartheta)$ may be obtained by neglecting the scattered wave in $\psi(r')$, Eq. (4). This is known as the first Born approximation [6]. Then

$$f(\vartheta)^{Born} = \left(\frac{2\pi m}{h^2}\right)\int e^{-ik'\cdot r'}V(r')\,e^{ikz'}d\tau' \tag{8}$$

and by integration over the angle parameters (ϑ', φ')

$$f(\vartheta)^{Born} = -\frac{8\pi^2 m}{h^2}\int_0^\infty V(r')\frac{\sin(sr')}{sr'}r'^2dr' \tag{9}$$

We now go back to Equation (3) and separate $\psi(\mathbf{r})$ into polar coordinates:

$$\psi(\mathbf{r}) = R_l(r)\cdot Y_l^m(\vartheta,\varphi) = (1/r)u_l(r)Y_l^o(\vartheta) \tag{10}$$

where $Y_l^m(\vartheta,\varphi)$ are the spherical harmonics. For reasons of symmetry ψ is not a function of φ, *i.e.* $m = 0$. The radial equation is then

$$\left[-\frac{d^2}{dr^2} + \frac{8\pi^2 m}{h^2}V(r) + \frac{l(l+1)}{r^2} - k^2\right]u_l(r) = 0 \tag{11}$$

If V(r) may be neglected beyond a certain r value equal to a, the solution of (11) is

$$(1/r)u_l(r) = A_l[\cos\delta_l j_l(kr) - \sin\delta_l n_l(kr)]\ (r > a). \tag{12}$$

$j_l(kr)$ are the spherical Bessel functions, and $n_l(kr)$ are the spherical Neumann functions. By substituting the asymptotic values for $j_l(kr)$ and $n_l(kr)$ in Equation (12) we obtain

$$\frac{u_l(r)}{r} = \frac{A_l}{kr}\sin(kr - l\pi/2 + \delta_l),\ (r\to\infty) \tag{13}$$

The constant introduced above, δ_l, has the physical meaning of a phase shift.

If V(r) falls to zero faster than 1/r, Equation (11) may be written

$$\left[-\frac{d^2}{dr^2} - k^2\right]u_l(r) = 0 \tag{14}$$

when $r\to\infty$.

Expression (13) is obviously the solution of this equation. From (10) it follows that the general solution of (3), having axial symmetry, may be written

$$\psi(\mathbf{r}) = \sum_{l=o}^{\infty} a_l R_l(r)P_l(\cos\vartheta) \tag{15}$$

where P_l are the Legendre polynomials, and a_l is a constant.

By comparing the asymptotic expression $\psi(\mathbf{r})$ according to (15) with (4), A_l and $f(\vartheta)$ may be found. Using an expression of e^{ikz} in terms of Legendre polynomials,

$$e^{ikz} = \sum_{l=o}^{\infty}(2l+1)i^l j_l(kr)P_l(\cos\vartheta), \tag{16}$$

$f(\vartheta)$ is found to be

$$(f\vartheta) = \sum_{l=o}^{\infty}(2l+1)\frac{e^{2i\delta_l}-1}{2ik}P_l(\cos\vartheta) \tag{17}$$

The phase shifts may now be determined by solving (11) for the potential considered and joining the solution smoothly to the expression (12) at r = a. The solution of (11) can always be found by numerical methods. An approximate expression for δ_l valid for $\delta_l \ll 1$ is

$$\delta_l \approx -\frac{8\pi^2 mk}{h^2}\int_0^\infty [j_l(kr')]^2 V(r')r'^2\,dr' \tag{18}$$

[3] *N. F. Mott* and *H. S. W. Massey*, The Theory of Atomic Collisions, Oxford University Press, London, 1949.

[4] *L. I. Shiff*, Quantum Mechanics, 2nd ed., McGraw-Hill, New York 1955.

[5] *E. Merzbacher*, Quantum Mechanics, Wiley, New York 1961.

[6] *M. Born*, Zeits. f. Physik, *38*, 803 (1926).

It is important to note that $f(\vartheta)$ as given by (17) is complex while $f(\vartheta)^{Born}$ (9) is real.

$f(\vartheta)^{Born}$ may also be obtained by approximating $(e^{2i\delta_l}-1)$ in (17) by $2i\delta_l$. If the potential V(r') calculated from the charge distribution of an atom is introduced into (9), the following expression is obtained.

$$f(\vartheta)^{Born} = (8\pi^2 me^2/h^2)(Z-F(\vartheta))/s^2 \qquad (19)$$

Here $F(\vartheta)$ is the atomic scattering factor introduced in (1). It is interesting to note that (19) is identical with the result of classical treatment.

If the complex function $f(\vartheta)$ is written as

$$f(\vartheta) = |f(\vartheta)|e^{i\eta(\vartheta)}, \qquad (20)$$

the structure-dependent part of the intensity scattered from a rigid molecule is

$$I_m(s) = K \sum_{i,j}' |f_i|\,|f_j| \frac{\sin(sR_{ij})}{sR_{ij}} \cdot \cos[\eta_i(s)-\eta_i(s)] \qquad (21)$$

If $f(\vartheta)^{Born}$ is used, $I^m(s)$ is identical with the second term in (1).

Thus Equation (1) is valid only if the Born approximation is accepted. This approximation is best for fast electrons and light atoms. Usually $f(\vartheta)$ is not too different from $f(\vartheta)^{Born}$; therefore if $|Z_i-Z_j|$ is large, the main difference between the expressions for $I_m(s)$ given by (1) and (21) is caused by the cosine factor.

Obviously, then, a calculation of $f(\vartheta)$ is much more complicated than the calculation of $f(\vartheta)^{Born}$. For many atoms approximate values for $f(\vartheta)$ have been calculated by *Ibers* and *Hoerni* [7] using δ_l from (18) when $\delta_l \ll 1$ and by the use of the W.K.B. method otherwise [4, 5]. In most cases the Thomas-Fermi potential was used.

Recently *Bonham* and *Karle* have calculated f for uranium and fluorine [8], and uranium and argon [9] using different assumptions. The η values obtained were similar to those obtained by *Ibers* and *Hoerni*.

The background term S_i in Equation (1) did not emerge from our quantum mechanical treatment because the atom was treated as a force field. Incoherent scattering has been taken into account in reference [3].

The preceding discussion is based on the assumption that atoms in molecules have spherical symmetry. This might appear to be a poor approximation – particularly in molecules where many of the electrons participate in bond formation. This approximation was first examined by *Massey* [10]. Later *Bonham* and *Iijima* [11–13] calculated the scattering from H_2 using an approximate molecular wave function, and the scattering from H_2^+ from the exact molecular wave function, and compared the results with the intensities calculated from (1). It was found that bonding causes a decrease in the intensity for low scattering angles (for H_2^+ at $s < 5$), but the effect can be largely compensated for by drawing a proper background for low values of s. It is thus probable that the effect of bonding can usually be neglected without serious error.

Let us now return to the question of how the atomic vibrations affect the intensity. If P(r)dr is the probability of an interatomic distance between r and r + dr, it follows from (1) that for a diatomic molecule

$$s^5 I_m(s) = \text{const}(Z_1-F_1)(Z_2-F_2)\int_0^\infty P(r)\frac{\sin(rs)}{r}\,dr \qquad (22)$$

or by a Fourier transformation

$$\frac{P(r)}{r} = \text{const.}\int_0^\infty \frac{s^5 I_m(s)\sin(rs)ds}{(Z_1-F_1)(Z_2-F_2)} = \text{const.}\int_0^\infty I(s)\sin(rs)ds \qquad (23)$$

If the vibrations are assumed to be harmonic, P(r) is a Gauss function. By integration of (22) an approximate expression for the intensity is found. For a polyatomic molecule the result is:

$$I_m(s) = \frac{K}{s^4}\sum_{i,j}' (Z_j-F_i)(Z_i-F_j)\frac{\sin(R_{ij}s)}{R_{ij}s}\exp\left(-\frac{1}{2}u_{ij}^2 s^2\right) \qquad (24)$$

u_{ij} is the root-mean-square deviation from the equilibrium distance. If anharmonic vibrations are considered, one may use the following approximation [14–16]

$$I_m(s) = \frac{K}{s^4}\sum_{i,j}' (Z_i-F_i)(Z_j-F_j)\frac{\sin[s(R_{ij}-s^2\varkappa_{ij})]}{R_{ij}s}\exp\left(-\frac{1}{2}u_{ij}^2 s^2\right) \qquad (25)$$

$\varkappa_{ij}$ is a constant characteristic of the anharmonicity. $\varkappa$ is very small for most bond types and is difficult to determine from electron diffraction data. However, since $\varkappa$ is strongly correlated with R_{ij} it may be worth while to include it in the calculations if it can be estimated from spectroscopic data. Equation (25) shows that anharmonicity causes an increase with s of the wavelength of the intensity function as demonstrated by *Bartell et. al.* in CH_4 [17].

3. Experimental

In accordance with Equation (1) the diffraction pattern of monochromatic electrons scattered from a gas is characterized by diffuse concentric rings superposed on a very steep background which falls off as $1/s^4$. The concentric rings constitute the molecular intensity (Equation (24)) which is the interesting part of the total intensity for determination of a molecular structure. A microphotometer trace of such a diffraction pattern is not suited for deducing the molecular intensity. Most gas

[7] *J. A. Ibers* and *J. A. Hoerni*, Acta Cryst. *7*, 405 (1954).

[8] *R. A. Bonham* and *J. Karle*, J. Phys. Soc., Japan, *17*, Suppl. B-II, 6 (1962).

[9] *J. Karle* and *R. A. Bonham*, J. chem. Phys. *40*, 1396 (1964).

[10] *H. S. W. Massey*, Proc. Roy. Soc. (London) *A 129*, 616 (1930).

[11] *T. Iijima* and *R. A. Bonham*, Acta Cryst. *16*, 1061 (1963).

[12] *R. A. Bonham* and *T. Iijima*, J. phys. Chem. *67*, 2266 (1963).

[13] *T. Iijima* and *R. A. Bonham*, J. phys. Chem. *67*, 2769 (1963).

[14] *L. S. Bartell*, J. chem. Phys. *23*, 1219 (1955).

[15] *Y. Morino*, *Y. Nakamura*, and *T. Iijima*, J. chem. Phys. *32*, 643 (1960).

[16] *K. Kuchitsu* and *L. S. Bartell*, J. chem. Phys. *35*, 1945 (1961).

[17] *L. S. Bartell*, *K. Kuchitsu*, and *R. J. de Neui*, J. chem. Phys. *35*, 1211 (1961).

electron-diffraction work done recently is therefore based upon the sector-microphotometer procedure, in which a rotating sector compensates for the rapid decrease of the total intensity with increasing scattering angle. The sector is placed near the photographic plate, with its axis coincidental with the incident beam. In the Oslo apparatus [18] the screening effect of the sector mostly used corresponds to multiplication of the intensity curve with a factor approximately proportional to s^3, except for small diffraction angles where the opening is larger. In spite of the variation of the steep background of an un-sectored pattern from compound to compound because of the factor $(Z_i-F_i)^2$ [Equation (1)], it proves practical and sufficient to use a standard sector of known shape.

The sector correction is based on measurement of the opening of the sector under a microscope. The difference between photometer curves of un-sectored and sectored patterns is most striking. A photometer curve of an un-sectored pattern is almost completely dominated by the rapidly decreasing background intensity, and the diffraction rings are nearly lost. A photometer curve of a sectored diagram, however, exhibits clear maxima and minima.

Special care must be taken in selection of a photographic emulsion, development of the diffraction photographs, and derivation of the blackness correction in order to obtain a quantitative description of the intensity curve. Kodak B 40 plates are used at present. Development is carried out in a thermostat with effective and well controlled mechanical stirring. The blackness correction is redetermined periodically. The photographic plate is oscillated around the center of the pattern during the photometering to reduce noise due to grain size and irregularities in the emulsion.

The concept of a "diffraction point" cannot, of course, be realized experimentally. Any gas jet into vacuum has a density distribution over a certain volume. To obtain the best approximation to the ideal diffraction point and at the same time obtain sufficient gas density, it is necessary to pay particular attention to the gas-nozzle design. The principle is to have the electron beam as close as possible to the nozzle tip without touching the metal. Even the slightest grazing leads to diffraction from the metal that swamps the gas diffraction. In order to maintain a low density of gas in the rest of the camera, an efficient liquid-air trap is placed close to the nozzle.

The distance between the diffraction point and the photographic plate can be varied from a few centimeters up to about 50 cm in the Oslo apparatus. In most cases three standard distances are used. They are approximately 48, 19, and 12 cm covering the s ranges 1.25–21 $Å^{-1}$, 7–45 $Å^{-1}$, and 15–65 $Å^{-1}$, respectively. A series of exposures at each distance is studied, though the 12 cm plates are not always found necessary. It may seem superfluous to work with three different distances and such large overlap ranges. However, experience proves it necessary. Each distance optimizes observation of only a limited s range, and without a large overlap it is difficult to scale the two curves with sufficient accuracy. An error in scaling does not appreciably influence the determination of internuclear distances, but the values of u are sensitive to such errors.

The outer part of the intentity curve is important for resolving almost equal bond distances. On the other hand the contribution of the non-bonded internuclear distances to this part of the curve is damped out by molecular vibrations. The very long internuclear distances which have large amplitudes of vibration contribute only to the inner part of the intensity curve. In order to improve this part, a new camera has just been put into operation which allows exposures at distances up to 2 m between the diffraction point and photographic plate. This camera makes possible intensity studies down to 0.3 $Å^{-1}$ and should lead to a more accurate knowledge of the important s range from 1–5 $Å^{-1}$.

A time-consuming part of an electron-diffraction study is the reading of the photometer curves. Equipment for obtaining the photometer results directly on tape or punched cards is therefore being built in several laboratories.

The most hopeful prospect for the future is the adoption of counting techniques for recording scattered intensities. This would eliminate the cumbersome and inaccurate steps of photographic recording, photometering, and reading of the photometer traces. The rotating sector could be eliminated. The output of the counter would further lend itself to a mechanization of the entire calculation. Also, by counting for a sufficiently long time it may be possible to determine the molecular intensity for all scattering angles. When photographic recording is used, the molecular intensity is most often lost in the background beyond s = 60 $Å^{-1}$.

4. Calculation Methods

A molecular structure can be determined by comparing the observed molecular intensity, I_m, or its Fourier transforms with the curves calculated for various assumed structures.

A radial distribution (RD) curve may be defined by

$$\sigma(r)/r = \int_0^\infty s^5\varphi(s)I_m(s)\sin(rs)ds \qquad (26)$$

The nature of the RD curve obviously depends on the choice of the moderating function [1] $\varphi(s)$. If for a diatomic molecule

$$\varphi(s) = 1/[(1-F_1/Z_1)(1-F_2/Z_2)] \qquad (27)$$

it follows from (23) that

$$\sigma(r)/r \propto P(r)/r \qquad (28)$$

where P(r) is the radial probability function.

In the case of a polyatomic molecule the peak in the RD curve corresponding to a certain internuclear distance, R_{ij}, can be obtained in this form (28) through the choice of a proper $\varphi(s)$.

Usually one selects:

$$\varphi(s) = \frac{\exp(-ks^2)}{(1-F_m/Z_m)(1-F_n/Z_n)} \qquad (29)$$

and introduces the approximate expression (24) for I_m. Then

$$\sigma(r)/r = \int_0^\infty s^5 I_m(s)\varphi(s)\sin(rs)ds = \int_0^\infty I(s)e^{-ks^2}\cdot\sin(rs)ds \qquad (30)$$

where

$$I(s) = \text{const.}\sum \frac{n_{ij}Z_iZ_j}{R_{ij}}\frac{(1-F_i/Z_i)(1-F_j/Z_j)}{(1-F_m/Z_m)(1-F_n/Z_n)}\exp\left(-\frac{1}{2}u_{ij}^2s^2\right)\sin(R_{ij}s) \qquad (31)$$

[18] *O. Bastiansen, O. Hassel,* and *F. Risberg*, Acta Chem. Scand. 9, 232 (1955).

The sum is taken over all different distances in the molecule; n_{ij} is the number of times equivalent distances occur. It is convenient to define a set of normal curves $N_{ij}(\rho)$ by

$$\frac{\sigma(r)}{r} = \sum \frac{n_{ij} Z_i Z_j}{R_{ij}} \cdot N_{ij}(R-r) \tag{32}$$

From (30) and (31)

$$N_{ij}(\rho) = \text{const.} \int_0^\infty \frac{(1-F_i/Z_i)(1-F_j/Z_j)}{(1-F_m/Z_m)(1-F_n/Z_n)} e^{-s^2(k + u_{ij}^2/2)} \cos(\rho s) ds \tag{33}$$

If m and n denote the same kind of atoms as i and j, $N_{ij}(\rho)$ may be integrated analytically, yielding a Gaussian peak. Since the scattering factors usually have approximately the same form, *i. e.*

$$\frac{(1-F_i/Z_i)(1-F_j/Z_j)}{(1-F_m/Z_m)(1-F_n/Z_n)} \approx 1 \tag{34}$$

it follows that the shape of the other peaks will be nearly Gaussian. If not, the curve can be found through numerical integration of (33).

The same technique may be applied if complex scattering factors are used. This will introduce the factor

$$\cos[\eta_i(s) - \eta_j(s)] = \cos[\Delta\eta_{ij}(s)]$$

in the integrand.

Alternatively one can express the factor containing the F values as a series

$$c + \sum_n a_n e^{-b_n s^2} \tag{35}$$

where c, a_n and b_n are constants.

The normal curve will then be a sum of Gauss curves. Similarly, when complex scattering factors are used, an analytical expression for the normal curve may be obtained by introducing

$$\Delta\eta_{ij}(s) \approx a + bs + cs^2 \tag{36}$$

where a, b and c are constants [19]. The effect of complex scattering factors is discussed in Section 6.

It follows from (28) that when $k = 0$, $\sigma(r)$, like $P(r)$, is symmetric in the case of harmonic vibrations. However, a normal curve in $\sigma(r)/r$ is symmetric according to Equation (33). This apparent contradiction is due to the use of the approximate expression for I_m in the derivation of (33). The distance determined from the maximum of the peak in the $\sigma(r)/r$ curve is usually called $r_m(1)$ [14]. The center of gravity of the peak is called $r_g(1)$, while the corresponding parameter in the $\sigma(r)$-curve is r_g or $r_g(0)$.

It may be shown that

$$r_g \approx r_g(1) + u_g^2/r_e \tag{37}$$

where r_e is the real equilibrium distance. The difference between r_g and $r_g(1)$ may be 0.001–0.002 Å for a C–C bond, but more than 0.005 Å for a C–H bond. It is not easy to find an exact relation between r_g and r_e, though for simple molecules good approximations may be obtained [16,20–22].

The experimental RD curve according to (30) requires intensity data from $s = 0$ to $s \to \infty$. Because of experimental limitations, data are known only for a finite s range. The effect of the upper limit in the integration may be suppressed by the artificial damping factor e^{-ks^2}. The lower integration limit will change the zero line in the RD curve. Alternatively one may use theoretical data for the inner part of the intensity curve.

When the first RD curve is obtained, a rough model is deduced. Theoretical intensity curves and RD curves are calculated in order to refine the background and the zero line in the RD curve (*viz.* the inner peak of the experimental intensity curve). One may carry out a complete structure determination by continuing a trial and error procedure with the RD curves. However, one may often achieve the final results easier by a least-squares refinement of the intensity data [23–25].

On a modern computer the calculations are performed very quickly. There are, however, some problems to be discussed. The question of how to weight the data, for example, is of great importance. At present it is common to transfer the photometer curves to tracing paper. At the same time, small irregularities are more or less smoothed out. By this procedure the intensity curve may be slightly too high or too low over a considerable s interval, whereas random errors are small. We may say that the smoothing out procedure increases the correlation between the data.

As a result, the proper weight matrix should perhaps not be assumed diagonal, as is usually done. Even then it is difficult to establish the proper form. By treating many plates independently one may find an experimental weighting function, but the amount of work required is then greatly increased. General experience suggests that the weight function should at least be a function of s, perhaps of the type suggested in Fig. 1. Functions of this type are often

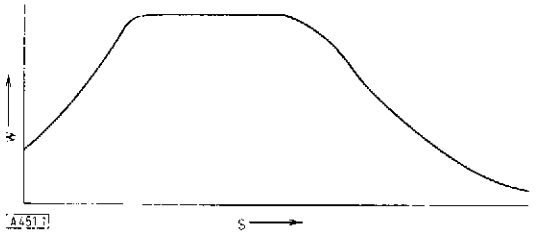


Fig. 1. Example of weight function used in least-squares calculation on intensity data.

used, but the weight should probably be a function of the slope of the photometer curve as well. The smoothing procedure mentioned above will increase the accuracy of the parameter determination by removing coarse errors and random errors to a certain extent, but reduces the estimates of standard deviations unrealistically. This agrees with general experience that standard deviations obtained through

[19] *R. A. Bonham* and *T. Ukajé*, J. chem. Phys. *36*, 72 (1962).

[20] *A. Reitan*, Acta Chem. Scand., *12*, 785 (1958).

[21] *L. S. Bartell* and *K. Kuchitsu*, J. Phys. Soc., Japan, *17*, Suppl. B-II 20 (1962).

[22] *K. Kuchitsu* and *L. S. Bartell*, J. Phys. Soc., Japan, *17*, Suppl. B-II 23 (1962).

[23] *O. Bastiansen*, *L. Hedberg*, and *K. Hedberg*, J. chem. Phys. *27*, 1311 (1957).

[24] *K. Hedberg* and *M. Iwasaki*, Acta Cryst. *17*, 529 (1964).

[25] *A. Almenningen*, *O. Bastiansen*, *R. Seip*, and *H. M. Seip*, Acta Chem. Scand. *18*, 2115 (1964).

least-squares refinement are smaller than a realistic estimate would suggest. It is possible to treat the data from each plate separately to improve error estimation.

For moderately complicated molecules the least-squares refinement yields the best estimate of the parameters without much work. For more complex molecules one may often refine some of the parameters by this method.

The method works well even when approximation (34) does not hold, and when phase shift cannot be ignored. Of course the results may also be obtained by comparing experimental and theoretical RD curves. However, the u values cannot be found directly from the experimental RD curve for non-Gaussian peaks. If the normal curves are found by numerical integration, the calculation must be carried out for a series of u values, and the correct value is determined by comparing the experimental and theoretical curves.

The examples given in Section 5 show that the interpretation of RD curves is complicated when there are many very similar distances. A peak composed of two slightly separated Gaussian peaks is itself very nearly Gaussian. This fact may be seen from Equation (42) which shows that the intensity contribution from two slightly different distances is a damped sine curve corresponding to the average distance, times a cosine factor. For small values of the argument, the form of the cosine term is very similar to that of an exponential function. Of course, for larger values of the argument the cosine function is very different from an exponential curve. For example, if $r_2 - r_1 = 0.1$ Å, the cosine term vanishes at $s = \pi/(r_2 - r_1) = 31.4$ Å^{-1}. The cosine term will thus in a certain region have nearly the same effect as an additional damping, and this region will be larger the smaller the difference between the distances. A whole series of r and u values may therefore give a good fit between the theoretical and experimental RD peak if the difference in the distances is increased while the two u values are decreased correspondingly. Therefore the outer part of the intensity curve is of great importance for the determination of overlapping distances. It is thus reasonable in such a case to calculate an undamped RD curve or even multiply the intensity data with an antidamping function (*e.g.* $\exp[-\alpha\,(s_{max} - s)]$, where α is a constant). A similar effect is obtained by the auto-correlation and crosscorrelation methods [26].

The convolution of the functions f(t) and g(t) is defined by

$$\varphi(\tau) = \int_{-\infty}^{+\infty} f(t) \cdot g(t-\tau)\,dt\,. \qquad (38)$$

If g is equal to f, $\varphi(\tau)$ is called the auto-correlation coefficient of the function. Otherwise $\varphi(\tau)$ is called the cross-correlation coefficient of the two functions f and g. Since the molecular intensity curve is composed of sine functions, it is clear that the auto-correlation function must have maxima for $\tau = \frac{2\pi n}{R_{ij}}$ (n an integer). By taking the cosine Fourier transform of the auto-correlation function, a power spectrum is obtained with peaks corresponding to the interatomic distances.

To calculate the cross-correlation function it is reasonable to let g be a damped or undamped sine curve. Since experimental intensity data can only be obtained over a finite range, Equation(38) cannot be used without modification for structure determination. However, a short interval function may be defined by

$$\varphi(\tau) = 2\alpha \int_{t_{min}}^{t_{max}} f(t) \cdot g(t-\tau) e^{-2\alpha(t_{max}-t)}\,dt \qquad (39)$$

Here t_{max} and t_{min} are the extremal values of the variable for which experimental data exist. α is a constant chosen such that

$$e^{-2\alpha(t_{max}-t_{min})} \ll 1\,. \qquad (40)$$

The corresponding short interval power spectrum is defined by

$$G(\omega) = 2 \int_{0}^{\infty} e^{-\alpha\tau} \varphi(\tau) \cos(\omega\tau)\,d\tau\,. \qquad (41)$$

The power spectra calculated by these methods give a better resolution of the peaks than the usual RD curve [26] because the intensity data for large s values are given greater weight in a power spectrum calculation than in a sine Fourier transformation of the intensity data. Since the relative errors in I(s) are greater at high than at intermediate s values (see Fig. 1), a compromise must be made between low resolution and high noise level.

5. Application to Structure Problems

The classical electron-diffraction studies of gases and vapors were nearly exclusively concentrated on the determination of the spatial structure of the molecules. During the 35 year history of the method, the accuracy of the determination of internuclear distances has steadily improved. While the method in its early development was rather crude, it has in recent years developed into a precise method, competing faforably with other structure methods. Another characteristic feature of the development of the method is its increased use for studying intramolecular motions. For simple molecules the intramolecular motion is successfully approximated by harmonic oscillations. Using this approximation the root-mean-square amplitudes (u values) are easily obtainable from electron-diffraction studies and in general agree well with those calculated from vibration spectra. In this approximation the peaks of the radial distribution curve, at least for the bond distances, should be very nearly Gaussian in shape if a proper modification function $\varphi(s)$ has been applied. However, close examination of the peaks often reveals a slight deviation from symmetry. For short distances, particularly for the bond distances, the peaks are slightly steeper on the short distance side, while the opposite is often observed for the longer, non-bonded, internuclear distances. This lack of symmetry of the bond distance peaks is associated with vibrational anharmonicity. Though the effect is small and its quantitative interpretation difficult, anharmonicity studies may well be listed among hopeful

[26] *M. Traetteberg* and *R. A. Bonham*, J. chem. Phys. *42*, 587 (1965).

prospects for the future. The asymmetry of the long distance peaks is often associated with more complex intramolecular motion. For example, the so called "shrinkage effect" [27–29], as well as restricted intramolecular torsional oscillations, lead to such asymmetry.

In Figure 2 the upper curve is the experimental RD curve for *cis*-1,3-dibromocyclobutane [30]. There are

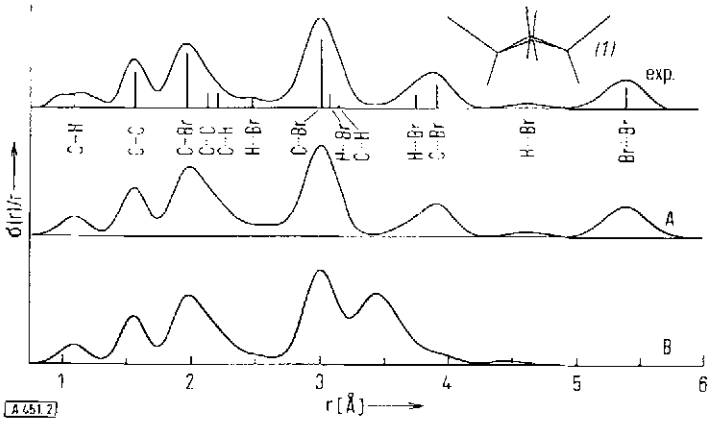


Fig. 2. Experimental and theoretical radial distribution curves for *cis*-1,3-dibromocyclobutane (k = 0.0036). Curve A: e,e conformation, curve B: a,a conformation.

eight individual peaks, each corresponding to easily identified internuclear distances as indicated on the figure. The contribution of each distance to the area under the peak is approximately proportional to the product of the atomic numbers of the two atoms involved and inversely proportional to their separation. In this case the number of internuclear distances that can be obtained directly from the RD curve is large enough for the determination of all the geometric structural parameters of the molecule. Both the bond distances and the longer distances determining the valence angles can be read directly from the curve. The conformation problem connected to the previously discovered deviation from planarity of the carbon skeleton [31,32] is also easily settled. The deviation from planarity makes the two C–X bonds from each carbon atom geometrically different like those in cyclohexanes. In the present molecule *(1)* the bromine atoms prefer the "equatorial" positions rather than the "axial" positions. This is readily seen by comparing the experimental RD curve with the corresponding theoretical ones also given in Figure 2.

The *cis*-1,3-dibromocyclobutane molecule has only one rather rigid conformation and the study of the RD curve leads to a quick and accurate solution for the geometry of the molecule as well as for the u values. Such a molecule is well suited for a least-squares refinement based on the intensity data. In other cases these straightforward procedures fail. An illustrative example is cyclooctane [33]. Bond lengths and valence angles can be readily obtained from the RD curve and can be refined by least-squares calculation. But for the investigation of conformation problems, a tedious study of the RD curve cannot be avoided. Since the inner part of the RD curve only contributes to the determination of bond distances and valence angles, the outer region from r approximately 2,9 Å has to be studied. In Figure 3 the upper curve is the experimental RD curve. Curves A to E are theoretical curves. Since the inner part is identical for all the theoretical curves, it is shown only once. The curves A to D represent examples of "rigid" conformations, *i.e.* conformation models for which the intramolecular motion is restricted to vibrations with small amplitudes. None of these theoretical curves agrees satisfactorily with the experimental curve. A systematic study of a large number of conformations seems to exclude any single "rigid" conformation. Further it can be shown that it is impossible to obtain satisfactory agreement between experimental and theoretical RD curves by combining a small number of different "rigid" conformations. The only solution that seems acceptable is a combination of a whole series of conformations based on a continuous variation of twist parameters. A

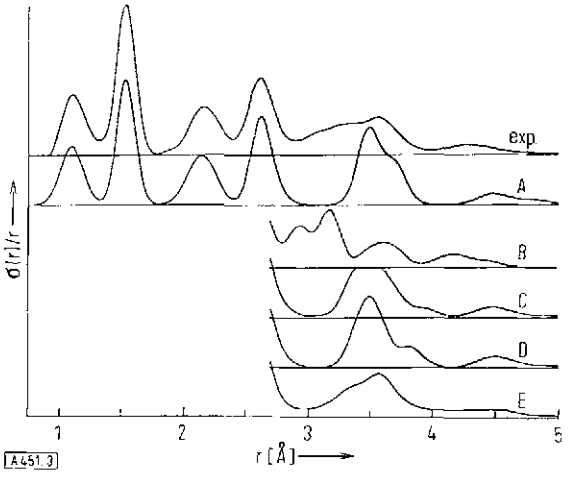


Fig. 3. Experimental and theoretical radial distribution curves for cyclooctane (k = 0.0015). Curves A to D are examples of various "rigid" conformations. Curve E corresponds to a non-rigid conformation.

theoretical RD curve based on such a non-rigid model is presented in curve E. This result does not exclude the existence of a single equilibrium conformation. It only shows that at the temperature of our experiment (40 °C) a large number of conformations occurs with approximately the same probability. These findings may also be described as restricted torsional oscillations of large amplitude.

There are many examples of intramolecular motion of the same degree of complexity as that observed in cyclooctane. In such cases it is necessary to assume that the

[27] *A. Almenningen, O. Bastiansen*, and *T. Munthe-Kaas*, Acta Chem. Scand. *10*, 261 (1956).

[28] *A. Almenningen, O. Bastiansen*, and *M. Traetteberg*, Acta Chem. Scand. *13*, 1699 (1959).

[29] *A. Almenningen, O. Bastiansen*, and *M. Traetteberg*, Acta Chem. Scand. *15*, 1557 (1961).

[30] *O. Bastiansen* and *L. Wallœe*, to be published.

[31] *J. D. Dunitz* and *V. Schomaker*, J. chem. Phys. *20*, 1703 (1952).

[32] *A. Almenningen, O. Bastiansen*, and *P. N. Skancke*, Acta Chem. Scand. *15*, 711 (1961).

[33] *A. Almenningen, O. Bastiansen*, and *Harald Jensen*, to be published.

intramolecular motion can be separated into a torsional oscillation and the vibration of a hypothetical molecule without torsional oscillation. This latter vibration is often referred to as the framework vibration. An example of considerable interest is the intramolecular motion of biphenyl and its derivatives. Biphenyls are nonplanar in the vapor phase with an angle of approximately 45° between the two ring planes [34–37]. The earlier electron-diffraction studies gave strong indications of a rather large torsional amplitude without giving quantitative information about the amplitude. A recent approach appears encouraging [38]. It is based on the study of the largest Br–Br distance of 3,3′-dibromobiphenyl and 3,5,3′,5′-tetrabromobiphenyl. This distance exhibits a well defined isolated peak on the RD curve near r = 9.2 Å. The peak is asymmetrical, being considerably steeper on the outer side. In order to estimate the framework vibration a similar molecule with a large Br–Br distance unaffected by torsion was studied. The natural choice was 3,5,4′-tribromobiphenyl, a molecule having a long Br–Br distance (3,4′) at r = 9.65 Å. The corresponding peak is less asymmetrical and not as broad as the long Br Br distance peak of the two other biphenyl derivatives. By comparing the u values of the long Br–Br distances, an estimate of the root-mean-square amplitude of the torsion angle is obtained. A preliminary calculation leads to a value of approximately 20°. This result depends on the assumption that the framework vibrational amplitude for the 3–3′ Br–Br distance is the same as the vibrational amplitude of the 3,4′ Br–Br distance in the reference substance. Further the magnitude of the amplitude of the torsional oscillation is very sensitive to errors in the u value determination.

In cases with two or three simultaneously existing conformations, each being rather rigid, the conformation problems are less complex. Classical examples of this are found among derivatives of cyclohexane. Thus *trans*-1,2-dibromo-, *trans*-1,4-dibromo-, and *trans*-1,4-dichlorocyclohexane [39, 40] exhibit two easily recognizable conformations. Other examples are the 1,2-dihaloethanes [41]. These molecules allow *trans* and *gauche* conformations. For 1,2-dichloroethane and 1,2-dibromoethane (Fig. 4) the *trans* form prevails, in agreement with earlier electron-diffraction results [42, 43] and with spectroscopic studies [44, 45]. In the bromo-compound the contribution of the *trans* conformation is 89 % (±5 %) at 20 °C. For the chloro compound the corresponding value is 73 % (±7 %) at 20 °C, a value in agreement with that found by *Ainsworth* and *Karle* [43].

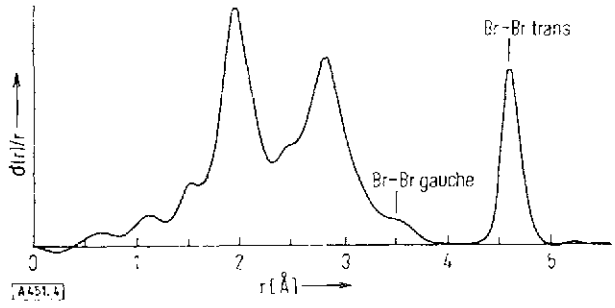


Fig. 4. Experimental radial distribution curve for 1,2-dibromoethane (k = 0.0036).

The difference in energy between the two conformations agrees reasonably with spectroscopic values for both these compounds. (The electron-diffraction values are 1630 cal/mole and 890 cal/mole for the bromo and chloro compounds, respectively; the corresponding spectroscopic values are 1700 cal/mole and 1140 cal/mole).

In 1,2-difluoroethane, however, the *gauche* conformation appears predominant. This is easily demonstrated on the experimental RD curve (Fig. 5) where both the

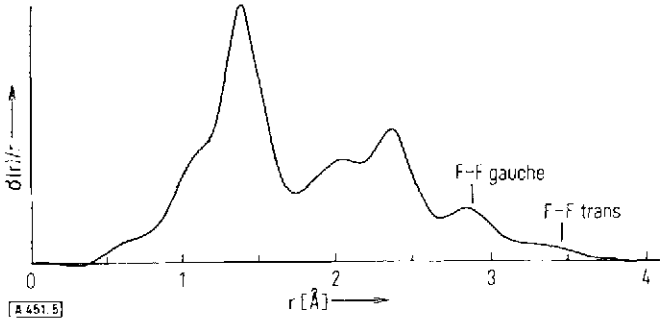


Fig. 5. Experimental radial distribution curve for 1,2-difluoroethane (k = 0.0036).

gauche and *trans* F–F distances are indicated. According to the electron-diffraction results, the fraction of the *gauche* conformation is even greater than the 67 % corresponding to energy equality of the two conformations. Spectroscopic studies by *Klaeboe* and *Rud Nielsen* [46] agree qualitatively with this result. However, they find zero energy difference, while an energy difference in the range 590–1420 cal/mole in favour of the *gauche* conformation is found by this electron diffraction study.

The structures of two sandwich compounds $(C_5H_5)_2Be$ [47] and $(C_6H_6)_2Cr$ [48], have recently been determined by electron diffraction. Careful analysis of the experimental RD curve of $(C_5H_5)_2Be$, shown in Fig. 6 A,

[34] *O. Bastiansen*, Acta Chem. Scand. *3*, 408 (1949).

[35] *O. Bastiansen*, Acta Chem. Scand. *4*, 926 (1950).

[36] *O. Bastiansen*, Acta Chem. Scand. *6*, 205 (1952).

[37] *A. Almenningen* and *O. Bastiansen*, Kgl. Norske Vid. Selsk. Skr. *1958*, No. 4.

[38] *A. Almenningen*, *O. Bastiansen*, and *Anne Holme*, to be published.

[39] *O. Bastiansen* and *O. Hassel*, Tidsskr. f. Kjemi, Bergv., Met. *6*, 96 (1946).

[40] *V. Atkinson* and *O. Hassel*, Acta Chem. Scand. *13*, 1737 (1959).

[41] *A. Almenningen*, *O. Bastiansen*, and *J. Brunvoll*, to be published.

[42] *O. Hassel* and *H. Viervoll*, Acta Chem. Scand. *1*, 149 (1947).

[43] *J. Ainsworth* and *J. Karle*, J. chem. Phys. *20*, 425 (1952).

[44] *K. Kuratani*, *T. Miazawa*, and *S. Mizushima*, J. chem. Phys. *21*, 1411 (1952).

[45] *S. Mizushima*, Structure of Molecules and Internal Rotation, Academic Press, New York, 1954.

[46] *P. Klaeboe* and *J. Rud Nielsen*, J. chem. Phys. *33*, 1764 (1960).

[47] *A. Almenningen*, *O. Bastiansen*, and *A. Haaland*, J. chem. Phys. *40*, 3434 (1964).

[48] *A. Haaland*, Acta Chem. Scand. *19*, 41 (1965).

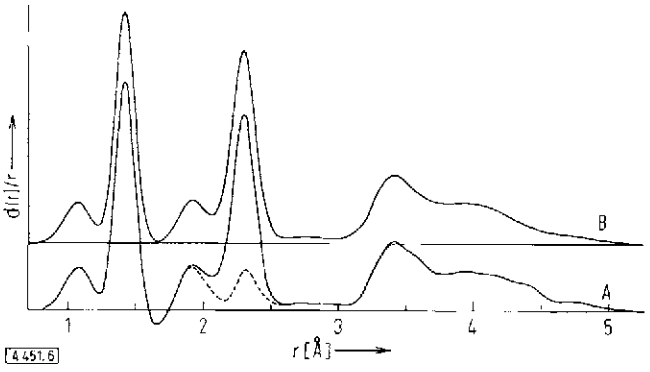
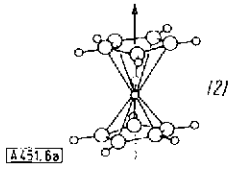


Fig. 6. Experimental (A) and theoretical (B) radial distribution curves for beryllocene (k = 0.0015).

yields the molecular structure *(2)*: The C_5H_5 ligands are planar and symmetrical with a C–C bond distance of 1.424 Å. The rings are parallel and staggered, and



except for the central atom, the molecular symmetry is as in ferrocene, D_{5d}. The beryllium atom may occupy *two* alternative positions on the fivefold axis, 1.48 Å from one ring and 1.98 Å from the other. The molecular symmetry is then C_{5v}. This surprising geometry explains two apparently contradictory observations: the large dipole moment, $\mu = 2.24 \pm 0.09$ D in cyclohexane solution [49], and the fact that the molecule occupies a centrosymmetric site in the crystal [50]. The peak at 1.1 Å in the RD curve corresponds to the C–H bond distance, the peak at 1.4 to the C–C bond distance, and the peak at 2.4 Å to the $C_1 \cdot\cdot H_2$ and $C_1 \cdot\cdot C_3$ nonbonded distances. The complex of unresolved peaks at $r > 3.0$ Å corresponds mainly to distances between atoms in different rings. The partly resolved peak at 1.9 Å must correspond to a Be–C distance; the area under it indicates that there are five such distances. An equally strong peak, corresponding to the five longest Be–C distances, is found at 2.3 Å after subtraction of the stronger $C_1 \cdot\cdot C_3$ and $C_1 \cdot\cdot H_2$ peaks. The difference curve containing only Be–C distances is given in the figure (dashed line). A theoretical RD curve calculated from the parameters of Table 1 is shown in Fig. 6B. An investigation of $(C_5H_5)_2Pb$ has been started. This molecule also has a sizable dipole moment, 1.29 ± 0.04 D in cyclohexane [51]. But the structure is rather different from that of beryllocene, in which the dipole moment arises because the tiny beryllium ion is free to move in the cavity formed between the rings. The large lead ion pushes the ligands apart, and the dipole moment is due to a non-parallel position of the rings. A preliminary RD curve indicates a closest approach of carbon atoms in different rings corresponding to an angle of 140° between the two fivefold axes, but it is not yet clear whether this is an equilibrium position.

Table 1. The molecular structure of $(C_5H_5)_2Be$ (symmetry C_{5v}) and $(C_6H_6)_2Cr$ (symmetry D_{6h}) with estimated errors.

	$(C_5H_5)_2Be$		$(C_6H_6)_2Cr$	
	r_g [Å]	u [Å]	r_g [Å]	u [Å]
(C_1-H_1)	1.076 ± 0.010	0.084	1.096 ± 0.010	0.084
(C_1-C_2)	1.425 ± 0.005	0.045	1.424 ± 0.005	0.045
(C–M)	1.918 ± 0.010	0.080	2.152 ± 0.005	0.070
(C'–M)	2.323 ± 0.015	0.080		

Two X-ray studies of the molecular structure of dibenzene chromium, $(C_6H_6)_2Cr$, have been reported. According to one of them the benzene ligands have threefold symmetry with bonds of 1.35 Å alternating with bonds of 1.44 Å, both ±0.014 Å [52]. In the other study no significant deviations from sixfold symmetry were found [53]. The experimental RD curve is very similar to that of $(C_5H_5)_2Be$, the main difference being a strong C–Cr peak at 2.15 Å. A peak at 1.09 corresponds to the C–H bond distance, and a peak at 1.42 Å corresponds to the C–C bond distance or distances, the halfwidth of the peak being determined by the bond-length difference – if any – and the root-mean-square amplitude of vibration.

As pointed out above, the sum of two closely-spaced Gaussian peaks is itself very nearly Gaussian, and a satisfactory fit can be obtained for a rather large range of bond-length differences if the u values are decreased as the difference increases. It is therefore necessary to obtain an independent estimate of u. A comparison of the C–C stretching frequencies of the two compounds shows that the u values of the C–C bond in $(C_6H_6)_2Cr$ must be equal to the corresponding u values in benzene, u = 0.045 Å [54] or slightly larger. The experimental RD curve then offers no evidence for the existence of two different C–C bond lengths: The halfwidth and shape of the peak could be accurately reproduced by assuming 12 identical C–C bonds with u = 0.045 Å. If one regards u = 0.043 Å as the lowest acceptable u value, an upper limit, $\Delta r = 0.02$ Å, on the bond-length difference is obtained.

6. Failure of the First Born Approximation

In Section 2 an expression is given for the molecular intensity when the first Born approximation does not hold [Equation (21)]. It was also shown that, except for small $|Z_i - Z_j|$ values, the main difference between the simple intensity formula (1) and Equation (21) is the factor $\cos(\Delta\eta_{ij}(s))$ [55, 56]. Since η_i is a monotonic increasing function of the atomic number Z_i, the choice of intensity expression is primarily determined by $|Z_i - Z_j|$. The complex scattering factors now available [7–9] suggest that when $|Z_i - Z_j| > 10$ the cosine term is important and should be included. For high atomic

[49] *E. O. Fischer* and *H. P. Hofmann*, Chem. Ber. *92*, 482 (1959).
[50] *R. Schneider* and *E. O. Fischer*, Naturwiss. *50*, 349 (1963).
[51] *E. O. Fischer* and *S. Schreiner*, Chem. Ber. *92*, 938 (1959).
[52] *F. Jellinek*, Nature *187*, 871 (1960); *F. Jellinek*, J. organomet. Chem. *1*, 43 (1963).
[53] *F. A. Cotton*, *W. A. Dollase*, and *J. S. Wood*, J. Amer. chem. Soc. *85*, 1543 (1963).
[54] *A. Almenningen*, *O. Bastiansen*, and *L. Fernholt*, Kgl. Norske Vid. Selsk. Skr. *1958*, No. 3.
[55] *V. Schomaker* and *R. Glauber*, Nature *170*, 290 (1952).
[56] *R. Glauber* and *V. Schomaker*, Phys. Rev. *89*, 667 (1953).

numbers the simple intensity expression may be used for somewhat greater values of $|Z_i - Z_j|$.

A normal curve (Section 4) calculated from an intensity curve containing the factor $\cos(\Delta\eta_{ij}(s))$ will be broader than a Gaussian peak with the same u value, but the form of the peak will be nearly Gaussian for moderate differences $|Z_i - Z_j|$. In such cases the Gaussian peak approximation may be used, but in order to obtain the u value, corrections have to be made. For greater differences in the atomic numbers the normal curve has two separate peaks. This fact may easily be understood by considering the molecular intensity calculated by the simple formula (31) for two nearly equal distances R_1 and R_2. The distances are assumed to have the same u value and the same value of the factor $n_{ij}Z_iZ_j$. Then from Equation (31)

$$I(s) - \text{const} \cdot \left(\frac{1}{R_1}\sin R_1 s + \frac{1}{R_2}\sin R_2 s\right) \exp(-1/2 u^2 s^2)$$
$$\approx \text{const} \cdot \frac{2}{R'} \cdot \sin(R's) \cdot \cos\left(\frac{\Delta}{2} \cdot s\right) \exp(-1/2 u^2 s^2) \quad (42)$$

where

$$R' = (R_1 + R_2)/2, \quad \Delta = R_1 - R_2.$$

In Equation (36), $\Delta\eta_{ij}(s)$ was assumed to be a polynomial of second degree. Curve A in Fig. 9 shows $\Delta\eta(s)$ for Os and O, as calculated by *Ibers* and *Hoerni* [7]. This curve suggests that one may use

$$\Delta\eta_{ij}(s) = b \cdot s \quad (43)$$

as a rough approximation.

It follows from (21) and (42) that the molecular intensity for one distance where the phase shift is included may be approximated by the molecular intensity for two distances calculated by the simple formula if $\Delta = 2b$. The experimental and theoretical molecular intensity curves for OsO_4 are shown in Fig. 7. The theoretica

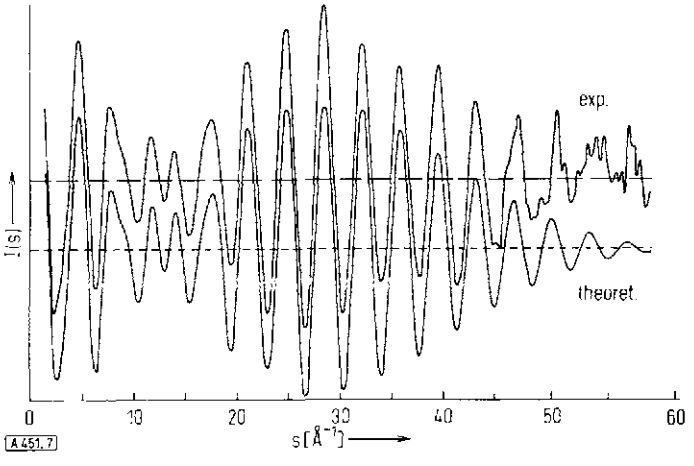


Fig. 7. Experimental and theoretical intensity curve for OsO_4.

curve was calculated using $|f(s)|$ and $\eta(s)$ values for Os and $\eta(s)$ values for O calculated by *Ibers* and *Hoerni* [7], while the assumption $|f(s)| \approx f(s)^{Born}$ was used for O [57]. Near $s = 13$ Å^{-1}, corresponding to $\Delta\eta(s) \approx \pi/2$, the intensities are very low. Fig. 7 shows that the experimental intensity data extend nearly to the point where $\Delta\eta(s) = 3\pi/2$. However, it is not possible to observe the intensity for sufficiently high values of s to see maxima beyond this point.

The theoretical intensity curve in Fig. 7 was calculated using parameters found by a least-squares refinement of the intensity data:

Os–O: $R = 1.7105$ Å ($\pm$ 0.0005); $u = 0.0339$ Å ($\pm$ 0.0007);
O–O: $R = 2.793$ Å; $u = 0.076$ Å ($\pm$ 0.0067).

The standard deviations obtained are given in parentheses; as mentioned in Section 4, they are too small. The weighting scheme used was of the form shown in Fig. 1. The parameters, in particular the distances, were not sensitive to a change in the weighting of the data.

Fig. 8 shows the experimental and theoretical RD curves for OsO_4. The theoretical curve was calculated with the

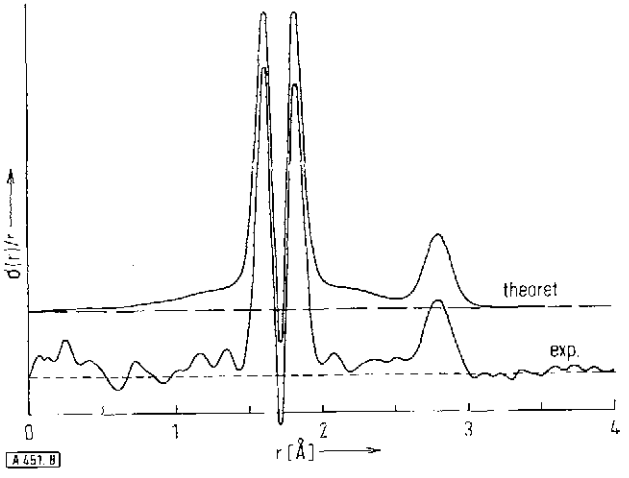


Fig. 8. Experimental and theoretical radial distribution curves for OsO_4 (k = 0.0009).

parameters obtained from the least-squares refinement, and the $|f|$ and η values were the same as used in the calculation of the theoretical intensity curve. In this case, where $Z_{Os} - Z_O = 68$, the RD curve shows two clearly separated peaks corresponding to the Os–O bond. It may be mentioned that the experimental RD curve for MoF_6 also shows a split peak corresponding to the Mo–F bond, though the separation of the maxima is smaller than observed for the Os–O bond, as expected from the smaller difference in atomic numbers ($Z_{Mo} - Z_F = 33$).

The mean amplitudes of vibration in OsO_4 have been calculated from spectroscopic data [58] to be $u_{OsO} = 0.0348$ Å and $u_{OO} = 0.070$ Å. The u values obtained in this way are fairly accurate. The distance parameters are not sensitive to small variations in the values of $|f|$ and η. All the molecular parameters are therefore known to a high degree of accuracy. It is thus possible to obtain experimental $\eta(s)$ values if the $|f(s)|$ functions are considered known. Various $|f|$ functions were assumed, and the constants in the expression (36) for the Os–O bond were obtained by a least-squares refinement of the intensity data. Fig. 9 shows the η function calculated by *Ibers* and *Hoerni* (curve A) and two experimental curves. B is found by using $|f|$ values from *Ibers* and *Hoerni* and C by assuming the same form for the $|f|$ functions for Os and O.

[57] *J. Berghuis, I. M. Haanappel, M. Potters, B. O. Loopstra, C. H. MacGillavry,* and *A. L. Veenendaal,* Acta Cryst. *8*, 478 (1955).

[58] *S. J. Cyvin, J. Brunvoll, B. N. Cyvin,* and *E. Meisingseth,* Bull. Soc. Chim. Belg., *73*, 5 (1964).

The latter approximation corresponds to (34). The result is insensitive to changes in the weighting of the intensity data. It is seen that curve B is very close to the calculated curve (A) except at very low and high s values. The standard deviation is rather high for the parameter c, which greatly influences the outer part of the curve. This investigation indicates that reliable structure determinations may be made

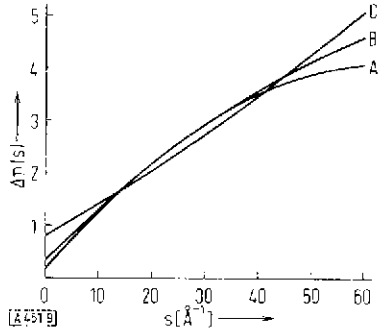


Fig. 9. $\Delta\eta(s)$ Functions for the osmium-oxygen distance.
Curve A: Calculated by *Ibers* and *Hoerni* [7].
Curve B: Experimental, based on $|f|$ values from [7].
Curve C: Experimental, assuming $|f_{Os}| \propto |f_O|$.

using $|f|$ and η data from *Ibers* and *Hoerni*. Other molecules (methyl iodide, tetramethyltin, diiodoacetylene, MoF_6, UF_6, WF_6, and TeF_6) are now being studied in a similar way to investigate further the reliability of the calculated scattering amplitudes and how errors in the $|f|$ and η data used influence the determination of structural parameters.

7. Error Estimates

In the following we will first consider experimental errors that lead to a proportionality error in the s scale and in turn to an equally great relative error in the measured distances and amplitude parameters. Errors in 1) the electron wavelength, 2) the adjustment of the accelerating potential, 3) the distance from the diffraction point to the plate, and in 4) the determination of the relative speeds of the photometer chart and plate stage all have this effect.

The wavelength of the electron beam can, of course, be calculated from the accelerating potential by means of the de Broglie relation. But sufficiently accurate measurement of potentials of this order of magnitude is difficult. In this laboratory the wave-length has till now been determined from the scattering pattern of a solid standard. The potential is then reproduced from day to day by means of an accurate potentiometer circuit. Several standards have been tried, but the most reproducible results were obtained from etched gold foil using a beam stop and a rotating sector with opening proportional to s. Eight values of the wavelength are computed and averaged. Each wavelength is calculated from the diameter of one diffraction ring measured on five plates. The difference between these values is insignificant. But the average wavelengths determined in this way over a long period of time have a standard deviation of 0.1 % from their mean. Since they appear to change smoothly with time, the last observed value rather than an average is used for the calculation of s scales. A new wavelength is determined every month. Assuming the variation to be random, we obtain an upper limit, 0.10 %, on the standard deviation of the wavelength from day to day. If it is further assumed that an equally great error is introduced when the diffraction pattern from the gas to be investigated is recorded, the standard deviation for the s scale on the photographic plate is $0.1 \cdot \sqrt{2}$ %. Since the variation of the relative speeds of the photometer chart and plate stage is insignificant, the standard deviation for the final s scale is less than 0.14 %.

The errors mentioned above strongly influence the distance parameters. Other errors influence mainly the u values, but the distance parameters will be affected if the correlation between r and u values is great. This is the case for strongly overlapping distances. Errors in the photographic blackness correction and in the opening of the sector as a function of s introduce errors in each photometer curve, and, more important, make the scaling of curves covering different s intervals uncertain. An error in the determination of the center of a plate will influence the result in a somewhat similar manner.

Large errors in the background are easily detected by comparing the experimental and theoretical intensity and RD curves. Small changes in the background will generally not influence the distance determination very much, but the u values are more sensitive to such changes. Finally, the uncertainties in the form factors should also be mentioned. Particularly for heavier atoms they are not known with the desired accuracy.

How these errors affect the result when different calculation methods are used is still rather uncertain. It was mentioned in Section 4 that the standard deviations obtained through a least-squares procedure are unrealistically small. This is at least partly due to correlation between the observed intensities. Proportionality errors in the s scale are of course not included. It seems likely that for a well separated distance the predominant source of error in r is the s scale. The standard deviation for such a distance is certainly less than 0.14 %. For the determination of u, scale errors are probably negligible compared to the other errors listed above. The magnitude and effect of these errors are hard to estimate but we believe that the u value at least for a non-overlapping C—C bond distance can be determined with an error of a few per cent. For overlapping distances the r and u are correlated, and the error limits must be considerably expanded.

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New Methods in Preparative Organic Chemistry IV [*]

New Reactions of Alkylidenephosphoranes and their Preparative Uses III [**]

Alkylidenephosphoranes and Reagents Containing Multiple Bonds

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A few examples of preparatively useful syntheses using alkylidenephosphoranes and substances containing a C–N or C–C double bond are the preparations of olefins, allenes, pyran derivatives, and cyclopropane derivatives. Olefins, ketones, and monocyclic compounds can be obtained by autoxidation of alkylidenephosphoranes; α,β-dioxo compounds (including cyclicones) can be prepared by oxidation with peroxy-acids. Alkylidenephosphoranes can also be used for the synthesis of azines and Schiff bases. Of the many possibilities offered by the Wittig reaction, only the preparation of tritiated aldehydes and olefins will be considered.

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A. Reaction with the Carbonyl Group (The Wittig Reaction)

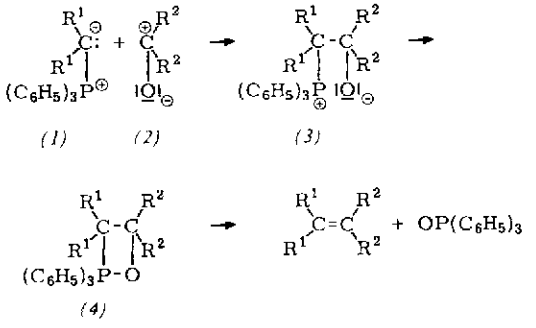
The renaissance of the chemistry of alkylidenephosphoranes (the first representative was prepared as early as 1919 [1]) began with *Wittig*'s discovery [2a–2c] that the

[*] The contributions in the previous three series have been published collectively in three volumes by Verlag Chemie, Weinheim/Bergstr. (Germany); English edition: Academic Press, New York-London.

[**] For Part I, see Angew. Chem. *77*, 609 (1965) Angew. Chem. internat. Edit. *4*, 583 (1965); for Part II, see Angew. Chem. *77*, 651 (1965); Angew. Chem. internat. Edit. *4*, 645 (1965).

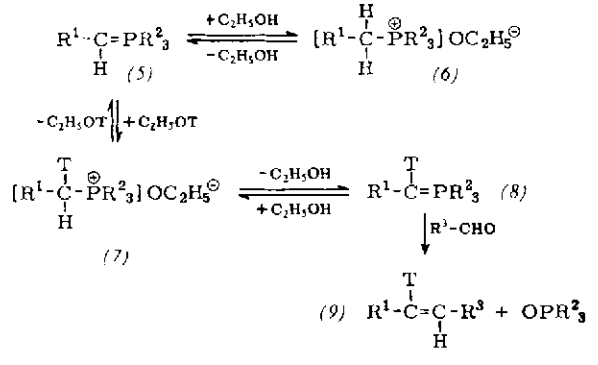
[1] *H. Staudinger* and *J. Meyer*, Helv. chim. Acta *2*, 635 (1919).

polarized C–P double bond of the ylides *(1)* can react with the polarized C–O double bond of carbonyl compounds *(2)*. The product of this reaction is a betaine *(3)*, which decomposes *via* the four-membered ring compound *(4)* into an olefin and triphenylphosphine oxide.



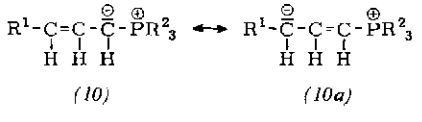
Of the many possibilities offered by the Wittig reaction, we shall discuss only the preparation of olefins labelled with tritium or deuterium [3].

Alkylidenephosphoranes *(5)* and ethanol undergo an equilibrium reaction with formation of the phosphonium ethoxide *(6)* [2c].

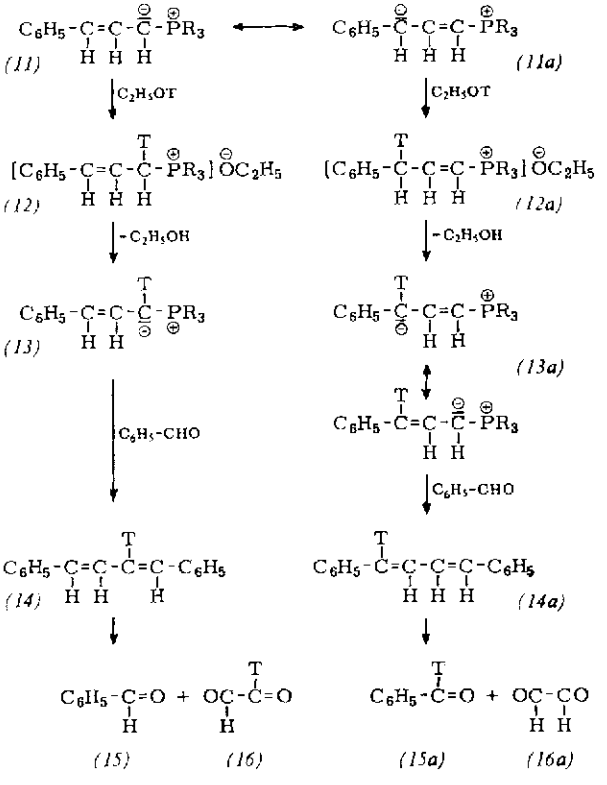


Addition of C_2H_5OT to a solution of an ylide leads to the tritiated phosphonium ethoxide *(7)*, which can lose C_2H_5OH in the equilibrium. The resulting labelled ylide *(8)* can be removed from the equilibrium by Wittig reaction with an aldehyde, giving an olefin with tritium on the C–C double bond.

Since the reaction of alkylidenetricyclohexylphosphoranes with carbonyl compounds leads only to *trans*-olefins [4], this provides a method of stereospecific labelling of olefins. This method was used to demonstrate the resonance of allylidenephosphoranes [3]. Allylidenephosphoranes of the type *(10)* should also be described by the resonance form *(10a)* [5].



Structure *(10)* shows the form which generally takes part in the Wittig reaction. Our own investigations have shown, however, that reactions of *(10a)* must also be expected in some cases, as has been confirmed for the reaction of allylidenetriphenylphosphorane with esters of chloroformic acid [6].



If a cinnamylidenephosphorane is treated with benzaldehyde in the presence of C_2H_5OT, tritium can add to both *(11)* and *(11a)*. The reaction proceeds *via* the phosphonium ethoxides *(12)* and *(12a)* to the labelled ylides *(13)* and *(13a)*, which react with benzaldehyde to 1,4-diphenylbutadienes *(14)* and *(14a)* with the T atoms in different positions. Cleavage of the double bonds with OsO_4/KIO_4 gives both labelled benzaldehyde *(15a)* and labelled glyoxal *(16)*. This shows that tritium was originally added to both *(11)* and *(11a)*.

Procedure:

[1-T]-trans-1,2-Diphenylethylene

An ethoxide solution is prepared under nitrogen from 0.40 g of sodium and 40 ml of absolute ethanol in a Schlenk tube. Most of the alcohol is evaporated off with a filter pump with the exclusion of moisture. 4.0 ml of tritiated absolute ethanol and 6.0 g of tricyclohexylbenzylphosphonium chloride are added, and the mixture is left for 1 h at room temperature to allow the tritium exchange to take place. Freshly distilled benzaldehyde (1.45 g) is then added, and the contents of the reaction vessel are refluxed for $1^1/_2$ h. At this point, it is possible to dispense with the nitrogen atmosphere. The mixture is poured into about 50 ml of 5 N hydrochloric acid, and the *trans*-stilbene which separates is filtered off. After recrystallization from methanol, the product is dried; m.p. 122 °C, yield 2.4 g (90 %).

[2a] *G. Wittig* and *G. Geissler*, Liebigs Ann. Chem. *580*, 44 (1953).

[2b] *G. Wittig* and *U. Schöllkopf*, Chem. Ber. *87*, 1318 (1954).

[2c] *G. Wittig* and *W. Haag*, Chem. Ber. *88*, 1654 (1955).

[3] *H. J. Bestmann*, *O. Kratzer*, and *H. Simon*, Chem. Ber. *95*, 2750 (1962).

[4] *H. J. Bestmann* and *O. Kratzer*, Chem. Ber. *95*, 1894 (1962).

[5] *U. Schöllkopf*, Angew. Chem. *71*, 260 (1959).

[6] *H. J. Bestmann* and *H. Schulz*, Angew. Chem. *73*, 27 (1961); Liebigs Ann. Chem. *674*, 11 (1964).

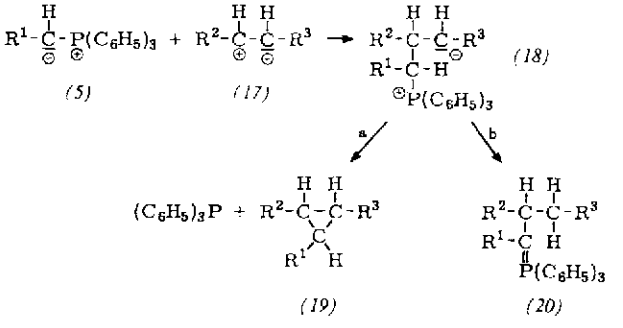
The T-activity of the ethanol before the exchange was 154 counts/min/μmole, and that of the stilbene obtained was found to be 96.2 counts/min/μmole [3].

B. Reaction with the C–C Double Bond

1. General

The Wittig reaction is introduced by a nucleophilic attack of the alkylidenephosphorane *(1)* on the polarized C–O double bond. It was expected that alkylidenephosphoranes would also react with other polarized multiple bonds to form betaines.

A series of systematic investigations was carried out, in which alkylidenephosphoranes *(5)* were treated with compounds *(17)* containing activated C–C double bonds. It was found that the initially formed betaine *(18)* can be stabilized by one of two secondary reactions (path a or path b) [7], and that the path actually followed is determined by group R^1 in the alkylidenephosphorane *(5)*.



(5) *(17)* *(18)* *(19)* *(20)*

2. Formation of Cyclopropane Derivatives

If the residue R^1 in the alkylidenephosphorane *(5)* is electron releasing, the betaine *(18)* (which can be isolated in some cases [8]) is stabilized by loss of triphenylphosphine and formation of the cyclopropane derivative *(19)* [7]. Cyclopropane formation had also been observed earlier in the reaction of a sterically hindered α,β-unsaturated ketone with an ylide [9] and in the reaction of butylidenetriphenylphosphorane with 9-butylidenefluorene [10]. The reaction can also be used for the preparation of cyclopropane derivatives which are difficult to prepare by the carbene method.

Procedure:

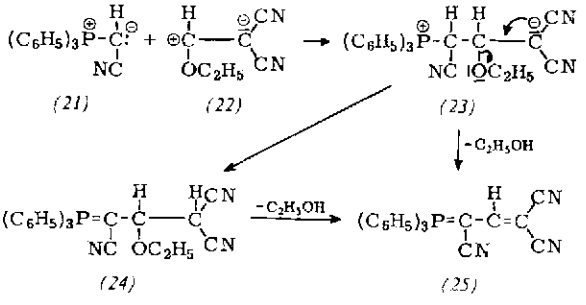
Ethyl 2,3-Dimethylcyclopropanecarboxylate

A salt-free ylide solution in benzene is prepared from 18.5 g (50 mmole) of ethyltriphenylphosphonium bromide, using the sodamide method (see Part I, Section D 2), and 5.7 g of ethyl crotonate is added. The light red solution becomes warm and turns dark red to black. After refluxing for 12 h, the reaction solution is shaken with 10 % sulfuric acid, and the benzene layer is dried over $MgSO_4$ and then boiled for 30 min with 10 g of methyl iodide to remove the triphenylphosphine. Methyltriphenylphosphonium iodide (12.1 g, 60 %) precipitates. The benzene is distilled off, and fractionation of the residue yields 3.6 g of the ethyl 2,3-dimethylcyclopropanecarboxylate, yield 50 %, b.p. 165–170 °C.

3. Michael Addition

If the group R^1 in *(5)* is electron-attracting, it loosens the α-H atom in the betaine *(18)*. The proton then migrates to the negative center of the molecule, with formation of *(20)*. The reaction may be regarded as a Michael addition of the alkylidenephosphorane *(5)* to the olefin *(17)* [7].

A third reaction path is possible if the olefin contains several strongly activating groups [11].



(21) *(22)* *(23)* *(24)* *(25)*

Cyanomethylidenetriphenylphosphorane *(21)* reacts with the strongly activated olefin *(22)* to form the betaine *(23)*. According to *Trippett*, *(23)* is stabilized by direct conversion to *(25)* accompanied by loss of alconol. It is not impossible, however, that the first step is a Michael addition to form *(24)*, followed by elimination of alcohol to give *(25)*. It is therefore not yet certain whether this reaction does in fact involve a third possibility for the stabilization of betaines [11].

Procedure:

1,2-Bis(methoxycarbonyl)-3-benzoylpropylidenetriphenylphosphorane

Equivalent quantities of methyl benzoylacrylate and methoxycarbonylmethylidenetriphenylphosphorane are boiled for 2 h in anhydrous ethyl acetate. The Michael addition product (m.p. 187 °C, yield 74 %) crystallizes on concentration of the solution in vacuum.

4. Synthesis of Pyran Derivatives

Pyran derivatives can be synthesized by Michael addition of acylalkylidenephosphoranes *(27)* to acylallenes *(26)* [12].

[7] *H. J. Bestmann* and *F. Seng*, Angew. Chem. *74*, 154 (1962); Angew. Chem. internat. Edit. *1*, 116 (1962).

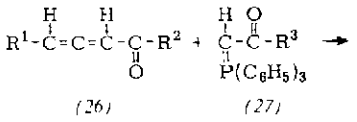
[8] *H. J. Bestmann* and *F. Seng*, unpublished work.

[9] *J. P. Freeman*, Chem. and Ind. *1959*, 1254.

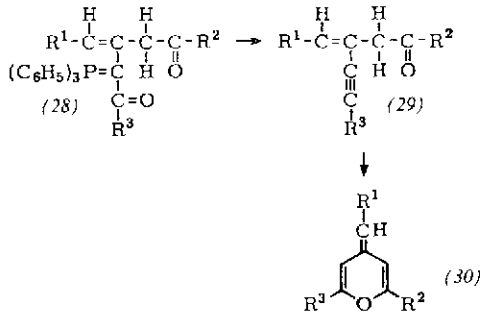
[10] *R. Mechoulam* and *F. Sondheimer*, J. Amer. chem. Soc. *80*, 4386 (1958).

[11] *S. Trippett*, J. chem. Soc. (London) *1962*, 4733.

[12] *H. Strzelecka*, *M. Simalty-Siemiatycki*, and *Ch. Prévost*, C. R. hebd. Séances Acad. Sci. *257*, 926 (1963).



(26) (27)



(28) (29) (30)

The addition product *(28)* loses triphenylphosphine oxide to form the acetylene derivative *(29)*, which undergoes ring closure in its enol form to give the pyran derivative *(30)* [12].

The allene derivative *(26)* is also postulated as an intermediate in the reaction of acid chlorides $R-CH_2-COCl$ with alkylidenetriphenylphosphoranes *(27)*, in which pyran derivatives *(30)* are also formed [12]. The mechanism of this reaction has not been fully elucidated, and no preparative data are available.

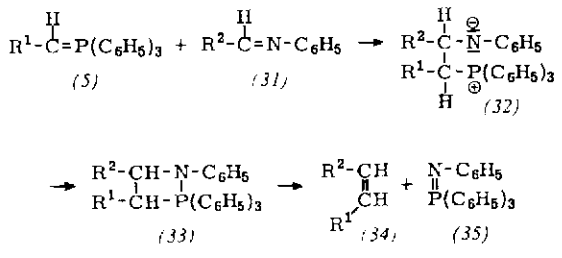
Acylethyleneimines [*(26)*, $R^1-N=$ instead of $R^1-CH=$] react in the same way as acylallenes *(26)* [13]. No preparative data are available as yet for this interesting reaction.

C. Reaction of Alkylidenephosphoranes with the C–N Double Bond

The reactions of alkylidenephosphoranes with the C–O and C–C double bonds suggest that the ylides might also react with the C–N double bond. Two such reactions are known at present [14].

1. Synthesis of Olefins by a Wittig-Type Reaction

Ylides *(5)* with no CH_2 group β to the P atom react with Schiff bases *(31)* at 150 to 180 °C. The reaction resembles the Wittig reaction, and leads to olefins *(34)* and *N*-phenyliminotriphenylphosphorane *(35)*.



(5) (31) (32) (33) (34) (35)

[13] *Idem, ibid. 258*, 6167 (1964).

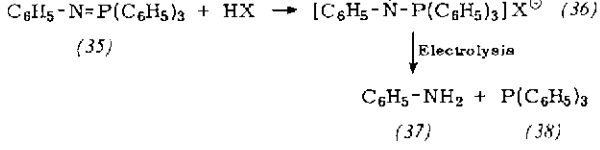
[14] *H. J. Bestmann* and *F. Seng*, Angew. Chem. *75*, 475 (1963); Angew. Chem. internat. Edit. *2*, 393 (1963); Tetrahedron 21, 1373 (1965).

It is assumed that as in the Wittig reaction, the initially formed betaine *(32)* forms a four-membered heterocyclus *(33)*, which then decomposes. Some examples of the resulting olefins *(34)* are given in Table 1.

Table 1. Olefins $R^1CH=CHR^2$ *(34)* obtained from alkylidenephosphoranes *(5)* and Schiff bases *(31)*.

R^1	R^2	Yield [%]
C_6H_5	C_6H_5	72
C_6H_5	$C_6H_5-CH=CH$	68
$C_6H_5-CH=CH$	C_6H_5	68

Triphenylphosphine can be easily recovered from the phenyliminotriphenylphosphoranes *(35)* [8].



(35) (36) (37) (38)

The iminophosphorane *(35)* readily reacts with hydrohalic acids to form a salt *(36)*, which decomposes into aniline and triphenylphosphine *(38)* on electrolysis in aqueous solution.

Procedure:

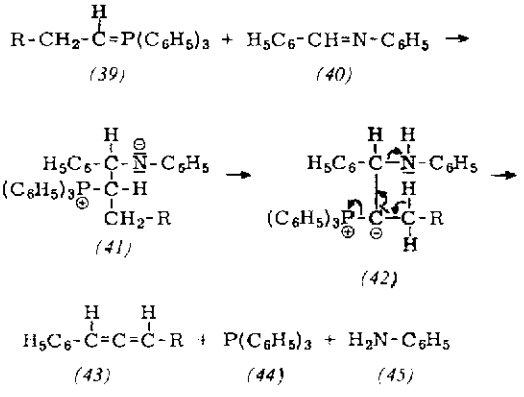
Stilbene

A benzene solution of benzylidenetriphenylphosphorane is prepared by the sodamide method (see Part I, Section D 2) from 7.8 g (20 mmole) of benzyltriphenylphosphonium chloride. 3.6 g (20 mmole) of benzylideneaniline is added to the red solution and the benzene is distilled off. The residue is heated for 5 min at 190–200 °C, cooled, and dissolved in 100 ml of ether. The ether solution is shaken with 100 ml of 2 N sulfuric acid. The ether is evaporated off, and the residue is recrystallized from methanol to give 2.6 g of *trans*-stilbene (72 %; m.p. 121–122 °C).

N-Phenyliminotriphenylphosphorane is precipitated from the acid phase with sodium hydroxide solution. The yield is 4.95 g (70 %), m.p. 131–132 °C.

2. Synthesis of Allenes

Ylides *(39)* with a CH_2 group β to the P atom react with benzylideneaniline *(40)* to form a betaine *(41)*, which decomposes into an allene *(43)*, triphenylphosphine *(44)*, and aniline *(45)* on heating to 120–130 °C [14].



(39) (40) (41) (42) (43) (44) (45)

The betaine *(41)* can be isolated [8]. The decomposition is presumably preceded by a proton shift to form the ylide *(42)*, which then undergoes an intramolecular Hofmann degradation by intramolecular β-elimination (transfer of a proton from the β position with respect to the P atom, to the lone electron pair on the nitrogen). This results in the formation of *(43)*, *(44)*, and *(45)* [cf. also the formation of allenes from alkylidenephosphoranes and 1-dimethylamino-1-chloro compounds, in which the last step of the reaction is similar (Part II, Section B 3b)].

The very high decomposition temperatures (150 to 200 °C) of the betaines *(41)* result in partial rearrangement of the allenes *(43)* formed into the isomeric acetylene derivatives.

Procedure:

Phenylallene

Benzylideneaniline (20 mmole) is added to a salt-free benzene solution of 20 mmole of ethylidenetriphenylphosphorane [*(5)*, R = CH_3] under nitrogen. The mixture is left for 1 h at room temperature, and the benzene is then evaporated off in vacuum at a maximum bath temperature of 60 °C. The betaine which remains solidifies to yellow crystals on addition of petroleum ether/ether (5:2). The crystals are filtered off and decomposed in a rotating bulb tube at about 15 mm Hg, the bath temperature being raised to 190 °C. It is now possible to dispense with the protective nitrogen atmosphere.

The distillate (aniline and phenylallene) is poured into 30 ml of 25 % sulfuric acid. The mixture is extracted with ether, the ether phase is dried, and the solvent is evaporated off. Vacuum distillation of the residue gives phenylallene, b.p. 69–70 °C/11 mm Hg, yield 58 %.

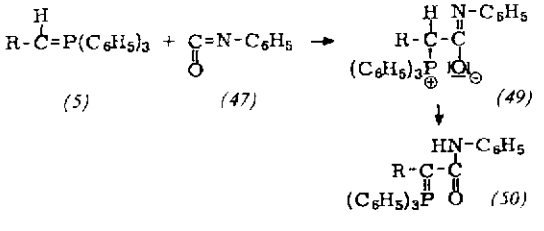
The residue from the decomposition consists of triphenylphosphine which can be recrystallized from methanol. Aniline is obtained from the sulfuric acid solution by treatment with alkali.

3. Reaction of Alkylidenephosphoranes with Phenyl Isocyanate

Diphenylmethylidenetriphenylphosphorane *(46)* reacts with phenyl isocyanate *(47)* to form diphenylketenephenylimine *(48)* [15].

$$(C_6H_5)_2C{=}P(C_6H_5)_3 + O{=}C{=}N{-}C_6H_5 \quad (47)$$
$$(46) \rightarrow (C_6H_5)_2C{=}C{=}N{-}C_6H_5 + OP(C_6H_5)_3$$
$$(48)$$

However, the reaction of phenyl isocyanate with alkylidenephosphoranes *(5)* in which the α carbon carries an H atom follows a different course: the initially formed betaine *(49)* is stabilized in this case by proton migration to form the new ylide *(50)* [16].



It still remains to be seen whether this reaction is generally suitable for the synthesis of anilides of carboxylic acids.

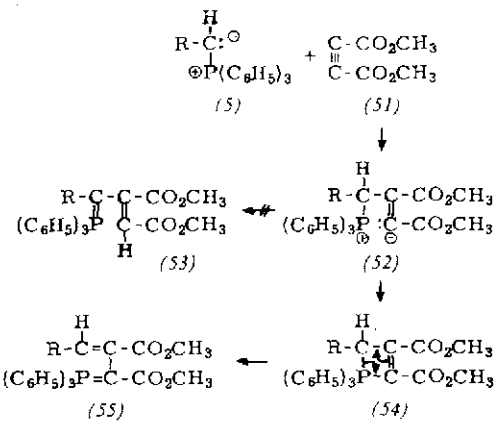
Procedure:

α-Ethoxycarbonyl-α-phenylcarbamoylmethylidenetriphenylphosphorane [(50), R = $CO_2C_2H_5$]

Phenyl isocyanate (2 g) is added to a solution of 3.5 g of ethoxycarbonylmethylidenetriphenylphosphorane in 40 ml of chloroform, and the reaction mixture is allowed to stand for 2 h at room temperature. The solvent is distilled off in vacuum, and the residue is recrystallized from n-butanol; m.p. 189–190 °C, yield 90 %.

D. Reaction of Alkylidenephosphoranes with Esters of Acetylenedicarboxylic Acid

Alkylidenephosphoranes *(5)* react spontaneously with esters of acetylenedicarboxylic acid *(51)* [17].



The initially formed betaine *(52)* is stabilized not by a proton shift to form *(53)* [18], but by formation of the ylide *(54)* *via* the four-membered heterocyclus *(54)*. The structure of *(55)* has been proved by degradation and by its infrared and NMR spectra. Alkylidenephosphoranes with no hydrogen on the α-C atom react similarly [17, 19, 20].

---

[15] *H. Staudinger* and *J. Meyer*, Ber. dtsch. Chem. Ges. *53*, 72 (1920).

[16] Cf. also *S. Trippett* and *D. M. Walker*, J. chem. Soc. (London) *1959*, 3874.

[17] *H. J. Bestmann* and *O. Rothe*, Angew. Chem. *76*, 569 (1964); Angew. Chem. internat. Edit. *3*, 512 (1964).

[18] *S. Trippett*, J. chem. Soc. (London) *1962*, 4733.

[19] On the basis of analogy, and with no proof of the structure of the products, *G. W. Brown*, *R. C. Cookson*, *I. D. R. Stevens*, *T. C. Mak*, and *J. Trotter*, Proc. chem. Soc. (London) *1964*, 86, postulated an identical mechanism for the reaction of diphenylmethylidenetriphenylphosphorane with esters of acetylenedicarboxylic acid.

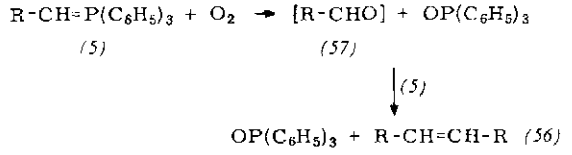
[20] *J. B. Hendrickson*, *R. Rees*, and *J. F. Templeton*, J. Amer. Chem. Soc. *86*, 107 (1964) report, without offering experimental data or evidence, that the reaction of *(51)* with benzoylmethylidenetriphenylphosphorane can yield both a Michael addition product *(53)* and a compound *(54)*. No mention is made in this paper of the article by *J. B. Hendrickson*, J. Amer. Chem. Soc. *83*, 2018 (1961), in which it is reported that this reaction gives rise to a heterocyclic compound containing pentavalent phosphorus.

E. Autoxidation of Alkylidenephosphoranes

1. Olefins from Primary Alkyl Halides or Alcohols

Alkylidenephosphoranes *(5)* with an H atom on the polarized double bond, *i.e.* obtained from primary alkyl halides or primary alcohols, are converted by oxygen into symmetrical olefins *(56)* and triphenylphosphine oxide [21].

It is assumed that one molecule of ylide and one molecule of oxygen first react to form triphenylphosphine oxide and the aldehyde *(57)*. The latter then enters into a Wittig reaction with an unoxidized ylide molecule to give the olefin *(56)* and a second molecule of triphenylphosphine oxide. Thus for ylides of the structure *(5)*, the Wittig reaction is faster than the autoxidation.



Ylides containing an aromatic group R react more slowly than those containing an aliphatic residue. Hexahydrobenzaldehyde [*(57)*, R = cyclohexyl] has been intercepted in 14% yield in the autoxidation of cyclohexylmethylidenetriphenylphosphorane.

Table 2. Olefins R—CH=CH—R *(56)* obtained by autoxidation of alkylidenephosphoranes R—CH=$P(C_6H_5)_3$ [21].

Alkyl halide [a]	R	Yield of olefin [%] [b]
Benzyl chloride	C_6H_5	72
p-Methoxybenzyl bromide	(*p*)$CH_3O-C_6H_4$	60
Ethyl bromide	CH_3	61
n-Propyl bromide	C_2H_5	68
n-Butyl bromide	n-C_3H_7	66
Cyclohexyl bromide	Cyclohexyl	61

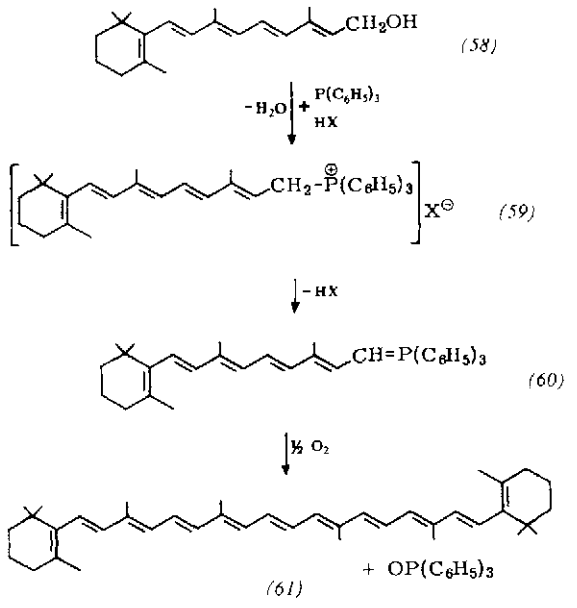
[a] Used for the preparation of the alkylidenephosphorane.

[b] Based on the phosphonium salt used for the preparation of the ylide.

The formation of olefins in the autoxidation of alkylidenephosphoranes makes possible the synthesis of β-carotene from two molecules of Vitamin A *(58)* [22].

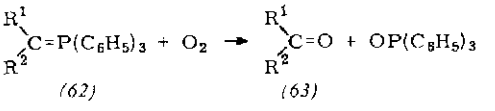
The phosphonium salt *(59)* can be obtained in almost 100% yield from *(58)*, and then converted to the ylide *(60)* [23,24].

If a solution of *(60)* is subjected to autoxidation with oxygen, crystalline β-carotene *(61)* is obtained immediately on working up. The yield of crude product is 35%.

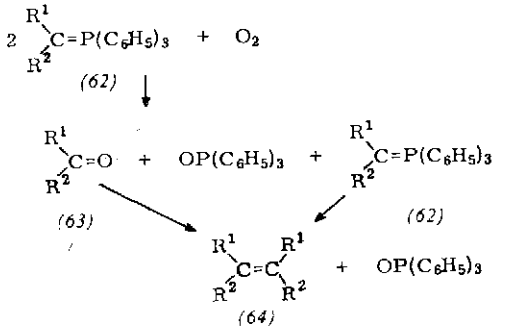


2. Olefins and Ketones from Secondary Alkyl Halides or Alcohols

Alkylidenephosphoranes *(62)* obtained from secondary alkyl halides or alcohols yield ketones *(63)* on autoxidation [21].



Owing to the low reactivity of the initially formed ketones, the autoxidation is faster than the Wittig reaction, so that the tetrasubstituted olefins *(64)* are not formed. These can be obtained, however, by stopping the supply of oxygen after the absorption of $^1/_2O_2$, and allowing the reaction mixture to stand at room temperature or, if necessary, refluxing the reaction mixture. In this case the ketone *(63)* reacts with unoxidized alkylidenephosphorane *(62)* to form the olefin *(64)*. This dimerization does not proceed if R^1 or R^2 is aromatic. The autoxidation of the ylide obtained from cyclohexyl bromide also fails to proceed beyond the cyclohexanone stage.



Alkylidenephosphoranes containing strongly resonance-stabilized groups ($R = CO_2-R^1$ or R^1-CO-) are not attacked by oxygen.

[21] *H. J. Bestmann*, Angew. Chem. *72*, 34 (1960); *H. J. Bestmann* and *O. Kratzer*, Chem. Ber. *96*, 1899 (1963).

[22] *H. J. Bestmann* and *O. Kratzer*, Angew. Chem. *73*, 757 (1961).

[23] German Patent 1046046 (Dec. 11th, 1958), BASF, inventors: *W. Sarnecki* and *H. Pommer*.

[24] German Patent 1068709 (April 28th, 1960), BASF, inventors: *H. Pommer* and *W. Sarnecki*.

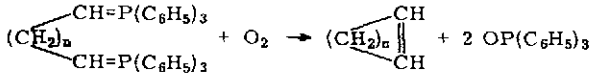
Table 3. Ketones $R^1R^2C=O$ and olefins $R^1R^2C=CR^1R^2$ obtained by autoxidation of alkylidenephosphoranes $R^1R^2C=P(C_6H_5)_3$.

Alkyl halide [a]	R^1	R^2	Yield of ketone [%]	Yield of olefin [%]
Isopropyl bromide	CH_3	CH_3	60	60
2-Bromobutane	CH_3	C_2H_5	55	57
1-Phenyl-1-bromoethane	CH_3	C_6H_5	68	
Diphenylbromomethane	C_6H_5	C_6H_5	70	
Cyclohexyl bromide	$-C_5H_{10}-$		65	

[a] Used for the preparation of the alkylidenephosphorane.

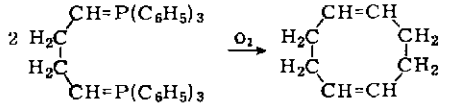
3. Cyclization by Autoxidation of Bis-Ylides. Synthesis of Monocyclic and Polycyclic Compounds

Cycloolefins *(66)* can be obtained by autoxidation of bis(alkylidenephosphoranes) *(65)* [25].



(65) *(66)*

Cyclic dimerization of the bis-ylide *(67)* leads to 1,5-cyclooctadiene *(68)*.



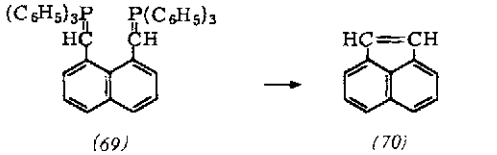
(67) *(68)*

Table 4. Cycloolefins *(66)* obtained by autoxidation of bis(alkylidenephosphoranes) *(65)*.

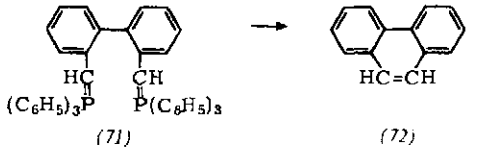
n	Cycloolefin	Yield [%]
5	Cycloheptene	61
4	Cyclohexene	60
3	Cyclopentene	68
2	1,5-Cyclooctadiene	52

Polycyclic compounds can also be synthesized with the aid of this principle.

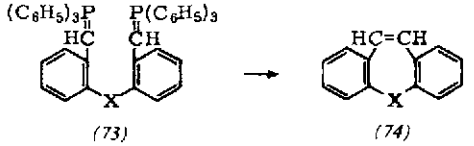
The naphthalene derivative *(69)* gives acenaphthalene *(70)* (54% yield), whereas the biphenyl derivative *(71)* yields phenanthrene *(72)* (70%). Autoxidation of *(73a)* leads to dibenzocycloheptatriene *(74a)*, (53%) and that of *(73b)* to dibenzoxepin *(74b)* (52%).



(69) *(70)*



(71) *(72)*



(73) *(74)*

(a) X = CH_2; *(b)* X = O

[25] *H. J. Bestmann, H. Häberlein,* and *O. Kratzer,* Angew. Chem. *76*, 226 (1964); Angew. Chem. internat. Edit. *3*, 226 (1964).

Autoxidation of Alkylidenephosphoranes

The ylide solution is prepared by the sodamide, alkoxide, or dimethylsulfinate method (see Part I, Section D 2), and oxidized in a Schlenk tube having an additional fused-on gas-inlet tube. Fig. 1 illustrates an oxidation apparatus in which a measured volume of oxygen can be recirculated by means of a pump.

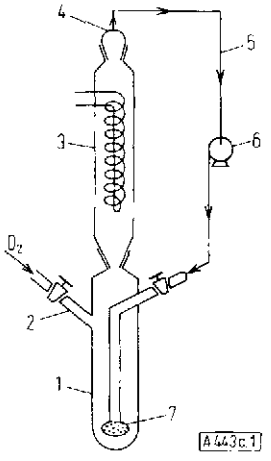


Fig. 1. Apparatus for the autoxidation of alkylidenephosphoranes. 1: Schlenk tube; 2: connector with tap; 3: reflux condenser; 4: olive; 5: tubing; 6: pump [26]; 7: gas-inlet tube with tap.

The apparatus is initially set up under nitrogen, and is then connected to the reservoir buret containing oxygen which has previously been dried over P_2O_5 and sulfuric acid. The pump is then started. The oxygen consumption can be read off from the buret.

In the preparation of olefins from the ylides *(5)* or of ketones from the ylides *(62)*, it is not essential to measure the oxygen consumption accurately. In these cases, dry oxygen can be passed through the solution of the alkylidenephosphorane until the solution is decolorized or undergoes no further color change (it often remains light brown). When R^1 and R^2 in *(5)* and *(62)* are aliphatic, the reaction is exothermic. If R^1 or R^2 is aromatic, the oxidation is best carried out at an elevated temperature. The same applies to the cyclization of bis-ylides by autoxidation.

If it is desired to obtain the olefins from the ylides *(62)*, the oxygen supply must be interrupted after $^1/_2$ molar equivalent of O_2 has been taken up. The oxygen in the apparatus is then displaced by nitrogen, and the reaction solution is allowed to stand at room temperature, or is heated under reflux, until the ylide solution is practically decolorized.

Olefins *(64)* are also obtained by the following variant: The ylide solution is halved. One half is oxidized to the ketone as described, and after the oxygen in the apparatus has been displaced by nitrogen, the unoxidized half is added. The subsequent procedure is as for a normal Wittig reaction.

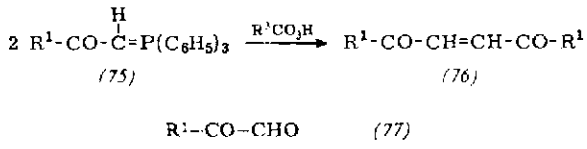
F. Oxidation with Peracids

A valuable complement to autoxidation is oxidation with peracids [27], which oxidize stable ylides not attacked by oxygen. Conversely, peroxy acids do not

[26] The laboratory pump Type LPA manufactured by Messrs. W. A. Bachofen, Basel (Switzerland), has been found to be very suitable.

[27] *G. B. Denney* and *L. C. Smith*, J. Amer. chem. Soc. *82*, 2396 (1960); *D. B. Denney, L. C. Smith, J. Song, C. J. Rossi,* and *C. D. Hall*, J. org. Chemistry *28*, 778 (1963).

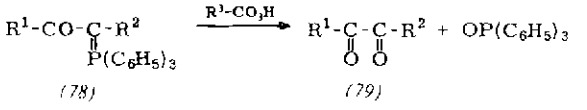
oxidize alkylidenephosphoranes capable of autoxidation. The rules governing both these reactions are the same.



(75) *(76)* *(77)*

Acylalkylidenephosphoranes [*(75)*, R^1 = alkyl, aryl, or OR^2] with an H atom on the C–P double bond are converted by peracids into diacylethylenes *(76)*. The first step is assumed to be the formation of an α-oxoaldehyde *(77)*, which reacts with unchanged ylide *(75)* to form the olefin *(76)*.

Stable alkylidenephosphoranes *(78)* with no H atoms on the C–P double bond are converted by peracids into α,β-dioxo compounds *(79)*. This method has been used



(78) *(79)*

for the preparation of cyclic 1,2-diketones [28].

Procedure:

1,2-Bis-(p-nitrobenzoyl)ethylene [27]

A solution of 2.56 g of peroxycaprylic acid in 20 ml of CH_2Cl_2 is added to a stirred solution of 6.5 g of *p*-nitrobenzoylmethylidenetriphenylphosphorane in 75 ml of CH_2Cl_2 at −30 °C and in an atmosphere of nitrogen. The stirring is continued for 90 min, and the solution is concentrated in vacuum until crystals separate out. These are filtered off, and 1.14 g of 1,2-bis-(*p*-nitrobenzoyl)ethylene are obtained; yield 46 %, m.p. 200 °C.

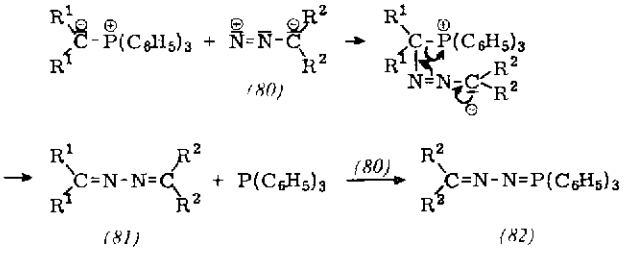
G. Cleavage with Ozone

Acylalkylidenephosphoranes *(78)*, in which R^1 or R^2 may be hydrogen, react with ozone at −70 °C to form α,β-dicarbonyl compounds *(79)* [29].

H. Other Reactions

1. Reaction with Aliphatic Diazo Compounds

Alkylidenephosphoranes react with aliphatic diazo compounds *(80)* to form azines *(81)* and triphenylphosphine [30, 31].



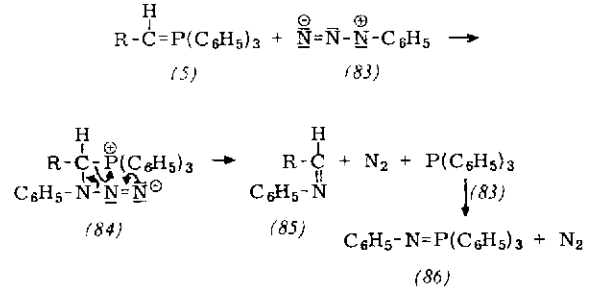
(80) *(81)* *(82)*

The triphenylphosphine formed frequently reacts with another molecule of the diazo compound *(80)* to yield the phosphazine *(82)*, so that the product in these cases contains both *(81)* and *(82)*.

2. Reaction with Phenyl Azide

Alkylidenephosphoranes *(5)* react with phenyl azide *(83)* to form Schiff bases *(85)* and phenyliminotriphenylphosphorane *(86)*, with evolution of nitrogen [32].

The first step is assumed to be the formation of a betaine *(84)*, which decomposes to the Schiff base *(85)*, triphenylphosphine, and nitrogen. The triphenylphosphine



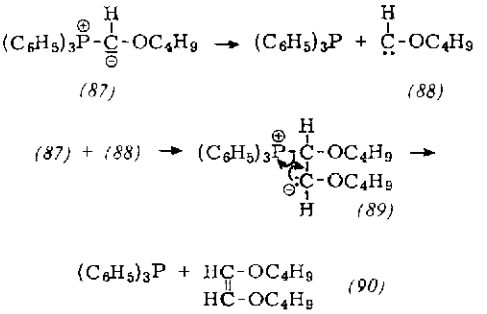
(5) *(83)* *(84)* *(85)* *(86)*

then reacts with a second molecule of azide to form the iminophosphorane *(86)* [1].

It still remains to be seen whether this reaction is generally suitable for the preparation of aldehydes or Schiff bases.

3. Reaction with Carbenes

The electrophilic carbenes react as expected with alkylidene phosphoranes, as was first observed by *Wittig* and *Böll* [33]. Butoxymethylidenetriphenylphosphorane *(87)* breaks down on heating into triphenylphosphine and butoxycarbene *(88)*. This carbene reacts with a second ylide molecule to dibutoxyethylene *(90)* and triphenylphosphine; the betaine *(89)* probably occurs as intermediate.



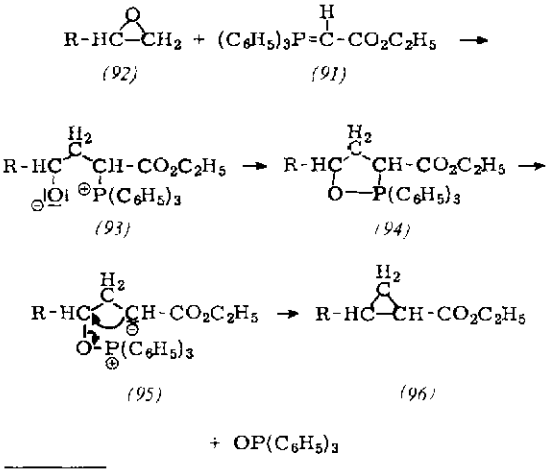
(87) *(88)* *(89)* *(90)*

[28] *H. O. House* and *H. Babad*, J. org. Chemistry *28*, 90 (1963).
[29] *F. Ramirez*, *R. B. Mitra*, and *N. B. Desai*, J. Amer. chem. Soc. *82*, 5763 (1960).
[30] *G. Wittig* and *M. Schlosser*, Tetrahedron *18*, 1023 (1962).
[31] *G. Märkl*, Tetrahedron Letters *1961*, 811.
[32] *H. Hoffmann*, Chem. Ber. *95*, 2563 (1962).
[33] *G. Wittig* and *W. Böll*, Chem. Ber. *95*, 2526 (1962).

The reaction of fluorenylidenetriphenylphosphoranes with halogenocarbenes leads to the formation of dihalogenomethylenefluorenylidenes in yields of 50 to 80 % [34].

4. Reaction of Ethoxycarbonylmethylidenetriphenylphosphorane with Epoxides

Ethoxycarbonylmethylidenetriphenylphosphorane *(91)* reacts with epoxides *(92)* to form ethyl cyclopropanecarboxylates *(96)* [35]. It is assumed that the reaction passes through the intermediates *(93)*, *(94)*, and *(95)* [35, 36a, 36b]. More strongly basic alkylidenephosphoranes do not give uniform reactions with epoxides [36a, 37–39]. An interpretation of the mechanism of this reaction is given by *Trippett* [39].



[34] *R. Oda, Y. Ito,* and *M. Okano,* Tetrahedron Letters *1964*, 7.

[35] *D. B. Denney* and *M. J. Boskin,* J. Amer. chem. Soc. *81*, 6330 (1959); *D. B. Denney, J. J. Vill,* and *M. J. Boskin,* J. Amer. chem. Soc. *84*, 3944 (1962).

Procedure:

Norcaranecarboxylic Acid

A mixture of 5 g of ethoxycarbonylmethylidenetriphenylphosphorane and 10 g of cyclohexene oxide are heated for 9 h at 200 °C. The product is hydrolysed by boiling for 12 h with a mixture of 50 ml of methanol and 15 ml of 6N KOH. The reaction mixture is diluted with 100 ml of water and shaken with chloroform. The aqueous phase is extracted with ether. The norcaranecarboxylic acid enters the ether phase, and can be recrystallized from methanol after the ether has been driven off. Yield 1.5 g (63 %), m.p. 87–89 °C.

It should finally be pointed out that *Wittig*'s investigations, which led to the "rediscovery" of the alkylidenephosphoranes and their reaction with the C–O double bond, are steadily gaining in importance as the basis of many new investigations. They have stimulated a development which has by no means reached its peak.

The work quoted as the author's is the result of investigations carried out in conjunction with B. Arnason, J. Bertold, G. Graf, Dr. H. Häberlein, Dr. H. Hartung, Dr. O. Kratzer, I. Pils, K. Rostock, O. Rothe, Dr. H. Schulz, and Dr. F. Seng. I am sincerely grateful to my co-workers for their perseverance and diligence in the solution of our common problems.

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German version: Angew. Chem. *77*, 850 (1965)
Translated by Express Translation Service, London

[36a] For studies on the reaction mechanism, cf. *W. E. McEwen, A. Bladé-Font,* and *C. A. Vander Werf,* J. Amer. chem. Soc. *84*, 677 (1962).

[36b] *I. Tömösközi,* Tetrahedron *19*, 1969 (1963).

[37] *W. E. McEwen* and *A. P. Wolf,* J. Amer. chem. Soc. *84*, 676 (1962).

[38] *F. Zbiral,* Mh. Chem. *94*, 78 (1963).

[39] *S. Trippett,* Quart. Rev. *17*, 406 (1963).

Progress in Optical Circular Dichroism

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An apparatus first described in 1961 for the measurement of circular dichroism down to 220 mμ has been improved and its range extended down to 185 mμ. Some examples are given in the field of dienes, conjugated ketones, and aromatic chromophores. A more extensive study of protein structures was developed with the following results: a) helical polypeptides show a complex dichroism in the far ultraviolet with three components (192 mμ, 204 mμ, 225 mμ), characteristic of the helical array of peptide groups; b) human serum albumin shows a very similar curve of dichroism and is 60 % helical; c) urea denaturation, as judged by dichroism, is a reversible phenomenon; d) a solvent such as chloroethanol increases the helical content of human serum albumin and clupein and has only a very small action on poly-L-glutamic acid; e) the rupture of S–S bonds in human serum albumin favors the attack of denaturing agents such as urea; f) detergents help to maintain the rigid structure of human serum albumin after the rupture of S–S bonds.

Introduction

The first apparatus for the convenient measurement of optical circular dichroism in the ultraviolet and visible regions, designed and developed in our laboratory [1], has led to a great interest in this subject. Many chemical laboratories working on optically active structures now use this method of analysis, as may be judged by the

[*] In collaboration with *R. Viennet* and *M. Mansart.*

[1] *M. Grosjean* and *M. Legrand,* C. R. hebd. Séances Acad. Sci. *251*, 2150 (1960).

large number of communications published since our first Note in this journal [2].

For the reasons already given [2], the principal chromophore studied has been the carbonyl group present in mono-, bi-, or polycyclic structures such as terpenes and steroids. In these fields, circular dichroism has led to absolute configurational determinations in numerous cases [3], and more recently to the elucidation of conformations, above all by working at low temperatures [4]. A detailed bibliography may be found in our recent monograph [5].

Despite these results, however, most functions other than the carbonyl group remained outside the scope of study because their absorption is either too strong or at too short a wavelength. Indirect methods have been employed for simple molecules, *e.g.* replacing the group by a chromophore of which the induced dichroism is measurable (OH replaced by ONO, NH_2 by $N{=}CH{-}C_6H_4OH$, *etc.* [5]), to increase considerably the usefulness of the method. However, the relationship between conformation and optical activity of complex molecules such as polypeptides and proteins can only be deduced by the direct measurement of circular dichroism.

I. Advances in Instrumentation

Most published results on circular dichroism have been obtained with apparatus similar to that built in 1959 in our laboratory by *Grosjean* and *Legrand* [1]. This design has the advantages of accuracy and rapidity of measurement, but there are some limitations in its use.

First, the limited beam intensity in the useful wavelength range leads to only moderate signal to noise ratios, which precludes accurate measurements when the anisotropy ratio $\Delta\varepsilon/\varepsilon$ of a sample is less than 5×10^{-4} ($\Delta\varepsilon$ is the difference in absorption coefficients for right-hand and left-hand circularly polarized light). The usefulness of the apparatus is therefore questionable for the measurement of the dichroism of allowed transitions of symmetric chromophores when optical activity is due to environment. In this case the absorption coefficient is more than a hundred times higher than that of forbidden transitions such as the $n \rightarrow \pi^*$ transition of the carbonyl group. Very dilute solutions must therefore be used in order to allow sufficient light to reach the photocell. However, for this type of transition, $\Delta\varepsilon$ values remain of the order of a few units. Consequently, the dichroic signal at the output of the photocell is very small and its detection becomes very difficult owing to background noise.

On the other hand, a limitation in wavelength is imposed by the use of natural quartz optics. This material limits to 2100 Å the shortest wavelength at which measurements are still possible. Below this point, the transmission of the optical part of the apparatus decreases abruptly.

In order to increase the range of the dichrograph previously described, it was thus necessary to modify the optics. This study was started by *Grosjean* and *Tari* [6] and has led to the experimental apparatus sketched in Fig. 1. An additive double monochromator is used to disperse and polarize the light at the same time. Light from a source S (deuterium lamp) is focused on the entrance slit f_1 and dispersed for the

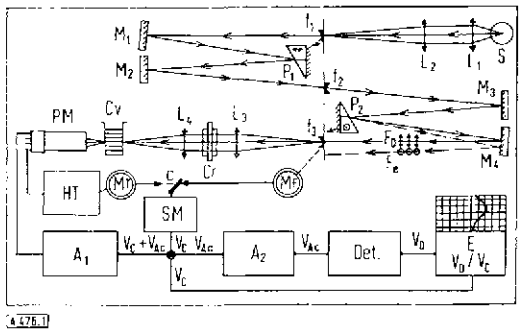


Fig. 1. Schematic design of the new apparatus.

S: light source, L_1–L_4 lenses, f_1–f_3 slits, M_1–M_4 mirrors, P_1, P_2 prisms, Cr polarisation modulator (ammonium dihydrogen phosphate), Cv cell, PM photomultiplier, HT dynode high-tension supply, MT dynode voltage servomotor, MF slits servomotor, SM slits or C dynode voltage servomechanism, A_1, A_2 amplifiers, Det. detector, E recorder, V_C direct voltage, V_{ac} alternating voltage, V_D rectified voltage.

first time by the prism P_1. This is made of crystalline quartz cut with its optic axis perpendicular to the aluminized face of the prism, so that there is no double refraction. Thus, a non-polarized monochromatic light beam coming from slit f_2 falls on the second prism P_2. The latter has its optic axis perpendicular to that of P_1 as shown in Fig. 1. In this way, the beam of light undergoes simultaneously a second dispersion and a polarization, so that two perpendicularly plane-polarized beams making an angle with each other leave the prism. The exit slit f_3 allows only the ordinary beam to pass.

With this design, the spectral purity of the monochromatic light is higher than before. This result is interesting in the short-wavelength range where stray light plays an important role. Further, the functions of the monochromator and polarizer (Rochon prism) of the previous apparatus have now been grouped together and this allows the use of additional optical parts as shown in Fig. 1 without loss of intensity. Finally, the prisms are cut in single crystals of *synthetic* quartz, which is more transparent below 2100 Å. These improvements have led not only to increased light intensity above 2000 Å but also to an extension of the limit of measurement to 1850 Å.

The rest of the apparatus is only slightly different from the first design: two amplifiers only are now necessary, following a small modification in the potentiometric recorder. A new arrangement has been added whereby the apparatus works either with variable slits as before or at fixed slits and variable dynode voltage.

The sensitivity of the apparatus with the modifications outlined above has been increased from 1.5×10^{-4} to 10^{-5} optical density unit per mm of recording chart. In the region below 200 mμ, it is possible to discern an optical activity corresponding to $\Delta\varepsilon/\varepsilon = 2\times10^{-5}$. In the near ultraviolet, where the emission of sources is much more intense, this limiting value becomes about 10^{-5}.

Chromophores with strong absorption such as dienes, trienes, conjugated ketones (transition $\pi \rightarrow \pi^*$), aromatic rings, *etc.* can be studied with this modified apparatus but the principal advantage of the new design is the possibility of determining circular dichroism below 220 mμ, making accessible to this method the important field of polypeptides, proteins, and nucleic acids.

Determinations are made with silica cells of $^1/_{10}$ mm thickness down to 210 mμ and $^1/_{100}$ mm below this wavelength. Such small thicknesses reduce the effect of the absorption of the solvent which is often important at short wavelengths. In

[2] *L. Velluz* and *M. Legrand*, Angew. Chem. *73*, 603 (1961).

[3] *R. Bucourt* and *M. Legrand*, C. R. hebd. Séances Acad. Sci. *258*, 3491 (1964).

[4] *G. Snatzke*, *D. Becher*, and *J. R. Bull*, Tetrahedron *20*, 2443 (1964).

[5] *L. Velluz*, *M. Legrand*, and *M. Grosjean*: Optical Circular Dichroism. Verlag Chemie, Weinheim, and Academic Press, New York-London 1965.

[6] *M. Grosjean* and *M. Tari*, C. R. hebd. Séances Acad. Sci. *258*, 2034 (1964).

any case, the solutions used should not have optical densities exceeding 1.5.

Six determinations on a solution of poly-L-glutamic acid gave a relative standard deviation of ± 5 % from 185 mμ to 210 mμ and ± 2.5 % at longer wavelengths.

II. Circular Dichroism of Chromophores Strongly Absorbing in the Near Ultraviolet

a) Diene Steroids

Figure 2 shows the dichrogram and the isotropic absorption spectrum of two diene steroids, ergosterol *(1)* and lumisterol *(2)*. The great similarity of the two sets of curves is in good agreement with the theory of *Moffitt* and *Moscowitz* [7] since the transition is electric

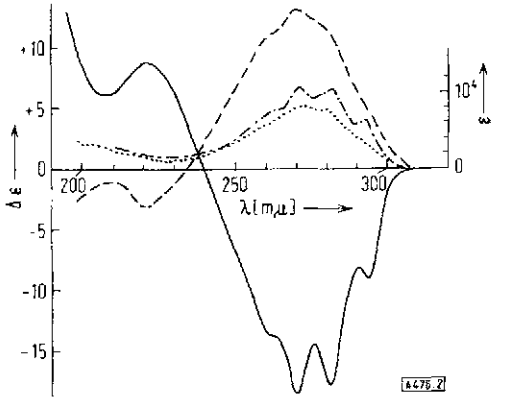
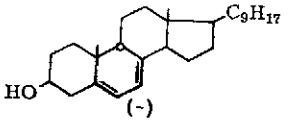


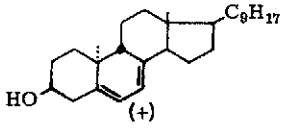
Fig. 2. Circular dichroism and ultraviolet absorption of ergosterol *(1)* and lumisterol *(2)* in ethanol.
(– · – · –) Absorption and (———) dichroism of ergosterol.
(· · · · · ·) Absorption and (– – –) dichroism of lumisterol.

dipole allowed. The antipodal character of the two dichroism curves seems logical because in this type of ring, the inversion of the two centers 9 and 10 should normally lead to an inversion of conformation.

The high amplitude of the dichroism is related to the bond angles of the carbon atoms 5-6-7-8. According to *Moscowitz et al.* [8], this angle is negative in ergosterol *(1)* and positive [8a] in lumisterol *(2)*.



(1)



(2)

b) Conjugated Ketones

In our preceding researches [5], conjugated ketones have been fairly thoroughly studied in the region of the n→π* absorption, and recently *Snatzke* published a series of papers on this question [9]. The situation is entirely different in the region near 240 mμ because up till now, the high absorption has prevented measurement of the optical activity of the π→π* transition. Figure 3 shows the circular dichroism of the three

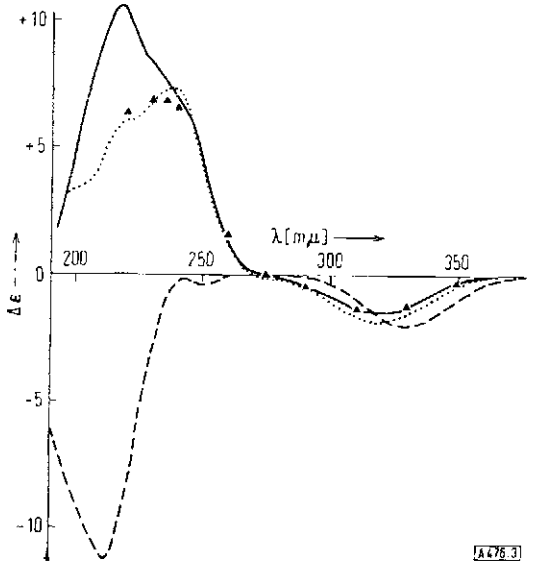
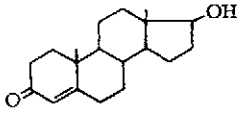
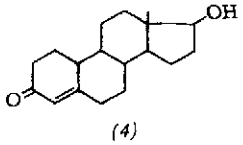


Fig. 3. Circular dichroism of some Δ4-3-keto steroids in ethanol.
▲ Testosterone *(3)* (old apparatus).
(———) Testosterone (new apparatus).
(· · · · · ·) 19-nor-Testosterone *(4)*.
(– · – · –) 10α-Testerone acetate *(5)*.

Δ4-3-keto steroids testosterone *(3)*, 19-nortestosterone *(4)*, and 10α-testosterone acetate *(5)* [*] in both wavelength ranges. As was known before, the dichroism of the three compounds is very similar near 330 mμ, but several differences are apparent at shorter wavelengths.



(3)



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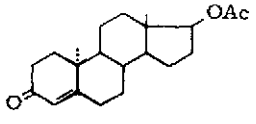


(5)

First, two bands are observed with relative amplitudes depending on the structure of the compounds. For instance, the absence of the 10-methyl group in 19-nortestosterone leads to a definite decrease of amplitude of the 220 mμ band but the 235 mμ band remains unchanged. On the other hand, with the 10α epimer of testosterone, the band at 235 mμ has practically disappeared. But the most important observation concerns the inversion of sign of the band at 220 mμ following the epimerization of the 10-methyl group while the optical activity remains the same in the near ultraviolet. This result gives a means of distinguishing this type of iso-

[7] *W. Moffit* and *A. Moscowitz*, J. chem. Physics *30*, 648 (1959).

[8] *A. Moscowitz, E. Charney, U. Weiss*, and *H. Ziffer*, J. Amer. chem. Soc. *83*, 4661 (1961).

[8a] The signs of the dihedral angles are given according to *Bucourt*'s rule [Bull. Soc. chim. *1964*, 2080].

[9] *G. Snatzke*, Tetrahedron *21*, 413, 421, 439 (1965).

[*] We are indebted to Dr. *R. Wenger* (Zürich) for a sample of 10α-testosterone.

merism. However, it invalidates the hypothesis proposed by one of us according to which the sign of the band at 240 mμ is always the inverse of the sign of the 330 mμ band [5].

c) Aromatic Rings

The circular dichroism of estradiol *(6)* and 9-isoestradiol *(7)* is shown in Fig. 4. It can be seen that the phenolic ring is sensitive to the asymmetry of the neighboring

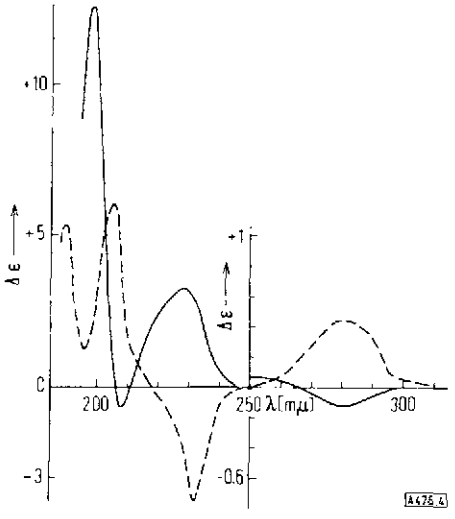
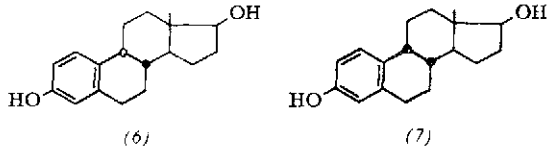


Fig. 4. Circular dichroism of (———) estradiol *(6)* and (– – –) 9-isoestradiol in ethanol.

centers. In particular, inversion at center 9 changes the sign of the optical activity of both bands located towards the long wavelength, but is without effect on the 200 mμ band.



(6) *(7)*

For this type of chromophore, dichroism maxima do not correspond to isotropic absorption maxima. This is particularly true for the dichroism band at 230 mμ, a wavelength where the isotropic absorption shows a strong minimum.

d) General Remarks

In these few examples from the field of conjugated chromophores, the anisotropy factor varies from 1.5×10^{-3} (ergosterol) to *ca.* 5×10^{-5} (280 mμ band of the phenol). In the most unfavorable case, it is possible to obtain an accuracy of 15 % by drawing a mean line through the noise background to obtain an average curve, more accurate than the record itself.

The new apparatus recently described by *Grosjean* and *Tari* [6] thus permits precise measurement of optical activity of chromophores with $\Delta\varepsilon/\varepsilon$ *ca.* 2×10^{-5}. Nevertheless, the older dichrograph [*] is still quite satisfactory for work with weakly absorbing chromophores. The new design gives little improvement in this connection. Semi-quantitative determinations of $\Delta\varepsilon/\varepsilon$ around 5×10^{-4} are possible in the old apparatus above 220 mμ if the dilution is chosen such that the isotropic optical density remains below 1.5. If measurements are repeated several times, an accuracy of around 30 % can be reached, thanks to the low background noise of this apparatus; this precision is often sufficient for qualitative discussions. For example, in Figure 3 we give the points obtained for testosterone with the first dichrograph.

On the contrary, for chromophores such as peptides and proteins which we will now discuss, the interesting absorptions are situated below 220 mμ and their optical activity can be measured only with the new design.

[*] Commercially available from Jouan, 113, Bd. St. Germain, Paris 6e.

III. Circular Dichroism of Some Proteins and Related Substances

The existence of a helical conformation in polypeptides and proteins, as proposed by *Pauling*, *Corey*, and *Branson* [10], and later proved by X-ray analysis of representative compounds, led to a great interest in optical rotatory dispersion in this branch of chemistry. The spatial disposition in the helix of the peptide bonds leads to interactions between the amide groups and consequently gives rise to a splitting of some transitions and a dichroism which is peculiar to this conformation. *Holzwarth* and *Doty* [11] recently found good agreement between experimental results and theoretical predictions by *Moffitt* [12] and by *Woody* [13]. We have studied the circular dichroism of poly-L-glutamic acid, a compound which serves as a model for proteins.

a) Dichroism of Poly-L-glutamic Acid [13a]

Near pH 4, poly-L-glutamic acid is 100 % in helix form. Its dichroism is shown in Figure 5. Three bands, one positive at 191 mμ, two others negative at 209 and 222

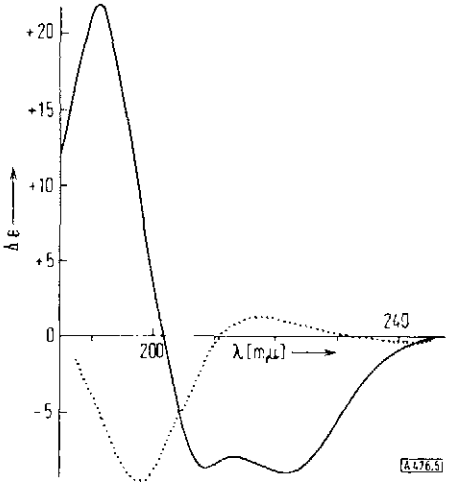


Fig. 5. Circular dichroism of aqueous poly-L-glutamic acid. (———) pH 4.3 (helix), (·····) pH 11 (random coil).

[10] *L. Pauling, R. B. Corey*, and *H. R. Branson*, Proc. nat. Acad. Sci. U.S.A. *37*, 205 (1951).

[11] *G. Holzwarth* and *P. Doty*, J. Amer. chem. Soc. *87*, 218 (1965).

[12] *W. Moffit*, J. chem. Physics *25*, 467 (1956); Proc. nat. Acad. Sci. U.S.A. *42*, 736 (1956).

[13] *R. W. Woody*, Dissertation, University of California, 1962.

[13a] The determinations were made on a sample of high molecular weight (50000) supplied by Mann Research Laboratory.

mμ, are clearly recognizable. Going from short to longer wavelengths, the bands correspond respectively to the $n\rightarrow\pi^*$ transition of the amide group and to the NV_1 transition of the same chromophore which is split by coupling between peptide bonds disposed in helical array.

The overall curve was resolved into three gaussian components by the use of a least squares method. The data obtained are given in Table 1. These results are in satisfactory agreement with *Holzwarth* and *Doty*'s values [11] for the methyl ester of poly-L-glutamic acid.

Table 1. Gaussian components of the dichrogram of poly-L-glutamic acid.

λ_{max} [mμ]	Θ [mμ] [a]	Δε/n [b]	$R\times10^{-40}$ [erg cm³ rad] [c]
192	8.9	27.1	51
204	12.7	9.7	29
224	10	8.1	15

[a] Half the width at 1/e the maximum height.
[b] n = Degree of polymerization.
[c] R = Rotational strength of the transition.

Above pH 6, poly-L-glutamic acid has a random-coil conformation. Its dichroism (Fig. 5) shows two bands. The first, near 218 mμ, is weak and corresponds to the $n\rightarrow\pi^*$ transition of the amide chromophore, the second, at 198 mμ, is much stronger and is probably due to the NV_1 transition although there is a significant wavelength difference between the dichroism maximum (198 mμ) and the isotropic absorption (191 mμ).

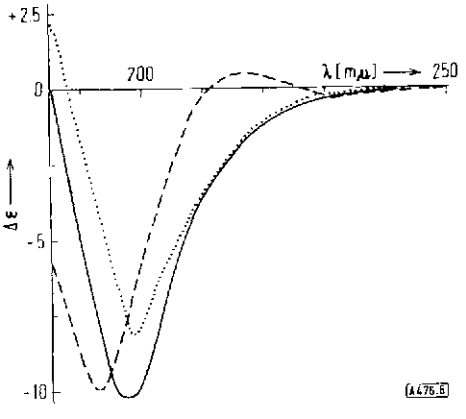


Fig. 6. Circular dichroism of aqueous α-glycyl-L-lysyl-L-glutamic acid at (———) pH 5.9, (— — —) pH 3.1, and (·····) pH 10.75.

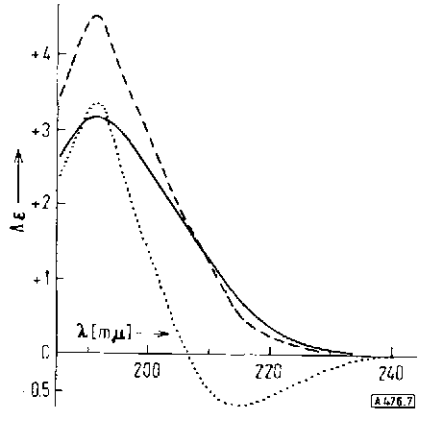
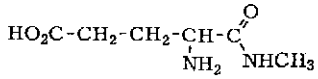


Fig. 7. Circular dichroism of aqueous L-*N'*-methylisoglutamine at (— — —) pH 3.4, (———) pH 6.5, and (·····) pH 10.4.

In Figures 6 and 7, it can be seen that a simple tripeptide α-glycyl-L-lysyl-L-glutamic acid and also *N'*-methyl-L-isoglutamine *(8)* [13b] give the same type of dichroism. However, the sign of the dichroism of the last compound is reversed, although it belongs to the same



(8)

optical series. This effect is probably due to the presence of an amine in the α-position to the amide instead of a second amide group. In any case, the dichroism of these two compounds is little affected by change of pH, and the variations observed have no resemblance to that presented by poly-L-glutamic acid. This shows that the peculiar dichroism of the latter in the helix state is due to the helical conformation of the chain and not to a variation of solvation at the level of the monomers as was recently proposed [14].

b) The Helix Content of Native Human Serum Albumin

Figure 8 shows the circular dichroism of human serum albumin (a) in aqueous solution, (b) denatured by urea (9 M), and (c) in 4 M urea, obtained by ultrafiltration of a

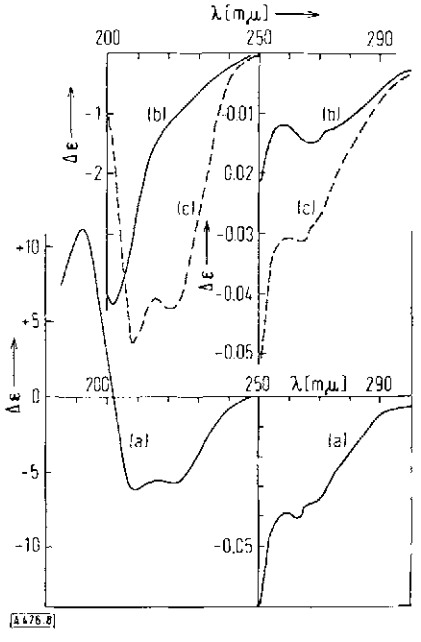


Fig. 8. Circular dichroism of human serum albumin: (a) native, (b) in 9 M urea after being heated at 78 °C for 1 h, and (c) in a solution of 3.9 M urea, obtained by ultrafiltration from a solution corresponding to (b).

9 M urea solution (b). In the case of (b) and (c), the measurements do not extend beyond 200 mμ owing to the absorption of urea at these wavelengths.

[13b] This compound (m. p. 200 °C) was synthesized in our laboratories by *G. Amiard* and *R. Heymes* from bis-(*N*-trityl-methyl-L-glutamic) anhydride by formation of the methyl amide using methylamine, followed by alkaline hydrolysis of the carbomethoxy group and acid hydrolysis of the trityl group.

[14] *L. I. Katzin* and *E. Gulyas*, J. Amer. chem. Soc. *86*, 1655 (1964).

The weak dichroic absorptions observed near 250 mμ arise from tyrosine, tryptophan, histidine and, above all, cystine residues. We have recently shown [15] that these amino-acids have a weak dichroism in this region, due respectively to the chromophoric groups phenol, indole, imidazole, and S–S present in these acids. However, quantitative agreement is not obtained, probably because, in proteins, the optical activity of each of these chromophores is modified by the environment.

Between 185 mμ and 250 mμ, the same type of curve is obtained for native human serum albumin and for helical poly-L-glutamic acid (Figs. 8a and 5). Furthermore, the transition from helix to random coil leads in both cases to a similar transformation of the curve.

From these observations, together with the fact that, after partial elimination of urea, the curve reverts to its original form, it can be inferred that this protein is, at least partially, in helical form.

In order to estimate the relative amounts of helical and random-coil states, we compared the experimental curve (Fig. 8a) with that derived by calculations based on data obtained from fully denatured human serum albumin [φ(λ)] and helical poly-L-glutamic acid [f(λ)] (Figs. 8b and 5). The weighted sum of the normalized curves of the components f(λ) and φ(λ)

$$m\, f(\lambda) + n\, \varphi(\lambda)$$

must be made to reproduce as closely as possible the experimental curve, m and n being determined by a least squares method over several wavelengths. The standard deviation should be of the same magnitude as the experimental error if the coefficients m and n have been correctly chosen [15a]. With native HSA, this method leads to a standard deviation of ± 2%, which is the order of magnitude of the experimental error. The hypothesis of a mixture of helical and random-coil forms in this protein is thus justified. The helical content is about 60%.

We consider that these results on the circular dichroism of human serum albumin, together with the determination of the optical rotatory dispersion curve of bovine serum albumin [16] in the region of 200 mμ, give the most direct proof so far of the existence of helix conformation in certain proteins in solution [17].

c) Denaturation of Serum Albumin

1. Influence of Ionic Strength

The influence of ionic strength was investigated at three pH values (1.5, *ca.* 6, and 12) and for three NaCl concentrations (0.05, 0.2, and 0.4 M). No significant changes were observed and consequently, in the subsequent measurements, no attempt was made to work at constant ionic strength.

2. Influence of pH

The dichroism of human serum albumin remains practically constant between pH 4 and pH 10. Beyond these limits, denaturation is not negligible. The variation of helix content with pH is given in Fig. 9. The curve is

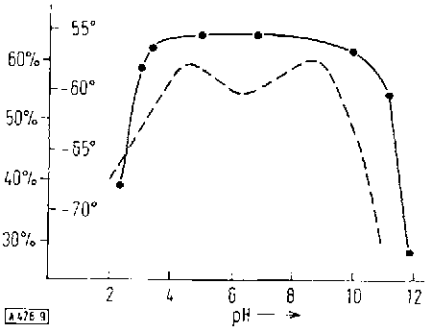


Fig. 9. Helix content [%] of human serum albumin in aqueous solution as determined from circular dichroism (curve ——, left-hand ordinate) and $[\alpha]_D$ according to *Jirgensons* and *Sirotzky* [18] (curve — — —, right-hand ordinate).

very similar to that of $[\alpha]_D$ published by *Jirgensons* and *Sirotsky* [18] which is also given in the figure. There seems to be a more abrupt change of slope at pH 3 in the curve representing helix content; however, the differences are almost within experimental error.

3. Influence of Temperature

The optical activity of human serum albumin is not very sensitive to temperature up to the coagulation limit of the protein [19]. Above this limit, measurement of dichroism is only possible if the aggregates are redissolved by addition of a few drops of concentrated ammonia. Figure 10 shows the dichroism observed under these

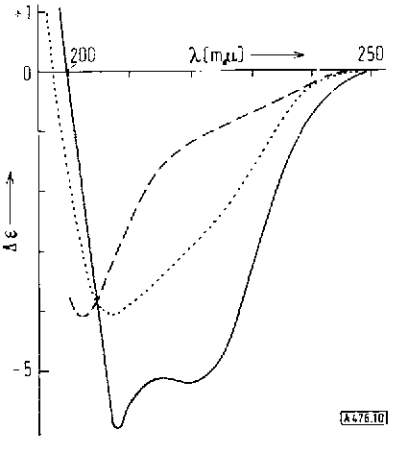


Fig. 10. Heat denaturation of human serum albumin, as evidenced by circular dichroism. (——) in aqueous ammonia; (·····) in aqueous ammonia after being heated for 1 h at 110 °C; (— — —) in 9 M urea after 1 h at 75 °C.

conditions, together with the dichroic curves of the native protein in ammoniacal solution and of the protein denatured by 9 M urea after heating at 75 °C. The results show that the presence of ammonia does not

[15] *M. Legrand* and *R. Viennet*, Bull. Soc. chim. *1965*, 679.

[15a] We have already applied this method to the study of diketones [2].

[16] *E. R. Blout, I. Schmier*, and *N. S. Simmons*, J. Amer. chem. Soc. *84*, 3193 (1962).

[17] In the solid state, the presence of helical regions has been proved by X-ray analysis; cf. *P. Urnes* and *P. Doty*, Advances in Protein Chemistry *16*, 483 (1961).

[18] *B. Jirgensons* and *S. Sirotzky*, J. Amer. chem. Soc. *76*, 1367 (1954).

[19] *M. A. Golub* and *E. E. Pickett*, J. Polymer Sci. *13*, 427 (1954).

affect the optical activity of native human serum albumin, and that denaturation by heating alone seems to be less important than by urea plus moderate heating.

4. Urea Denaturation

When urea is added to an aqueous solution of human serum albumin at pH 6.9, the circular dichroism is greatly modified (Fig. 11). In particular, the maximum at 222 mμ

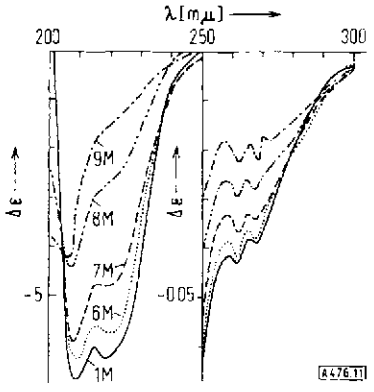


Fig. 11. Circular dichroism of human serum albumin after denaturation at various concentrations of urea.

decreases considerably. Although it is impossible to follow the concomitant modifications of the maximum at 192 mμ because of the absorption of urea, the curves of Figure 11 and the analogy with the "denaturation" of poly-L-glutamic acid (Fig. 5) indicate that urea destroys the helix in the protein, thus confirming the results of *Callaghan* and *Martin* [20]. Calculation of the helix content at 220 and 210 mμ gives the following values:

Urea concentration (moles/l):	2	4	6	7	8	9
% Helix content:	55	55	53	41	22	7

Denaturation occurs only above 6 M; it is not complete at 9 M. The maximum at 222 mμ ($n \rightarrow \pi^*$ transition of the helix form) disappears only after slight heating.

The denaturation seems to be reversible, at least as far as dichroism is concerned, since after partial removal of urea by ultrafiltration (9M → 4 M), the initial dichroism is practically restored. However, if the solution in 9 M urea is heated at 75 °C, no such reversibility is obtained and the dichrogram remains that of a denatured form. This observation indicates that heat plus urea leads to rearrangement of some S–S bonds [21].

5. Solvent Effects

Some solvents favor helix formation in polypeptides and proteins. We chose 2-chloroethanol because of its good transparency in the far ultraviolet. The circular dichroism of clupein sulfate shows that the helical conformation, absent in aqueous solution, appears in 2-chloroethanol (Fig. 12). With a 100% helical polypeptide, no such effect should be found. However, with poly-L-glutamic acid in a 50–50 water-2-chloroethanol solution [*], an apparent increase of about 6% in the helical content is observed, which is probably to be ascribed to the direct effect of the solvent on the dichroism of the helix.

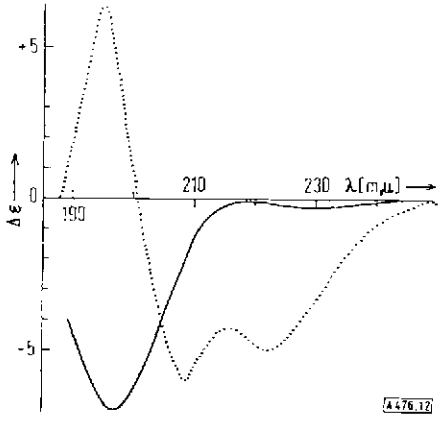


Fig. 12. Circular dichroism of clupein sulfate (———) in aqueous solution at pH 6.15 and (· · · · ·) in 2-chloroethanol.

The helical content of human serum albumin is notably increased in chloroethanol solution. With the method described above, a value of 75% is found, the action of the solvent upon the dichroism of the helix having been taken into account. This value is definitely higher than that in aqueous solution (60%) but still less than 100%. According to *Callaghan* and *Martin* [20], this incapacity to reach 100% helix content is due to structural factors such as S–S bonds.

6. Reduction of Disulfide Bonds

In proteins such as human serum albumin with many S–S bonds linking the protein chain in some points more or less far apart, it can be easily understood that rupture of such bonds leads to conformational changes. However, this phenomenon is difficult to isolate because the protein must first be denatured before the S–S linkage can be severed by chemical means. This denaturation can be effected by adding urea or a detergent such as dodecyl sulfate [22,23].

We denatured human serum albumin with dodecyl sulfate and used the method of reduction of *Würz* and *Haurowitz* [23] using 2-mercaptoethanol. Figure 13 shows the results obtained from which the following conclusions can be drawn:

α) 2-Mercaptoethanol alone does not reduce S–S bonds in human serum albumin.

β) Dodecyl sulfate (0.2 M) decreases the helical content to 40% (least squares method).

γ) Dodecyl sulfate plus 2-mercaptoethanol leads to the almost complete disappearance of the dichroism in the

[20] *P. Callaghan* and *N. H. Martin*, Biochem. J. *83*, 144 (1962).

[21] *V. D. Hospelhorn* and *E. V. Jensen*, J. Amer. chem. Soc. *76*, 2830 (1954).

[*] The compound is insoluble at higher concentrations of chloroethanol.

[22] *G. Markus* and *F. Karush*, J. Amer. chem. Soc. *79*, 134 (1957).

[23] *H. Würz* and *F. Haurowitz*, J. Amer. chem. Soc. *83*, 280 (1961).

250–300 mμ region. This confirms the assignment of the greater part of the optical activity in this region to S–S bonds.

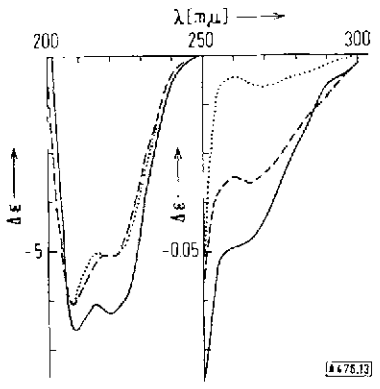


Fig. 13. Reduction of S—S bonds in human serum albumin by mercaptoethanol in the presence of dodecyl sulfate.
(———) in water with mercaptoethanol.
(— — —) in water with dodecyl sulfate.
(·····) in water with dodecy sulfate and mercaptoethanol.

δ) The dichroism in the 250–200 mμ region remains constant, indicating that the helical content is also invariant. This last point confirms that the increase of the molar optical rotation $[M]_D$ during the reduction of S–S bonds is due to the breaking of the S–S bond [23] and not to an increase of the helical content consecutive to the rupture of S–S linkages [22]. Quantitatively, the explanation is not so easy. The increase of $[M]_D$ (by 27 °) cannot be ascribed to the diminution of the negative dichroism at 270 mμ (contribution 2 to 3 ° only). It must be concluded that a strong negative band due to the S–S bond is situated below 200 mμ and cannot be measured in these experiments because of absorption of dodecyl sulfate and 2-mercaptoethanol. Actually, the

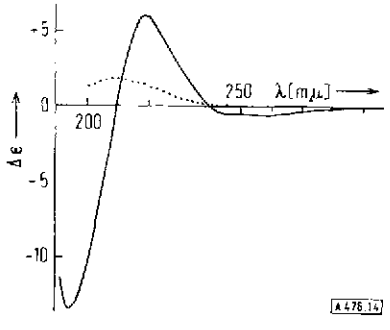


Fig. 14. Circular dichroism in N/10 HCl of (———) L-cystine and (·····) L-cysteine.

dichrogram of cystine shows such a band which is missing in the dichrogram of cysteine (Fig. 14). A crude calculation, based on this hypothesis, gives the right order of magnitude (+ 20 to + 25 °).

If urea is used as denaturing agent instead of dodecyl sulfate, the curves (Fig. 15) are entirely different. The comparison with the dichrogram of Fig. 11 shows that the efficiency of urea is reinforced when 2-mercaptoethanol is present, since the helix content is lowered at a smaller concentration (5 M) than without the reducing agent (7 M). Furthermore, at complete denaturation (9 M urea), the curve differs from that observed for the same concentration in urea but without the reducing agent and seems to be similar to that of random-coil poly-L-glutamic acid.

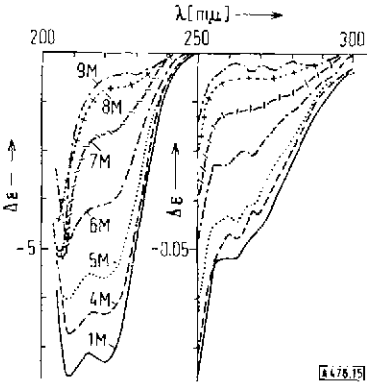


Fig. 15. Circular dichroism of human serum albumin after reduction of S—S bonds with mercaptoethanol in the presence of urea of various concentrations.

This phenomenon may be related to an increased flexibility when S–S bonds are broken. On the other hand, this effect is not observed in the presence of dodecyl sulfate since the curves are practically the same before and after reduction.

From all these observations, we can tentatively deduce that the S–S bonds act as a protector of the rigid structures (helix or random-coil) before denaturation [24], probably by maintaining a conformation which isolates the sensitive groups from the medium [25]. The dodecyl sulfate seems to prevent the collapse of the rigid structures when S–S bonds are broken.

Conclusions

These few examples from the field of polypeptides and proteins show the potentialities of dichroism measurements in the far ultraviolet. The determinations are complicated by the absorption of usual solvents in this region but the difficulties are compensated by the possibility of observing directly the optical activity of transitions which govern the behavior of rotatory power in the near ultraviolet and the visible range.

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[24] In native protein, the non-helical portions do not present a periodic geometry but the positions of groups with respect to a coordinate frame attached to the molecule are perfectly determined (see X-ray diagram of proteins). On the contrary, after denaturation, the chain must be flexible.

[25] *G. Markus* in *H. Peeters*: Proceedings 11th Colloquium on Protides of the Biological Fluids, Bruges (Belgium) 1963. Elsevier, Amsterdam 1964.

Chemistry and Biochemistry of α-Lipoic Acid

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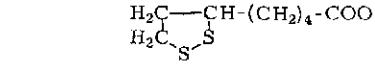
The principal physiological function of lipoic acid appears to be its action as coenzyme in the oxidative decarboxylation of α-oxo acids. In order to find out whether lipoic acid is essential to higher organisms, structurally modified lipoic acids were prepared as potential antagonists. Only 4-oxalipoamide promotes the growth of S. faecalis 8043; the other substances tested are inactive or else inhibit growth. In experiments to determine the substrate specificity of lipoamide oxidoreductase and its inhibition by structurally modified lipoic acids, no strong inhibitors were discovered. – Ring strain, spectra, and ring cleavage of compounds containing the 1,2-dithiolane ring are discussed in relation to the biological function and the reactivity of lipoic acid.

A. Introduction

Lipoic acid *(1)* first became known as a growth factor for many bacteria and protozoa under the name of acetate-replacing factor or protogen-A [1–7]. It occurs widely in plants and animals [7a], and acts as a coenzyme



(1)

in many enzyme-catalysed reactions, particularly in oxidative decarboxylations. Several reviews on the chemistry and biochemistry of lipoic acid have been published [8–10]. The present paper gives a detailed survey of the chemical properties and enzymatic function of lipoic acid. The still controversial effect of lipoic acid on photosynthesis and pharmacological reactions is only briefly mentioned.

Table 1 shows the enzymes involved in lipoic acid-dependent reactions. The α-oxo-acid oxidases (or dehydrogenases) mentioned, *e.g.* pyruvate oxidase and α-oxoglutarate dehydrogenase, are multienzyme complexes.

Table 1. Enzymes and enzyme complexes participating in lipoic acid-dependent reactions.

Enzyme	Origin	Substrate	Ref
Pyruvate dehydrogenase complex	Pig heart muscle	[a]	[11–13]
	pigeon breast muscle		[14–21]
	plants		[22]
	yeast		[23,24]
	E. coli		[21,25–39]
	S. faecalis		[21,38–43]
	M. tuberculosis		[44–46]
	Cl. sporogenes		[47,48]
	Micrococcus pyogenes var. aureus		[49]
	Cl. saccharobutyricum		[50]
	A. aerogenes		[51]
α-Oxoglutarate dehydrogenase complex	Pig heart muscle	[b]	[12,13,15,21,52–62]
	pigeon breast muscle		[13,16]
	E. coli		[21,27,32,33,36]
	S. faecalis		[42,43]
Lipoic acid reductase-transacetylase or -succinylase	*S. faecalis*	[c]	[63]
	E. coli		[26,29–31,64]
Lipoamide oxidoreductase	Pig heart muscle	[d]	[53–58,65–77]
	yeast		[78]
	E. coli		[26,28,30,31,37,73,79–81]
Lipoamidase	Pigeon liver	[d]	[82]
	S. faecalis or yeast		[84–86]
Lipoic acid activating system	*E. coli*	[d]	[64,83,84,87]
	S. faecalis		[41,83,84]

[a] Pyruvate; [b] α-Oxoglutarate; [c] (−)-6-*S*-Acetyldihydrolipoic acid; [d] α-Lipoic acid.

[1] *B. M. Guirard, E. E. Snell,* and *R. J. Williams,* Arch. Biochem. Biophysics *9,* 381 (1946).

[2] *I. Kline* and *H. A. Barker,* J. Bacteriol. *60,* 394 (1950).

[3] *L. G. Colio* and *V. Babb, J.* biol. Chemistry *174,* 405 (1948).

[4] *L. J. Reed, B. G. de Busk, P. M. Johnston,* and *M. E. Getzendaner,* J. biol. Chemistry *192,* 851 (1951).

[5] *E. L. R. Stokstad, C. E. Hoffmann, M. A. Regan, D. Fordham,* and *T. H. Jukes,* Arch. Biochem. Biophysics *20,* 75 (1949).

[6] *E. E. Snell* and *H. P. Broquist,* Arch. Biochem. Biophysics *23,* 326 (1949).

[7] *G. W. Kidder* and *V. C. Dewey,* Arch. Biochem. Biophysics *8,* 293 (1945).

[7a] For chromatographic detection, cf. [142].

[8] *H. Grisebach,* Angew. Chem. *68,* 554 (1956).

[9] *L. J. Reed,* Advances in Enzymol. *18,* 319 (1957).

[10] *L. J. Reed* in *P. D. Boyer, H. Lardy,* and *K. Myrbäck*: The Enzymes. Academic Press, New York 1960, p. 195.

[11] *S. Korkes, A. Del Campillo,* and *S. Ochoa,* J. biol. Chemistry *195,* 541 (1952).

[12] *D. R. Sanadi* and *R. L. Searls,* Biochem. biophysica Acta *24,* 220 (1957).

[13] *S. Kaufmann, C. Gilvarg, O. Cori,* and *S. Ochoa,* J. biol. Chemistry *203,* 869 (1953).

B. The Structures of Enzymes Containing Lipoic Acid

The most thoroughly investigated enzyme containing lipoic acid is the pyruvate oxidase of *E. coli*, a multienzyme complex with a molecular weight of about 4.8×10^6 [25,26]. It consists of pyruvate decarboxylase *(2)*, lipoic acid reductase-transacetylase *(3)*, and lipoamide oxidoreductase *(4)*. The molecular weights of these three enzymes are 1.83×10^5, 1.6×10^6, and 1.12×10^5 respectively; lipoic acid reductase-transacetylase probably consists of sub-units with a molecular weight of 26000 each.

[14] *R.S.Schweet* and *K.Cheslock*, J. biol. Chemistry *199*,749(1952).

[15] *M. Goldberg* and *D. R. Sanadi*, J. Amer. chem. Soc. *74*, 4972 (1952).

[16] *D. R. Sanadi* and *J. W. Littlefield*, J. biol. Chemistry *193*, 683 (1951).

[17] *R. S. Schweet, M. Fuld, K. Cheslock*, and *M. H. Paul* in *W. D. McElroy* and *B. Glass*: Phosphorus Metabolism. The Johns Hopkins Press, Baltimore 1951, Vol. 1, p. 246.

[18] *S. Korkes* in *W. D. McElroy* and *B. Glass*: Phosphorus Metabolism. The Johns Hopkins Press, Baltimore 1951, Vol. 1, p. 259.

[19] *V. Jagannathan* and *R. S. Schweet*, J. biol. Chemistry *196*, 551 (1952).

[20] *R. S. Schweet, B. Katchman, R. M. Bock*, and *V. Jagannathan*, J. biol. Chemistry *196*, 563 (1952).

[21] *S. Ochoa*, Advances in Enzymol. *15*, 183 (1954).

[22] *D. A. Walker* and *H. Beevers*, Biochem. J. *62*, 120 (1956).

[23] *H. Holzer* and *H. W. Goedde*, Biochem. Z. *329*, 175 (1957).

[24] *A. Alvarez, E. Vanderwinkel*, and *J. M. Wiame*, Biochim. biophysica Acta *28*, 333 (1958).

[25] *H. Fernandez-Moran, L. J. Reed, M. Koike*, and *R. Willens*, Science (Washington) *145*, 930 (1964).

[26] *L.J.Reed*: Abstr. 6th Internat. Congr. Biochem. New York, 1964.

[27] *M. L. Das M. Koike*, and *L. J. Reed*, Proc. nat. Acad. Sci. U.S.A. *47*, 753 (1961).

[28] *L. P. Hager*, J. biol. Chemistry *229*, 251 (1957).

[29] *A. D. Gounaris* and *L. P. Hager*, J. biol. Chemistry *236*, 1013 (1961).

[30] *L. P. Hager* and *H. L. Kornberg*, Biochem. J. *78*, 194 (1961).

[31] *M. Koike* and *L. J. Reed*, J. biol. Chemistry *236*, No. 6, PC 33 (1961).

[32] *M. Koike* and *L. J. Reed*, J. biol. Chemistry *235*, 1931 (1960).

[33] *H. Nawa, W. T. Brady, M. Koike*, and *L. J. Reed*, J. Amer. chem. Soc. *82*, 896 (1960).

[34] *C. H. Chin* and *I. C. Gunsalus*, Federat. Proc. *13*, 191 (1954).

[35] *M. Koike* and *L. J. Reed*, J. Amer. chem. Soc. *81*, 505 (1959).

[36] *M. Koike, L. J. Reed*, and *W. R. Carroll*, J. biol. Chemistry *235*, 1924 (1960).

[37] *L. J. Reed* and *M. Koike*, Federat. Proc. *18*, 308 (1959).

[38] *S. Korkes, A. Del Campillo, I. C. Gansulus*, and *S. Ochoa*, J. biol. Chemistry *193*, 721 (1951).

[39] *S. Korkes, J. R. Stern, I. C. Gunsalus*, and *S. Ochoa*, Nature (London) *166*, 439 (1950).

[40] *I. C. Gunsalus*, Federat. Proc. *13*, 715 (1954).

[41] *F. R. Leach, K. Yasunobu*, and *L. J. Reed*, Biochem. biophysica Acta *18*, 297 (1955).

[42] *M. I. Dolin* and *I. C. Gunsalus*, Federat. Proc. *11*, 203 (1952).

[43] *I. C. Gunsalus*, J. cellular comparat. Physiol. *41* (Suppl. 1), 113 (1953)

[44] *D. S. Goldman*, Biochim. biophysica Acta *45*, 279 (1960).

[45] *L. J. Reed* in: Proc. Internat. Sympos. Enzyme Chemistry. Maruzen, Tokio 1958, p. 71.

[46] *D. S. Goldman*, Biochim. biophysica Acta *27*, 513 (1958).

[47] *B. Nisman*, C. R. hebd. Séances Acad. Sci. *230*, 248 (1950).

[48] *B. Nisman* and *S. B. Wiesendanger*, C. R. hebd. Séances Acad. Sci. *238*, 292 (1954).

[49] *M. J. Wolin, J. B. Evans*, and *C. F. Niven*, Arch. Biochem. Biophysics *58*, 356 (1955).

[50] *B. Nisman* and *J. Mager*, Nature (London) *169*, 709 (1952).

[51] *H. J. Strecker* and *S. Ochoa*, J. biol. Chemistry *209*, 313 (1954).

[52] *D. R. Sanadi, M. Langley*, and *R. L. Searls*, J. biol. Chemistry *234*, 178 (1959).

[53] *V. Massey*, Biochim. biophysica Acta *38*, 447 (1960).

[54] *R.L.Searls* and *D. R. Sanadi*, J. biol. Chemistry *236*, 580 (1961).

[55] *R. L. Searls, J. M. Peters*, and *D. R. Sanadi*, J. biol. Chemistry *236*, 2317 (1961).

[56] *R. L. Searls* and *D. R. Sanadi*, Proc. nat. Acad. Sci. U.S.A. *45*, 697 (1959).

[57] *R. L. Searls* and *D. R. Sanadi*, J. biol. Chemistry *235*, 2485 (1960).

[58] *R. L. Searls* and *D. R. Sanadi*, J. biol. Chemistry *235*, No. 8, PC 32 (1960).

[59] *D. R. Sanadi, J. W. Littlefield*, and *R. M. Bock*, J. biol. Chemistry *197*, 851 (1952).

[60] *D. R. Sanadi* and *R. L. Searls*, Federat. Proc. *16*, 241 (1957).

[61] *S. Kaufman* in *W. D. McElroy* and *B. Glass*: Phosphorus Metabolism. The Johns Hopkins Press, Baltimore 1951, Vol. 1, p. 370.

[62] *D. R. Sanadi* and *J. W. Littlefield*, Science (Washington) *116*, 327 (1952).

[63] *I. C. Gunsalus* in *W. D. McElroy* and *B. Glass*: The Mechanism of Enzyme Action. The Johns Hopkins Press, Baltimore 1954.

[64] *I. C. Gunsalus, L. S. Barton*, and *W. Gruber*, J. Amer. chem. Soc. *78*, 1763 (1956).

[65] *V. Massey*, J. biol. Chemistry *235*, No. 10, PC 48 (1960).

[66] *V. Massey* and *C. Veeger*, Biochem. biophysica Acta *48*, 33 (1961).

[67] *C. Veeger* and *V. Massey*, Biochim. biophysica Acta *37*, 181 (1960).

[68] *G. Palmer* and *V. Massey*, Biochim. biophysica Acta *58*, 349 (1962).

[69] *V. Massey* and *N. M. Atherton*, J. biol. Chemistry *237*, 2965 (1962).

[70] *V. Massey*, Biochim. biophysica Acta *37*, 314 (1960).

[71] *V. Massey*, Biochim. biophysica Acta *37*, 310 (1960).

[72] *R. L. Searls* and *D. R. Sanadi*, Biochim. biophysic. Commun. *2*, 189 (1960).

[73] *G. W. Notani* and *I. C. Gunsalus*, Federat. Proc. *18*, 295 (1959).

[74] *N. Savage*, Biochem. J. *67*, 146 (1957).

[75] *V. Massey* and *C. Veeger*, Biochim. biophysica Acta *40*, 184 (1960).

[76] *H. S. Corran, D. E. Green*, and *F. B. Straub*, Biochem. J. *33*, 793 (1939).

[77] *D. R. Sanadi* and *R. L. Searls*, Federat. Proc. *18*, 320 (1959).

[78] *E. Cutolo*, Arch. Biochem. Biophysics *64*, 242 (1956).

[79] *M. Koike, L. J. Reed*, and *W. R. Carroll*, Biochem. biophysic. Res. Commun. *7*, 16 (1962).

[80] *M. Koike* and *L. J. Reed*, J. biol. Chemistry *235*, 1931 (1960).

[81] *M. Koike, P. C. Shah*, and *L. J. Reed*, J. biol. Chemistry *235*, 1939 (1960).

[82] *G. R. Seaman* and *M. D. Dell Naschke*, J. biol. Chemistry *213*, 705 (1955).

[83] *L. J. Reed, F. R. Leach*, and *M. Koike*, J. biol. Chemistry *232*, 123 (1958).

[84] *L. J. Reed, M. Koike, M. E. Levitch*, and *F. R. Leach*, J. biol. Chemistry *232*, 143 (1958).

[84a] The following abbreviations will be used:

ADP	= adenosine diphosphate
ATP	= adenosine triphosphate
CoA	= coenzyme A
DCP	= 2,6-dichlorophenolindophenol
FAD	= flavinadenine dinucleotide
HETPP	= 2-(α-hydroxyethyl)thiamine pyrophosphate
$Lip(SH)_2$	= dihydrolipoic acid
$LipS_2$	= lipoic acid
NAD	= nicotinamide adenine dinucleotide
NADH	= hydrogenated NAD
NADP	= nicotinamide adenine dinucleotide phosphate
TPP	= thiamine pyrophosphate

[85] *G. R. Seaman*, J. biol. Chemistry *234*, 161 (1959).

[86] *K. Suzuki* and *L. J. Reed*, J. biol. Chemistry *238*, 4021 (1963).

[87] *L. J. Reed* and *B. G. De Busk*, Federat. Proc. *13*, 723 (1954).

The whole complex appears to contain 16 molecules of decarboxylase, 64 sub-units of lipoic acid reductase-transacetylase, and 8 molecules of lipoamide oxidoreductase. This opinion has been confirmed by *Reed* et al. [25,26] by electron-microscopic studies. According to these authors the complex has the shape of a disk about 350 Å in diameter and about 250 Å in height. The diameters given for the enzyme components *(2)*, *(3)*, and *(4)* are 75, 40, and 64 Å, respectively. Two superimposed rings, each consisting of 8 molecules of pyruvate decarboxylase *(2)* and 4 molecules of lipoamide oxidoreductase *(4)*, surround an aggregate of 64 lipoic acid reductase-transacetylase sub-units *(3)* arranged in four piles. A model is shown in Figure 1.

Fig. 1. Model of the structure of pyruvate dehydrogenase [25,26].
Large spheres: pyruvate dehydrogenase *(2)*; Medium spheres: lipoamide oxidoreductase *(4)*; Small spheres: subunits of the lipoic acid reductase-transacetylase *(3)*.
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C. Coenzyme Action of Lipoic Acid in Oxidase and Dehydrogenase Systems

The mode of reaction of these oxidases will be explained here using the most thoroughly investigated substrate, *i.e.* pyruvate, as an example. The coenzymes required for the overall oxidative decarboxylation [Equation (a)] of pyruvate are thiamine pyrophosphate (TPP), Mg^{2+}, nicotinamide adenine dinucleotide (NAD), lipoic acid *(1)*, coenzyme A, and flavin adenine dinucleotide (FAD) [84a].

$$CH_3{-}CO{-}CO_2H + NAD^+ + CoA{-}SH \xrightarrow[\text{lipoic acid, FAD}]{\text{TPP, } Mg^{2+}} CH_3{-}CO{-}SCoA + NADH + H^+ + CO_2 \quad (a)$$

The reaction is catalysed by the enzymes *(2)*, *(3)*, and *(4)* described in Section B. It starts with the formation of "active acetaldehyde", *i.e.* 2-(α-hydroxyethyl)thiamine pyrophosphate (HETPP) [88–91], *via* a thiamine pyrophosphate (TPP)-pyruvate compound [91]. Figure 2 shows the component reactions.

In yeast cells there are two routes for the conversion of pyruvate into acetyl-coenzyme A. Equation (b) shows a

$$\text{Pyruvate} \xrightarrow[\text{Pyruvate decarboxylase}]{\text{TPP, } Mg^{2+}} \text{acetaldehyde} \xrightarrow[\text{Acetaldehyde dehydrogenase}]{NAD^+\ (NADP)^+} \text{acetate} \xrightarrow[\text{Thiokinase}]{\text{ATP, } Mg^{2+}\text{, CoA-SH}} \text{acetyl-SCoA} \quad (b)$$

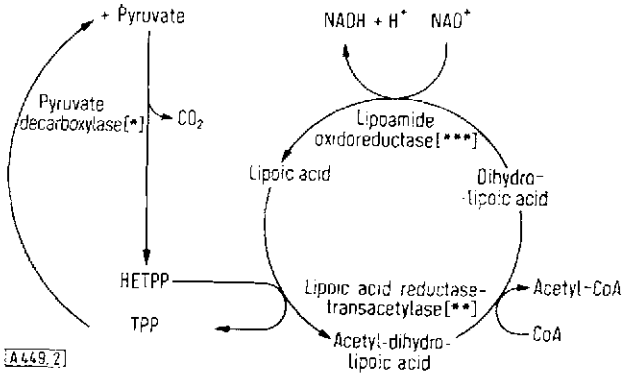


Fig. 2. Reactions participating in the oxidation of pyruvate to acetyl-coenzyme A by the pyruvate oxidase multienzyme complex.

[*] Although the three enzymes have actually been isolated, the revised nomenclature of the Enzyme Commission groups together the decarboxylating and the lipoic acid-reducing and -acetylating activities under the heading pyruvate: lipoate oxidoreductase (acceptor-acetylating), E.C. 1.2.4.1. The corresponding 2-oxoglutarate degrading enzyme is 2-oxoglutarate: lipoate oxidoreductase (acceptor-acylating) E.C. 1.2.4.2.

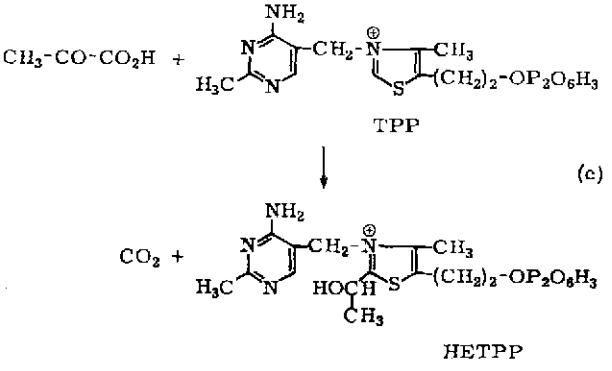
[**] The transacetylating activity with respect to CoA is described by the Enzyme Commission as acetyl-CoA: dihydrolipoate *S*-acetyltransferase, E.C. 2.3.1.12.

[***] E.C. 1.6.4.3.

reaction sequence the intermediates of which were identified by *Holzer* and *Goedde* [23]. *Cutolo* [78] discovered in 1956 that yeast cells contain lipoamide oxidoreductase. In 1957, the present authors [23] showed that in yeast, pyruvate can also be oxidized directly since yeast contains a pyruvate oxidase system which behaves like pyruvate oxidase from animals and bacteria [Equation (a)]. Reaction (b) takes place in the yeast cytoplasm, and Reaction (a) in the mitochondria.

I. Pyruvate Decarboxylase

The synthesis of 2-(α-hydroxyethyl)thiamine pyrophosphate (HETPP) is catalysed by pyruvate dehydrogenase:



The subsequent reactions leading to acetyl-coenzyme A have also been elucidated, except for a few details concerning the action of lipoic acid. [^{14}C]-HETPP obtained by both enzymatic [92] and chemical methods [93,94] has been converted to [^{14}C]-acetyl-CoA [95].

[88] *H. Holzer*, Angew. Chem. *73*, 721 (1961).

[89] *H. W. Goedde*, Int. Z. Vitaminforsch. *33*, 18 (1963).

[90] *H. W. Goedde, C. Stahlmann, B. Ulrich*, and *H. Holzer*, Biochem. Z., in the press.

[91] *H. Holzer* and *K. Beaucamp*, Biochim. biophysica Acta *46*, 225 (1961).

[92] *H. Holzer, H. W. Goedde, K. H. Göggel*, and *B. Ulrich*, Biochem. biophysic. Res. Commun. *3*, 599 (1960).

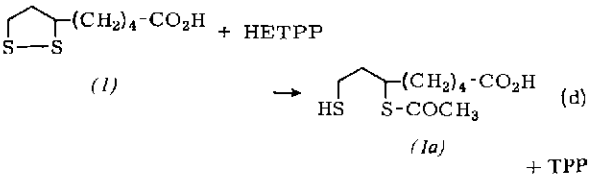
[93] *H. W. Goedde, B. Ulrich, K. G. Blume*, and *H. Holzer*, Angew. Chem. *73*, 772 (1961).

[94] *H. Holzer, H. W. Goedde*, and *B. Ulrich*, Biochem.biophysic. Res. Commun. *5*, 447 (1961).

[95] *H. W. Goedde, H. Inouye, H. Holzer*, Biochim. biophysica Acta *50*, 41 (1961).

II. Lipoic Acid Reductase-Transacetylase

This enzyme, originally known as thiol transacetylase, was first detected in extracts of *E. coli* by *Gunsalus* [40, 63, 64]. It catalyses the acetylation of lipoic acid *(1)* and the transfer of the acetyl group from acetyldihydrolipoic acid *(1a)* to coenzyme A.



(1) *(1a)* + TPP (d)

(1a) + Coenzyme A → Acetyl–CoA + Dehydrolipoic acid (e)

Acetylthiamine pyrophosphate (acetyl-TPP) was postulated as an intermediate in Reaction (d). This highly unstable compound [96–98] would be the first oxidation product of active acetaldehyde (HETPP). Experiments by *Das* et al. [27] indicated the occurrence of acetyl-TPP in reactions with non-physiological electron acceptors. *Holzer* and *Goedde* [99] have demonstrated the formation of acetate from pyruvate in reaction sequences involving TPP, yeast pyruvate decarboxylase, and 2,6-dichlorophenolindophenol. Further experiments [100] suggested the intermediate formation of acetyl-TPP according to Reaction (f), since acetate was detected and lipoic acid was not involved.

Pyruvate → HETPP → acetyl–TPP → acetate (f)

However, on repeating this experiment with various enzymes [11, 23, 51] and acceptors, and starting with [^{14}C]-HETPP instead of pyruvate, we were unable to detect any intermediate formation of [^{14}C]-acetyl-TPP [101]. Nothing is known yet about the occurrence of acetyl-TPP in the oxidation of pyruvate or of α-oxoglutarate under physiological conditions.

The isolation of acetyl and succinyl thioesters of dihydrolipoic acid by *Gunsalus* [63, 102, 103] proved that lipoic acid acts as an acyl acceptor. *S*-Acetyldihydrolipoic acid [Eq. (d)] is formed by a redox process, in which the oxidation of the aldehyde to the carboxylic acid is accompanied by reductive cleavage of the 1,2-dithiolane ring of lipoic acid. The dihydrolipoic acid is acetylated exclusively at the C-6 sulfur atom [63, 83].

Sanadi et al. [52, 104] and *Goldmann* [44] have prepared lipoic acid reductase-transacetylase from pyruvic oxidase obtained from *M. tuberculosis*. *Hager* et al. [28–30] have purified the enzyme from *E. coli* mutants. According to *Reed* [84], the enzyme reacts with both enantiomers of lipoamide. *Hager* and *Kornberg* [30] developed a test for lipoic acid transsuccinylase obtained from *E. coli* mutants using succinate thiokinase to prepare succinyl-coenzyme A [Eq. (g)] and treating the product with dihydrolipoic acid [Eq. (h)]. This second step is catalysed by lipoic acid transsuccinylase.

ATP + Succinate + CoA–SH ⇌ ADP + P + Succinyl–SCoA (g)

Succinyl–SCoA + Lip(SH)$_2$ ⇌ CoA–SH + Succinyl–S–Lip(SH) (h)

The *S*-succinyldihydrolipoic acid is quantitatively determined as succinylhydroxamic acid obtained by reaction with hydroxylamine (see also [105]).

In the reactions described in Fig. 2, (−)-dihydrolipoic acid appears to be the biologically active form. *Reed* [32, 84] has shown that lipoic acid reductase-transacetylase can react with bound or free *S*-acetyldihydrolipoic acid, as does lipoamide oxidoreductase. In contrast, enzyme-bound lipoic acid is essential to Reaction (d).

a) *Removal of Enzyme-Bound Lipoic Acid Using Lipoamidase, and Reactivation of the Apoenzyme*

Lipoic acid reductase-transacetylase is the only enzyme of the pyruvate oxidase complex containing protein-bound lipoic acid. The latter can he removed using an enzyme from pigeon liver [82, 106]. According to *Reed*, lipoic acid is joined by a peptide linkage to the ε-amino group of one of the lysine residues in the enzyme protein [33]. Correspondingly, lipoamide and dihydrolipoamide are more effective than lipoic acid in model reactions [34, 107, 108]. *Reed* [33, 109] has shown that *N*(ε)-DL-lipoyl-L-lysine is reduced three times as fast as DL-lipoamide by NADH and lipoamide oxidoreductase from *E. coli*.

Two enzymatic reactions are required to link lipoic acid to the apoenzyme: (a) the ATP-dependent activation of lipoic acid to form lipoyladenylate, and (b) the transfer of the lipoyl residue to the apoenzyme. Lipoic acid reductase-transacetylase from which lipoic acid has been removed, can be reactivated by incubating it with ATP plus lipoic acid (or synthetic lipoyladenylate) and a lipoic acid-activating system from *S. faecalis* or *E. coli* [83, 109].

b) *Type of Linkage and Amino-Acid Sequence at the Site of the Lipoic Acid-Protein Link*

Oxo-acid oxidases containing radioactively labelled lipoic acid can be prepared in two ways:

(a) By culturing *E. coli* strains in the presence of [^{35}S]-lipoic acid.

(b) By allowing lipoamidase to act on oxo-acid oxidases. The apoenzyme formed is isolated by centrifugation at 144000 g and is reactivated by incubation with ATP, [^{35}S]-lipoic acid, and the lipoic acid-activating system.

Oxo-acid oxidases containing labelled lipoic acid have been oxidized with performic acid and hydrolysed for 3 h at 100 °C with 12 N HCl. It was possible to isolate

[96] *R. Breslow* and *E. McNelis*, J. Amer. chem. Soc. *82*, 2394 (1960).

[97] *C. P. Nash*, *C. W. Olsen*, *F. G. White*, and *L. L. Ingraham*, J. Amer. chem. Soc. *83*, 4106 (1961).

[98] *K. Daigo* and *L. J. Reed*, J. Amer. chem. Soc. *84*, 659 (1962).

[99] *H. Holzer* and *H. W. Goedde*, Biochem. Z. *329*, 192 (1957).

[100] *H. Holzer* and *R. M. M. Crawford*, Nature (London) *188*, 410 (1960).

[101] *H. W. Goedde* and *B. Ulrich*, unpublished work.

[102] *I. C. Gunsalus*, J. Vitaminol. (Kyoto) *4*, 52 (1958).

[103] *I. C. Gunsalus*: Abstr. Amer. chem. Soc. 133rd Meeting 1958, 3c.

[104, 105] *D. R. Sanadi*, *M. Langley*, and *F. White*, J. biol. Chemistry *234*, 183 (1959).

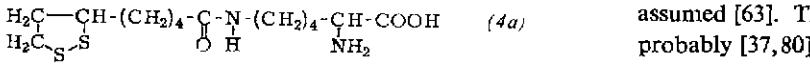
[106] *G. R. Seaman*, J. Amer. chem. Soc. *76*, 1712 (1954).

[107] *V. Massey*, Biochim. biophysica Acta *30*, 205 (1958).

[108] *H. W. Goedde*, unpublished work.

[109] *H. Nawa*, *W. T. Brady*, *M. Koike*, and *L. J. Reed*, J. Amer. chem. Soc. *81*, 2908 (1959).

$N(\varepsilon)$-lipoyl-L-lysine *(4a)* [109a], the hydrolysis of which gave L-lysine and lipoic acid in the ratio of 1 : 1 [41,45,83]. This result has been confirmed by *Goldman*.



(4a)

Reed treated highly purified enzyme preparations from *E. coli* containing [^{35}S]-lipoic acid with performic acid and partially hydrolysed the product. The [^{35}S]-peptides of lipoic acid were isolated and identified. From pyruvate dehydrogenase the sequence glycine-asparagine-lipoyllysine-alanine was obtained, while in oxoglutarate dehydrogenase the sequence threonine-asparagine-lipoyllysine-valine-(valine, leucine)-glutamine [112] was present.

III. Lipoamide Oxidoreductase

This flavin-adenine dinucleotide enzyme catalyses the reoxidation of dihydrolipoic acid in the presence of NAD:

$$\text{Dihydrolipoic acid} + \text{NAD}^+ \rightleftharpoons \text{lipoic acid} + \text{NADH} + \text{H}^+ \quad \text{(i)}$$

Lipoamide oxidoreductase has been studied since 1958 [35, 53–58, 65–73, 79, 84, 104, 107, 113–117]. It is identical with the diaphorase [119–121] isolated from heart muscle by *Straub* [118] and *Savage* [74], and can be estimated photometrically by Reactions (i) or (j). In the latter, hexacyanoferrate(III) or 2,6-dichlorophenolindophenol (DCP) can act as hydrogen acceptors.

$$\text{NADH} + \text{H}^+ + \text{Acceptor} \rightleftharpoons \text{NAD}^+ + \text{Acceptor–H}_2 \quad \text{(j)}$$

Unlike lipoic acid reductase-transacetylase, lipoamide oxidoreductase is not specific for either (+)- or (−)-lipoic acid. However, a lipoamide oxidoreductase obtained by *Basu* and *Burma* [122] from *Spinacia oleracea* reacts only with (−)-dihydrolipoic acid.

Flavin-adenine dinucleotide (FAD) can dissociate reversibly from the enzyme. The enzyme is decolorized by NADH or dihydrolipoic acid but the color is restored on addition of lipoic acid. This is taken to indicate that enzyme-bound dihydrolipoic acid is oxidized by FAD, and not directly by NAD, as had previously been assumed [63]. Thus the electron transfer sequence is probably [37, 80]

$$\left[\begin{matrix}\text{oxoglutarate}\\ \text{pyruvate}\end{matrix}\right] \rightarrow \text{lipoic acid} \rightarrow \text{FAD} \rightarrow \text{NAD}.$$

a) *Properties of Lipoamide Oxidoreductase*

Lipoamide oxidoreductase has been detected in the pyruvate oxidase and oxoglutarate dehydrogenase complexes of many organisms (see Table 1) [36, 53, 57, 80, 81, 123]. Highly purified preparations of lipoamide oxidoreductase are intensely yellow, exhibit fluorescence, and have absorption maxima at 273, 359, and 456 mμ with a shoulder at 480 mμ [37].

The highly purified enzyme contains 1.16 % of FAD ≙ 0.56 % of riboflavin [74, 76]. Its fluorescence and the absorption at 456 mμ disappear in the presence of excess NADH. The enzyme is inhibited by *p*-chloromercuribenzoate, and reactivated by glutathione [123].

pH optima of 5.6 to 5.9 and 6.5 to 7.0 are found for lipoic acid and DL-lipoamide, respectively [107]. By reduction of the flavoprotein in various NADH/NAD equilibria *Sanadi* found a reduction potential of about −0.34 volt at pH 7.0 and 22 °C for lipoamide oxidoreductase from pig heart oxoglutarate dehydrogenase [56, 57].

Turnover number: Measurements using Reaction (j) show that 8500 moles of substrate react per minute with 10^5 g of enzyme protein [76] (for data on the reaction of lipoic acid, see [71, 115] and Table 2).

It was originally thought that lipoamide oxidoreductase resulted from the breakdown of cytochrome reductase. *Massey* [71] however disproved this by isolating both enzymes separately from pig heart.

b) The Mode of Action of Lipoamide Oxidoreductase

Lipoic acid transacetylase-reductase containing bound lipoic acid is inhibited by arsenite even in concentrations as low as 10^{-3}–10^{-5} M [40, 52, 59, 66, 125–128]. (For inhibition experiments using other arsenic compounds or heavy metal cations, see [104, 105, 128, 129]). The inhibition can be reversed by the addition of dithiols, *e.g.* 2,3-dimercaptopropanol.

Highly purified lipoamide oxidoreductase, which does not contain bound lipoic acid, is also inhibited by

[109a] Biotin, which plays an important part in carboxylation reactions, (*e.g.* in fatty acid synthesis) likewise occurs bound to lysine. Biocytin [$N(\varepsilon)$-biotinyl-L-lysine] has been isolated from yeast autolysates [110, 111].

[110] *R. L. Peck, D. E. Wolf,* and *K. Folkers,* J. Amer. chem. Soc. *74,* 1999 (1952).

[111] *L. D. Wright, E. L. Cresson, H. R. Skeggs, T. R. Wood, R. L. Peck, D. E. Wolf,* and *K. Folkers,* J. Amer. chem. Soc. *74,* 1996 (1952).

[112] *K. Daigo* and *L. J. Reed,* J. Amer. chem. Soc. *84,* 666 (1962).

[113] *V. Massey, Q. H. Gibson,* and *C. Veeger,* Biochem. J. *77,* 341 (1960).

[114] *C. J. Lusty,* J. biol. Chemistry *238,* 3443 (1963).

[115] *H. W. Goedde, P. Grafen,* and *U. Schmidt,* Biochem. Z. *339,* 23 (1963).

[116] *H. W. Goedde, C. Stahlmann, P. Grafen,* and *U. Schmidt,* Arch. Mikrobiol. *45,* 359 (1963).

[117] *H. W. Goedde* and *U. Schmidt,* unpublished work.

[118] *F. B. Straub,* Biochem. J. *33,* 787 (1939).

[119] *H. v. Euler* and *H. Hellström,* Hoppe-Seylers Z. physiol. Chem. *252,* 31 (1938).

[120] *J. G. Dewan* and *D. E. Green,* Nature (London) *140,* 1097 (1937).

[121] *J. G. Dewan* and *D. E. Green,* Biochem. J. *32,* 626 (1938).

[122] *D. K. Basu* and *D. P. Burma,* J. biol. Chemistry *235,* 509 (1960).

[123] Note added in proof: According to *Lusty* and *Singer,* J. biol. Chemistry *239,* 3733 (1964), 23% of the lipoamide oxidoreductase contained in heart mitochondria is present in α-oxoglutarate dehydrogenase; 52% are found in pyruvate oxidase, and the remaining 25% are present either as free enzyme or linked to an as yet unknown enzyme complex. In liver mitochondria the figures are 6%, 66%, and 28%, respectively. The fraction denoted "free lipoamide oxidoreductase" is identical in electrophoretic mobility, substrate specificity, and arsenite inhibition with lipoamide oxidoreductase isolated from pig heart or beef liver by the usual procedures.

[124] *M. M. Weber* and *N. O. Kaplan,* Science (Washington) *123,* 844 (1956).

[125] *D. R. Sanadi, M. Langley,* and *F. White,* Biochim. biophysica Acta *29,* 218 (1958).

[126] *R. A. Peters,* Symposia Soc. exp. Biol. *3,* 36 (1949).

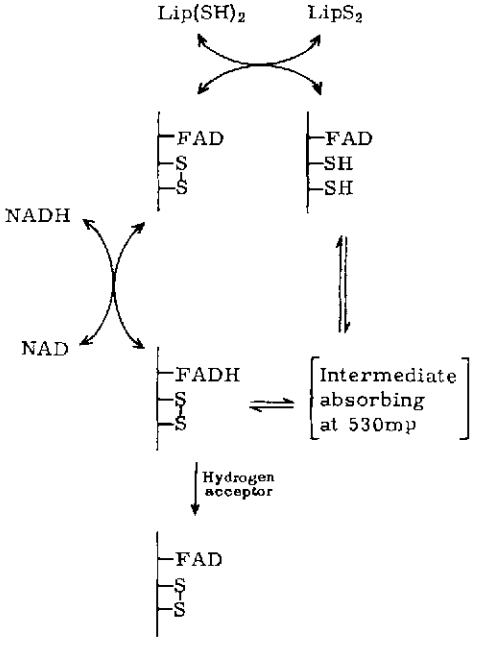
[127] *R. A. Peters, H. M. Sinclair,* and *R. H. S. Thompson,* Biochem. J. *40,* 516 (1946).

[128] *O. K. Reiss,* J. biol. Chemistry *233,* 789 (1958).

[129] *O. K. Reiss* and *L. Hellermann,* J. biol. Chemistry *231,* 557 (1958).

arsenite (or Cd^{2+}) but only if it is reduced by simultaneous incubation with NADH [55, 72, 66, 75]. After reduction, 2 moles of SH groups per mole of enzyme can be detected [55]. Apparently a disulfide bridge between two cysteine residues is cleaved by NADH. By ultracentrifugation experiments in 6.5 M urea, *Massey* [65, 130] was able to show that on reduction of the enzyme its molecular weight decreases to about half. This was taken to indicate that the disulfide bridge cleaved by NADH links two peptide chains in the native enzyme.

When lipoamide oxidoreductase is inhibited by arsenite, only Reaction (i) is affected, *i.e.* the enzyme loses the ability to catalyse the oxidation of dihydrolipoic acid (or the reduction of lipoic acid). However, it still catalyses the transfer of hydrogen from NADH to hexacyanoferrate(III) or 2,6-dichlorophenolindophenol, *i.e.* Reaction (j) is not affected by arsenite [55, 72]. From this it follows that NADH first reduces the FAD component of the enzyme (Scheme 1). The FADH formed then transfers hydrogen to the disulfide bridge of the enzyme, thus forming two SH groups. Under physiological conditions, the disulfide bridge is reduced by dihydrolipoic acid. FAD accepts the hydrogen from the SH groups (with reformation of the disulfide bridge) and transfers it to NAD. Non-physiological hydrogen acceptors (hexacyanoferrate(III) or 2,6-dichlorophenolindophenol) accept hydrogen directly from FADH, *i.e.* without SH groups being involved. Therefore, catalysis of Reaction (j) is independent of arsenite.



Scheme 1. The mode of action of lipoamide oxidoreductase [55, 72].

Savage [74] showed that the addition of NADH to lipoamide oxidoreductase alters the spectrum. The compound formed is stable and it appears to be analogous to flavin semiquinone [131] (see also [57, 113]). The absorption maximum at 530 mμ of the reduced enzyme disappears on addition of arsenite or cadmium ions. ESR-spectrometric investigations showed no free radicals in the reduced enzyme. The intramolecular electron transfer from enzyme dithiol to flavin proceeds *via* an intermediate with an absorption peak at about 530 mμ. An intermediate denoted as a "charge-transfer complex" or as the "red form" was studied by *Sanadi* et al. and also by *Massey* et al. [30, 52, 55, 58, 65, 66, 68, 69, 72, 113]. Its structure remains unidentified.

D. Studies on Modified Lipoic Acids [133]

No avitaminoses or metabolic alterations associated with lipoic acid deficiency have so far been recorded. Whether lipoic acid is an essential factor for higher organisms can be decided only by the use of lipoic acid antagonists. A lipoic acid-free diet can hardly be maintained, since the substance is widely distributed in foodstuffs and presumably is formed by the intestinal flora.

Several laboratories [134–137] have synthesized lipoic acid derivatives in which the carboxy group was altered and the number of ring members was varied. Only one of the diastereomers of 8-methyllipoic acid exhibited a detectable inhibitory effect on the growth of bacteria.

We have synthesized compounds resembling lipoic acid [138, 139a, 139b], to investigate whether the distance of four methyl groups between the carboxy group and the 1,2-dithiolane ring or the length of the (eight-membered) carbon chain is necessary for the action of lipoic acid. Accordingly lipoic acids with the CH_2 groups replaced by heteroatoms (S, O) and, in addition, an acid in which the ring was displaced toward the carboxy group were synthesized. Further, hydroxy groups and carbonyl oxygen were introduced into the ring or side-chain, since these substituents often give rise to antagonistic effects in biologically active substances. Table 2 gives a list of these compounds.

The growth of the following microorganisms depends on lipoic acid: *Tetrahymena pyriformis*, *Corynebacterium bovis*, *E. coli* mutants and lactic acid bacilli. For the growth of the first two organisms lipoic acid is an absolute requirement. In other bacteria (*Lactobacillus casei*, *L. arabinosis*, *S. lactis*, *S. faecalis R.*, *S. faecalis* 8043) lipoic acid reverses the inhibition of growth caused by substances such as propionate. In our studies we used *S. faecalis* 8043 the growth of which is inhibited by 1–3 mg/ml propionate but which starts to grow again after the addition of lipoic acid or some of its analogues (cf. Fig. 3). The rate of growth was determined by measuring the turbidity of a diluted sample of a culture with a Zeiss PMQ II spectrophotometer at 660 mμ [116].

[130] *V. Massey*, *T. Hofmann*, and *G. Palmer*, J. biol. Chemistry *237*, 3820 (1962).

[131] *H. Beinert*, J. Amer. chem. Soc. *78*, 5323 (1956).

[133] For the chromatographic detection of lipoic acid, see [142].

[134] *M. W. Bullock*, *J. J. Hand*, and *E. L. R. Stokstad*, J. Amer. chem. Soc. *79*, 1975 (1957).

[135] *R. C. Thomas* and *L. J. Reed*, J. Amer. chem. Soc. *78*, 6150 (1956).

[136] *E. L. R. Stokstad*, Federat. Proc. *13*, 712 (1954).

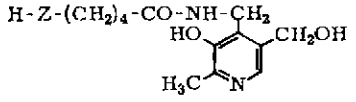
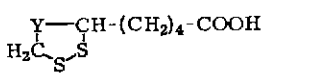
[137] *E. L. Patterson*, *J. V. Pierce*, *E. L. R. Stokstad*, *C. E. Hoffman*, *J. A. Brockman jr.*, *F. P. Day*, *M. E. Macchi*, and *T. H. Jukes*, J. Amer. chem. Soc. *76*, 1823 (1954).

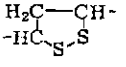
[138] *U. Schmidt*, *H. Alpes*, *J. C. Loewenguth*, *P. Grafen*, and *H. W. Goedde*, Liebigs Ann. Chem. *666*, 201 (1963).

[139a] *U. Schmidt*, *P. Grafen*, and *H. W. Goedde*, Liebigs Ann. Chem. *670*, 157 (1963).

[139b] *U. Schmidt*, *J. Malone*, and *H. W. Goedde*, unpublished work.

Table 2. Michaelis constants K_M and turnover numbers for the reaction of modified lipoic acids with lipoamide oxidoreductase.

Modified lipoic acid [a]		$10^3 K_M$ [mole/l]	Turnover number $\times 10^{-3}$ [83]	Ref.
H–Z–$(CH_2)_4$–COOH	*(1)*	2.3	3.15	[181]
H–Z–$(CH_2)_4$–$CONH_2$	*(5)*	2.8	14.0	[181]
	*(6)*	1.54	—	[140]
 Y = CH–CH_3	*(7)*	—	—	[139a]
Y = CH–OH	*(8)*	—	—	[139a]
Y = CO	*(9)*	3.7	4.65	[139a]
H–Z–CH_2–O–$(CH_2)_2$–COOH	*(10)*	6.25	2.4	[138]
H–Z–CH_2–O–$(CH_2)_2$–$CONH_2$	*(11)*	4.0	13.1	[138]
H–Z–CH_2–$CH(CH_3)$–$(CH_2)_2$–COOH	*(12)*	11.0	2.54	[139a]
H–Z–$(CH_2)_2$–S–CH_2–COOH	*(13)*	·	—	[139c]
H–Z–CO–$(CH_2)_3$–COOH	*(14)*	5.0	0.96	[139a]
H–Z–$(CH_2)_3$–CHF–COOH	*(15)*	3.2	9.87	[139b]
CH_3–$(CH_2)_3$–Z–COOH	*(16)*	—	—	[138]

[a] Z = 

I. Growth and Inhibition Studies on S. faecalis 8043 with Modified Lipoic Acids [116, 138, 139a, 139b]

The results of the growth test are shown in Fig. 3 [116]. Replacement of a CH_2 group in the chain between the carboxy group and the ring by an S-atom [3-thialipoic acid *(13)*] or an O-atom [4-oxalipoic acid *(10)*] leads to compounds which are either inactive or have a very weak activating effect on the growth of *S. faecalis* 8043.

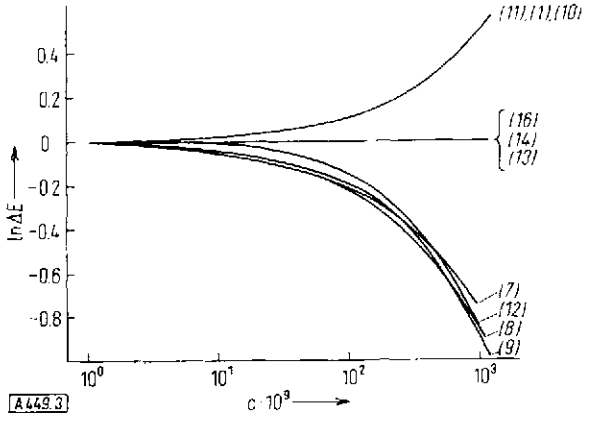


Fig. 3. Rate of growth of *S. faecalis* 8043 in the presence of modified lipoic acids [116].

Abscissa: Concentration of modified lipoic acid in 10^{-9} mole/l.

Ordinate: Natural logarithm of the change in extinction ΔE at 660 mμ in a given time relative to a standard solution containg no bacteria. The smoothed curves were normalized to ln E = 0 at c = 5×10^{-9}/6 mole/l. Compounds *(7)*, *(12)*, *(8)*, and *(9)* inhibit growth, *(16)*, *(14)*, and *(13)* have no effect, while *(11)* like lipoic acid *(1)* and 4-oxalipoic acid *(10)*, stimulates growth.

Introduction of a methyl group [4-methyllipoic acid *(12)*] at the CH_2-chain produces an inhibitory effect whereas introduction of a keto group [5-oxolipoic acid *(14)*] does not. Substitution on the ring carbons leads to compounds with inhibitory action, *e.g.* 7-methyllipoic acid *(7)*, 7-hydroxylipoic acid *(8)*, 7-oxolipoic acid *(9)*, and also the 8-methyllipoic acid synthesized by *Stockstad*. Alterations in ring size or in the position of the disulfide bridge [2,4-lipoic acid *(16)*] lead to loss of activity.

II. Inhibition and Substrate Specificity of Lipoamide Oxidoreductase [115, 138, 139a, 139b]

Since lipoamide oxidoreductase containing modified lipoic acids still reacts with free lipoic acid according to Equation (i), this enzyme is particularly suitable for the investigation of inhibition and substrate specificity. Michaelis constants, turnover numbers, and inhibition constants were determined by the method of *Massey* [53, 66, 71, 107] (see Table 2). 7-Methyllipoic acid *(7)* and 3-thialipoic acid *(13)* are the only acids which give rise to competitive inhibition of the reduction of lipoic acid. The inhibition constant for 7-methyllipoic acid was 2.8×10^{-3}, and that for 3-thialipoic acid 8.0×10^{-4}. The following conclusions may be drawn from the results:

2,4-Lipoic acid *(16)* is inert, *i.e.* it is unable to form an enzyme-substrate complex. Replacement of the carbon atoms 3 or 4 in lipoic acid by a hetero-atom leads to complete loss of activity in 3-thialipoic acid *(13)* and to reduced affinity in 4-oxalipoic acid *(10)*. The amide *(11)* of this latter acid is the only derivative of lipoic acid which has almost the same activity as lipoamide. 4-Methyl- *(12)* and 5-oxolipoic acid *(14)* have properties similar to those of 4-oxalipoic acid, *i.e.* both the reaction rate and enzyme affinity are reduced.

Substitution on C-7 produces varying effects. 7-Methyllipoic acid *(7)* is not transformed by lipoamide oxidoreductase but has an inhibitory effect, while 7-hydroxylipoic acid *(8)* is entirely inactive. 7-Oxolipoic acid *(9)* is transformed more rapidly than the physiological substrate, which indicates an activating effect of the carbonyl group on the S–S bridge. The amides of lipoic acid and 4-oxalipoic acids show high turnover numbers and relatively high Michaelis constants as does lipoylpyridoxamine *(6)* (see also [71, 107]). 2-Fluorolipoic acid *(15)* [117] exhibits no inhibitory action.

[139c] *D. Sorg*, Doctorate Dissertation, Universität Freiburg 1961; *A. Lüttringhaus* and *D. Sorg*, Liebigs Ann. Chem., in the press.

[140] German Pat. Appl. M 57881 IVd/12p (Aug. 20th, 1963), E. Merck, inventor: *U. Schmidt*.

E. Further Reactions of Lipoic Acid

The main physiological function of lipoic acid appears to be its role as coenzyme during the oxidative decarboxylation of α-oxo acids. Oxidative splitting of diacetyl by *S. faecalis* requires the presence of lipoic acid in addition to that of TPP and Mg^{2+} [141]. Acetyldihydrolipoic acid is formed intermediately.

Calvin et al. [143–150] have discussed the participation of lipoic acid in photosynthesis. Studies on green algae with [^{35}S]-lipoic acid led to the characterization of several biologically active forms of the acid indicating its participation in the Hill reaction. However, other investigations produced conflicting results [151]. Some evidence for the participation of dihydrolipoic acid in the Hill reaction is provided by the arsenite sensitivity of the latter reaction, which is catalysed by chloroplast preparations from spinach leaves [152].

F. The Pharmacology of Lipoic Acid

The therapeutic use of lipoic acid in liver diseases has not so far given concordant results. The findings of a response of hepatic coma to lipoic acid have not been confirmed, but a beneficial effect on liver afflictions has been reported from numerous sources [153–159]. Many publications have described the protective and curative effect of lipoic acids in heavy-metal poisoning (As, Pb, Hg, Se, $Ni(CO)_4$). The effect produced is frequently superior to that of BAL [159a]. A similar beneficial effect has been reported in liver damage induced experimentally by CCl_4, allyl alcohol, and narcotics. The clinical testing of easily resorbed lipoic acid derivatives, *e.g. (6)* [140], which are readily incorporated into lipoic acid-containing enzymes, appears to be promising [140] (Lipoic acid: DL_{50} (mouse) 160–275 mg/kg intraperitoneally).

G. Reactivity, Ring Cleavage, and Ultraviolet Absorption of 1,2-Dithiolanes

The biological activity of lipoic acid depends on the great reactivity of the disulfide bond of the dithiolane ring. Earlier attempts to interpret this reactivity of (five-membered) 1,2-dithiolanes over the (six-membered) 1,2-dithianes and open-chain disulfides by the higher strain in the five-membered ring [160], and a calculation of the strain from the shift of the ultraviolet absorption towards longer wavelengths [161] were unsuccessful. The strain in the dithiolane ring is only 4–6 kcal/mole [162, 163]. Also, it is not permissible to use thermodynamic data, such as the energy content as expressed by the ring strain, to interpret kinetic factors (reactivity).

Such a relationship is found only in very simple cases, *e.g.* in unsubstituted 1,2-dithiolane and 1,2-dithiane. Here no mesomeric groups are present to influence the S–S bond and no deformation of the ring through steric interactions between substituents is possible, so that bathochromic shift and ring strain are predominantly determined by the interplanar angle. Even so, no quantitative relationship exists among reactivity, ring strain, and ultraviolet absorption.

I. Ring Strain in 1,2-Dithiolanes

The angle φ (Fig. 4) which the two R–S bonds form in strain-free open-chain disulfides is about 90° [164]. Under these conditions the repulsion between the lone p_Z-electron pairs of the sulfur atoms is at a minimum, and an interchange of these electrons with the free d-

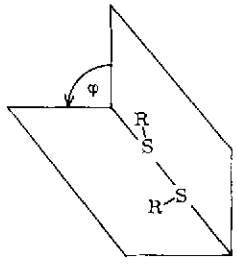


Fig. 4. Interplanar angles φ in aliphatic disulfides.

[141] *M. Brenner, A. Niederwieser*, and *C. Pataki*, Experientia *17*, 145 (1961).

[142] *L. Reio*, J. Chromatogr. *4*, 458 (1960).

[143] *M. Calvin, H. Grisebach*, and *R. C. Fuller*, J. Amer. chem. Soc. *77*, 2659 (1955).

[144] *M. Calvin* and *J. A. Barltrop*, J. Amer. chem. Soc. *74*, 6153 (1952).

[145] *D. F. Bradley* and *M. Calvin*, Arch. Biochem. Biophysics *53*, 99 (1954).

[146] *M. Calvin*, Angew. Chem. *68*, 263 (1956).

[147] *J. A. Barltrop, P. M. Hayes*, and *M. Calvin*, J. Amer. chem. Soc. *76*, 4348 (1954).

[148] *M. Calvin*, Federat. Proc. *13*, 697 (1954).

[149] *D. F. Bradley* and *M. Calvin*, Proc. nat. Acad. Sci. U.S.A. *41*, 563 (1955).

[150] *H. Grisebach, R. C. Fuller*, and *M. Calvin*, Biochim. biophysica Acta *23*, 34 (1957).

[151] *R. Lumry, J. D. Spikes*, and *H. Eyring*, Annu. Rev. Plant Physiol. *5*, 271 (1954).

[152] *D. I. Arnon, M. B. Allen*, and *F. R. Whatley*, Biochim. biophysica Acta *20*, 449 (1956).

[153] Pharm. Symp. on Thioctic Acid, Naples 1955; Chem. Abstr. *51*, 8153 (1957).

[154] *Shutari Nakai*, Naika Hôkan *6*, 1189 (1959); Chem. Abstr. *54*, 11274 (1960).

[155] *S. Tasaka*: Second Japanese Symp. on Thioctic Acid. Tokyo 1959.

[156] *T. Yoshida*: Third Japanese Symp. on Thioctic Acid. Osaka 1960.

[157] *H. Redetzki, H. Bloedron*, and *H. W. Bans*, Klin. Wschr. *34*, 845 (1956).

[158] *W. Eger*, Arzneimittel-Forsch. *7*, 601 (1957).

[159] *W. Eger*, Ärztl. Forsch. *11*, 251 (1957).

[159a] 2,3-Dimercaptopropanol.

[160] *J. G. Affleck* and *G. Dougherty*, J. org. Chemistry *15*, 865 (1950).

[161] *J. A. Baltrop, P. M. Hayes*, and *M. Calvin*, J. Amer. chem. Soc. *76*, 4348 (1954); *M. Calvin*, Federat. Proc. *13*, 697 (1954).

[162] *S. Sunner*, Nature (London) *176*, 217 (1955).

[163] *A. Fava, A. Iliceto*, and *E. Camera*, J. Amer. chem. Soc. *79*, 833 (1957).

[164] *O. Foss* in *N. Kharasch*: Organic Sulfur Compounds. Pergamon Press, London 1961, Vol. I, p. 75.

levels of the neighboring sulfur atoms is possible to give the S–S bond a partial double bond character (p_π–d_π bonding) [165–167]. The energy required for rotation about the S–S bond, *i.e.* for a reduction of the interplanar angle from 90° to 0°, was found to be 3–14 kcal/mole [168–170]. Measurements by *Fehér* on disulfane seem to confirm the lower value of 3 kcal/mole [168].

It has not been resolved whether the bond between "normal" divalent sulfur atoms is formed by an overlap between pure p- or sp-hybridized orbitals. The bond length gives no indication of the nature of the bond since the "normal" length of the single S–S bond is unknown. In the case of disulfides with potentially mesomeric groups in the conjugated position with respect to the disulfide bridge (*e.g.* in aromatic disulfides), the electrons of the sulfur atoms are included in the mesomeric system. The homolysis of the S–S bond in aromatic disulfides depends on the polarity of the *p*-substituents on the benzene ring [171]. An increase in the electron donating character of the substituents leads to a more ready splitting of the S–S bond in diaryl sulfides by a radical mechanism.

Incorporation of the disulfide group into a carbocyclic ring without deformation of the interplanar angle of about 90° is possible only in large rings. With decreasing number of ring members (7 → 6 → 5) φ becomes smaller and hence the strain increases. For the 1,2-dithiolane ring φ is only about 27°. The double bond character of the S–S bond (p_π–d_π bonding) disappears and almost maximum repulsion of the p_z-electron occurs. In addition, the deformation and alteration of the bond angles at the carbon and sulfur atoms have an effect on the strain of the dithiolane ring.

From a determination of bond lengths and angles by X-ray analysis [173] of 1,2-dithiolane-4-carboxylic acid [172] a value of 16–26 kcal/mole was calculated for the strain energy [171a]. More recent thermochemical measurements have indicated a value of only 4 kcal/mole for unsubstituted dithiolane and a value of 3.5 kcal/mole for lipoic acid [162].

II. Ultraviolet Absorption of 1,2-Dithiolanes

In comparison to the open-chain disulfides, the ultraviolet absorption of 1,2-dithiolanes is strongly displaced toward longer wavelengths [161]. If there are no substituent effects, a simple relationship can be recognized between the ultraviolet absorption of cyclic disulfides and their interplanar angle φ. The interplanar angle diminishes with decreasing size of the ring and the ultraviolet absorption is displaced toward longer wavelengths with a simultaneous fall in the molar extinction (six-membered ring: φ = 60° [172], λ_{max} = 286 mμ: five-membered ring: φ = 27° [172], λ_{max} = 330 mμ). By incorporation into polycyclic systems [172a] the dithiolane ring can be flattened with a further shift of the absorption peak [174] towards longer wavelengths. Tetramethylation at C-3 and C-5 has a bathochromic effect [175, 175a].

Polar and potentially mesomeric substituents have an appreciable effect on the UV absorption of the dithiolane ring. Electron attracting groups are weakly hypsochromic [176]. Carbonyl groups in the neighborhood of the sulfur atoms displace the absorption peaks towards shorter wavelengths. According to *Bergson* [177], however, it is not the absorption of the S–S chromophore which is observed here, but the absorption of the carbonyl group which is disturbed by the S atoms (Table 3).

Table 3. Ultraviolet absorption of organic disulfides.

Disulfide	λ_{max} [mμ]
Dimethyl disulfide	255
Di-t-butyl disulfide	*ca.* 230
1,2-Dithiolane	330
3-Aminomethyl-1,2-dithiolane hydrochloride	322
3,3,5,5-Tetramethyldithiolane	358
1,2-Dithiolane-3-carboxylic acid	280
1,2-Dithiolane-3,5-dicarboxylic acid	250
3-Acetyl-1,2-dithiolane	307
Lipoic acid *(1)*	333
7-Methyllipoic acid *(7)*	350
7-Hydroxylipoic acid *(8)*	340
5-Oxolipoic acid *(14)*	312

In his study of the electronic spectra of aliphatic disulfides, *Bergson* [178] considers the S–S chromophore as an isolated π-electron system and its excitation as a transition from a nonbonding π(3pπ) level to a nonbonding σ(σ3p) level (Fig. 5).

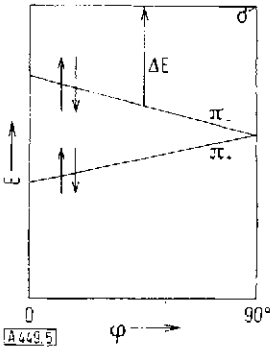


Fig. 5. Dependence of excitation energy ΔE on the interplanar angle φ in the electronic spectra of aliphatic disulfides [178].

[165] *H. Krebs*, Z. Naturforsch. *12b*, 795 (1957).

[166] *O. Foss* and *O. Tjomsland*, Acta chem. scand. *44*, 1799 (1958).

[167] *G. Cilento*, Chem. Reviews *60*, 147 (1960).

[168] *F. Fehér* and *R. Schulze-Rettmer*, Z. anorg. allg. Chem. *295*, 262 (1958).

[169] *D. W. Scott* et al., J. Amer. chem. Soc. *72*, 2424 (1950); *74*, 2478 (1952); *76*, 1488 (1954); *80*, 3547 (1958).

[170] *L. Pauling*: The Nature of the Chemical Bond. 2nd edit. Cornell University Press, Ithaca 1948.

[171] *U. Schmidt* and *A. Müller*, Liebigs Ann. Chem. *672*, 90 (1964).

[171a] In this calculation the rotational barrier for S–S bonds was assumed to be 12–14 kcal/mole. However, this value appears much too high.

[172] *O. Foss* and *L. Schotte*, Acta chem. scand. *11*, 1424 (1957); *O. Foss* and *T. Reistad*, ibid. *11*, 1427 (1957); *O. Foss* and *O. Tjomsland*, ibid. *12*, 1810 (1958).

[172a] *G. Bergson*, Acta chem. scand. *14*, 222 (1960).

[173] *G. Bergson* and *L. Schotte*, Acta chem. scand. *12*, 367 (1958); Ark. Kemi *13*, 43 (1958).

[174] *L. Schotte*, Ark. Kemi *9*, 309 (1956).

[175] *G. Claeson*, Svensk kem. Tidskr. *69*, 395 (1957).

[175a] It is not clear whether this effect is produced by the inductive effect of the methyl groups on the S–S bond or whether it is a consequence of the flattening of the ring brought about by steric hindrance between the methyl groups. Disubstitution of adjacent carbon atoms by alkyl or hydroxy groups can likewise produce displacement of the absorption peak when the substituents produce flattening of the ring due to steric hindrance. (7-hydroxylipoic acid: λ_{max} = 340.5 mμ; 7-methyllipoic acid: λ_{max} = 350 mμ).

[176] *G. Bergson*, Acta Univ. Upsaliensis *13*, 24 (1962).

[177] *G. Bergson* and *A. L. Delin*, Ark. Kemi *18*, 489 (1962).

[178] *G. Bergson*, Ark. Kemi *12*, 233 (1958); *18*, 409 (1962).

Because of the different symmetries of the π- and σ-levels with respect to the S–S bond axis, the energy of the ground-state but not that of the excited state must depend on the interplanar angle φ. The result is the angle-dependence of the excitation energy ΔE (Fig. 5).

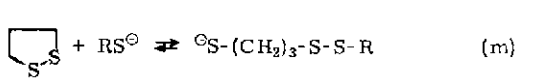
III. The Reactivity of 1,2-Dithiolanes

The fact that 1,2-dithiolanes are more reactive at the S–S bond than open-chain disulfides becomes apparent in radical, electrophilic, and nucleophilic reactions:

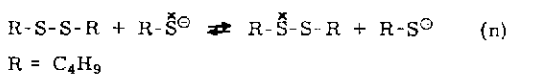
Polymerization to linear disulfides is characteristic of 1,2-dithiolanes. Therefore, solutions of unsubstituted 1,2-dithiolane can be kept only for short periods. The low activation energy (8.6 kcal/mole) [161] and the low collision rate for the thermal polymerization of 1,2-dithiolane in iso-octane point to a free-radical chain mechanism. Opening of the S–S bond by cyanopropyl radicals is much faster in dithiolanes than in dithianes, but the latter still react more rapidly than open-chain disulfides [171].

Electrophilic persulfate oxidation to thiosulfinates does not succeed in the case of open-chain disulfides and (seven-membered) dithiepanes. Dithianes react slowly and dithiolanes most rapidly [161]. Hence the electrophilic attack of the oxidizing agent on a pair of p_z-electrons of one of the S-atoms of the disulfide group proceeds all the more rapidly (the activation energy decreases) the less the electrons participate in the π-electron system of the S–S bond. This participation of the p_z-electrons diminishes as the interplanar angle φ decreases (*i.e.* falls in the order open-chain > seven-membered ring > six-membered ring > five-membered ring disulfides). In addition a bimolecular reaction on a relatively rigid ring has lower entropy of activation than a reaction on a flexible chain. The increase in the rate of electrophilic attack on the disulfide bond on passing from open-chain disulfides to the dithiolane ring *via* dithiepane and dithiane is thus caused by a decrease in activation energy and activation entropy. Hence the interplanar angle (ring strain) and the reactivity of the disulfide group towards electrophilic and radical reagents alter analogously.

Nucleophilic reactions at the sulfur atoms in cyclic disulfides have received little attention in the past. Activation energies for the reaction of 1,2-dithiolane [13 kcal/mole; Equation (m)] and of dibutyl disulfide [14.45 kcal/mole; Equation (n)] with butanethiolate differ only slightly [163] and the difference found may be within the experimental error (the Arrhenius curve of Reaction (m) is not linear).



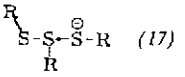
(m)



(n)

R = C_4H_9

The rate of Reaction (m) is almost 10^4 times greater than that of Reaction (n). This must be caused mainly by a much lower activation entropy in the case of Reaction (m). In the transition state *(17)* of the nucleophilic opening of a disulfide ring by a thiolate the three sulfur atoms lie in a straight line, and the two sulfur-sulfur distances are equal; the valence angle at the attacked sulfur atom is decreased to 90° and the bond to be opened is lengthened.



(17)

The ground state of 1,2-dithiolane (valence angle at the S atom: 92°; S–S bond length: 2.1 Å) is therefore much more similar geometrically to the transition state than is the ground state of an open-chain disulfide (valence angle at S: 107°; S–S distance: 2.05 Å). The transition state is therefore reached with greater ease from the 1,2-dithiolane ground state than from that of the open-chain disulfide. The somewhat greater S–S distance in the cyclic disulfide possibly explains the somewhat lower activation energy of Reaction (m) [178a].

Molecular models show that the formation of an analogous transition state in dithianes is much more difficult. It is accompanied by an appreciable deformation of the C–C valence angles and the elimination of the staggered ground-state arrangement of the CH_2 groups. Not surprisingly, sensitive dithianes are therefore less sensitive towards nucleophilic cyanide splitting than are dithiolanes and open-chain disulfides [179].

H. Recent Lipoic Acid Syntheses [180]

Numerous routes lead to octanoic acids carrying halogen, hydroxy, or other groups on the carbon atoms 6 and 8. Treatment of these with HI/thiourea [181], with sodium disulfide [182a, 182b], thiocyanate [182b], thiosulfate [182b], or thioacetate [182b] leads to the formation of lipoic or dihydrolipoic acid. The lengthening of the carbon chain from heptanoic acids by means of the Prins reaction [183] or by acylation of ketones and enamines, *e.g.* by reaction of cyclopentenylpyrrolidine

[178a] *R. E. Davis*, J. Amer. chem. Soc. *85*, 3050 (1963), has pointed out the general relationship between the S–S bond length (which varies between 1.97 and 2.2 Å) and the activation energy of the nucleophilic S–S bond opening. For many compounds the activation energy for the cyanide splitting is given by $E_a = 99.9/r^3$ [kcal/mole] and for the sulfite splitting by $E_a = 110/r^3$ [kcal/mole].

[179] *A. Schöberl* and *H. Gräfje*, Liebigs Ann. Chem. *614*, 66 (1958).

[180] Synthesis of optically active lipoic acid: *K. Folkers* et al., J. Amer. chem. Soc. *77*, 5144 (1955); [182a]. Synthesis of lipoamide, lipoyl chloride, lipol: *A. F. Wagner, E. Walton, G. E. Boxer, M. P. Pruss, F. W. Holly*, and *K. Folkers*, J. Amer. chem. Soc. *78*, 5079 (1956); *T. Kishi*, J. pharmac. Soc. Japan (Yakugakuzasshi) *81*, 787 (1961); Chem. Abstr. *55*, 24718i (1961). Acyldihydrolipoic acids: *J. Nakano*, J. pharmac. Soc. Japan (Yakugakuzasshi) *76*, 943, 1207 (1956)].

[181] See [185]; *U. Schmidt* and *P. Grafen*, Chem. Ber. *92*, 1177 (1959); *A. Segre, R. Viterbo*, and *G. Parisi*, J. Amer. chem. Soc. *79*, 3503 (1957).

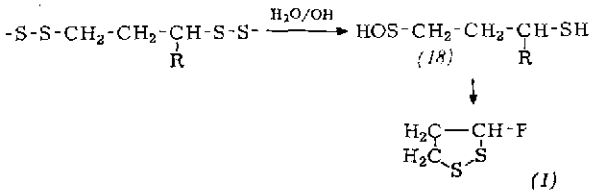
[182a] *D. S. Acker* and *W. J. Wayne*, J. Amer. chem. Soc. *79*, 6483 (1957).

[182b] *S. Yurugi, T. Fushini*, and *M. Murata*, J. pharmac. Soc. Japan (Yakugakuzasshi) *80*, 1686 (1960); Chem. Abstr. *55*, 12287 (1961).

[183] *E. A. Braude, R. P. Linstead*, and *K. R. H. Woolridge*, J. chem. Soc. (London) *1956*, 3074; *K. Hägele*, Doctorate Dissertation, Universität Freiburg 1956; German Published Pat. Appl. 1046016 (Oct. 13th, 1956), Merck, inventors: *A. Lüttringhaus* and *K. Hägele*.

with β-butoxypropionyl chloride [184], cannot compete on a technical scale with the synthesis by addition of ethyl adipate chloride to ethylene to form the 8-chloro-6-oxooctanoate [185]. After elimination of HCl to form 6-oxo-7-octenoic acid, dihydrolipoic acid is obtained directly by treatment with H_2S/H_2 in the presence of MoS_x under vigorous conditions [186]. However, it appears to be difficult to perform this reaction on a large scale. Reduction of the 8-chloro-6-oxo-octanoate with $NaBH_4$ to form the 6-hydroxy compound proceeds particularly readily. The latter is converted into lipoic acid *via* 6,8-dichloro-octanoic acid [187]. Addition of alcohol or carboxylic acids to 6-oxo-7-octenoic acid and catalytic hydrogenation to form ethers or esters of 6,8-dihydroxyoctanoic acid, which can be readily transformed into lipoic acid, have been described [188].

Advantages for the large-scale manufacture are provided by the addition of ethyl adipate chloride to acetylene and treatment of the reaction product with alcohol to form 8,8-dialkoxy-6-oxo-octanoic acid. This compound is then hydrogenated to form 8-alkoxy-6-hydroxy-octanoic acid, whose esters or lactones readily yield dihydrolipoic acid on treatment with HI/thiourea [189].



Almost all these syntheses proceed *via* dihydrolipoic acid. This compound can be oxidized to form lipoic acid with I_2 or $FeCl_3$, or better catalytically with air/$FeCl_3$ [185]. Varying amounts of polymeric disulfides are obtained as by-products, and, provided the molecular weight is not too high, can be thermally depolymerized *in vacuo*. Suprisingly, aqueous solutions of the alkali metal salts of polymeric lipoic acids are depolymerized by small quantities of alkali [190]. Possibly this reaction proceeds *via* a mercaptosulfenic acid *(18)* to lipoic acid.

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[184] *S. Yurugi, T. Fushini,* and *M. Murata,* J. pharmac. Soc. Japan (Yakugakuzasshi) *80,* 1165 (1960); Chem. Abstr. *55,* 4503 (1961).

[185] *M. W. Bullock, J. A. Brockman, E. L. Patterson, J. V. Pierce,* and *E. L. R. Stockstad,* J. Amer. chem. Soc. *74,* 3455 (1952); *M. W. Bullock, J. A. Brockman, E. L. Patterson, J. V. Pierce, M. H. v. Saltza, F. Sanders,* and *E. L. R. Stockstad,* ibid. *76,* 1828 (1954).

[186] *M. W. Bullock, J. H. Hand,* and *E. L. R. Stockstad,* J. Amer. chem. Soc. *79,* 1978 (1957).

[187] cf. [183]; *L. J. Reed* and *Ching-J Niu,* J. Amer. chem. Soc. *77,* 416 (1955).

[188] *S. Yurugi, M. Murata,* and *T. Fushini,* J. pharmac. Soc. Japan (Yakugakuzasshi) *81,* 299 (1961); *80,* 1317, 1686 (1960); Chem. Abstr. *55,* 14302, 5335, 12287 (1961).

[189] *U. Schmidt* and *P. Grafen,* Chem. Ber. *92,* 1177 (1959); German Patent 1134370 (April 4th, 1958), E. Merck, inventor: *U. Schmidt; Y. Deguchi,* J. pharmac. Soc. Japan (Yakugakuzasshi) *80,* 933 (1960); *D. S. Acker,* J. org. Chemistry *28,* 2533 (1963).

[190] *R. C. Thomas* and *L. J. Reed,* J. Amer. chem. Soc. *78,* 6148 (1956).

The Use of Electron Paramagnetic Resonance in Organic Chemistry

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The more recent applications of electron paramagnetic resonance (EPR) to organic chemistry include the investigation of triplet states, donor-acceptor complexes, short-lived free-radical intermediates, and reaction kinetics. The principles of the theoretical calculations required to obtain the maximum information from EPR spectra are outlined for free radicals containing π-electron systems. EPR intensities, line widths, hyperfine splitting, and g factors permit the determination of free-radical yields, ionic charges, rotation frequencies in rotamers, electron density distributions, electronegativities, intramolecular torsion angles, solvent effects (resulting from hydrogen bonding), and π-orbital energies. -- The production of free radicals with the aid of initiation reactions in flow systems, by irradiation, and by electrolysis seems particularly promising.

I. Introduction

Absorption spectroscopy has always enjoyed an important position among the physical methods used in analytical chemistry. In addition to the classical ultraviolet and infrared absorption spectroscopy, electron paramagnetic resonance (EPR) and nuclear magnetic resonance (NMR) spectroscopy have also become important in recent years. However, electron paramagnetic resonance (EPR) spectroscopy [*] has not yet become so widely used as infrared and nuclear magnetic resonance spectroscopy. There are two reasons for this: infrared and nuclear magnetic resonance spectroscopy are more widely applicable, and the spectra can be identified by

[*] The frequently used abbreviation ESR (electron-spin resonance) is less general than EPR, since the former does not take into account orbital magnetism.

comparison with those of known substances. The individual lines or bands of these spectra are characteristic of certain groups of atoms, so that the spectra of complex molecules can be built up from those of simpler compounds. It has been possible, therefore, to compile collections of infrared and nuclear magnetic resonance spectra, which allow an empirical evaluation by a routine procedure.

EPR spectra, on the other hand, are obtainable only for paramagnetic substances containing unpaired electrons, and the form of the spectrum depends on the structure of the molecule as a whole. Therefore the EPR spectrum of each substance must be analysed individually. It is however now possible to prepare paramagnetic modifications of a large variety of compounds [1] (see Section III), and the theory relating the experimental results to molecular properties has been perfected.

At this stage, we shall give only enough of the theory of electron paramagnetic resonance to enable the reader to understand the first few sections (the theory will be discussed in more detail in Section IV). We start with *Bohr*'s model of the atom, in which the electrons circle the atomic nucleus in definite orbits, while spinning at the same time about their own axes. The orbital motion and the spin give rise to circular electric currents, which produce a magnetic field. The electron is therefore associated with a magnetic moment μ, due partly to the orbital angular momentum and partly to the spin, the two components being combined vectorially.

If an atom is subjected to an external magnetic field H, the total energy of the atom changes by an amount equal to the potential energy of the magnetic dipole in the field H, which depends on the angle between H and μ. Owing to space quantization, only certain discrete angles are possible, so that the original energy level E_0 is split in the magnetic field into discrete levels in accordance with Equation (1) (g is the spectroscopic splitting factor, μ_B is the Bohr magneton, and m_s is the magnetic spin quantum number [*].

$$E_s = E_0 + g\mu_B m_s H \qquad (1)$$

For magnetic fields of about 3000 oersted, which are easily attained, the energy difference $\Delta E = g\mu_B H$ between two adjacent orientations of the magnetic moment is equal to the energy of a microwave quantum with $\nu_0 \simeq 9000$ Mc/s. Transitions between the various energy levels are induced when the atom is irradiated in a magnetic field H_0 with microwaves having a frequency ν_0 given by the resonance condition (2). These transitions are governed by the selection rule $\Delta m_s = \pm 1$, *i.e.* there

$$h\nu_0 = g\mu_B H_0 \qquad (2)$$

can be transitions from a higher to a lower energy level, with emission of energy, as well as from a lower to a higher level, with absorption of energy. Since there are more atoms in the lower energy states, the net result is absorption, referred to as electron paramagnetic resonance. Owing to the interaction of the unpaired electrons in an atom with one another (fine splitting) or with the magnetic moments of neighboring nuclei (hyperfine splitting), EPR spectra can contain a very large number of lines.

EPR spectra are interpreted in three steps. The quantities that characterize the spectrum are first found from the recorded curves; these quantities are the width ΔH, the form f(H), and the number n and relative amplitudes A_i of the individual lines, as well as the field strength H_0 at the center of the spectrum and the distances δH_i between the lines. In the second step these quantities are used to determine the g factor, spin densities, the concentration of free radicals, and relaxation times [1a]. Finally, the quantities derived in the second step are used to obtain information about molecular structure and the course of chemical reactions. The hyperfine structure of the spectrum, for example, permits a very accurate determination of the orbital distribution of the unpaired electron, and hence of the reactivities of the various positions in the molecule. Information about the structure of the molecule can be obtained from the number of lines and their relative intensities. The frequencies of the internal rotations of parts of the molecule can be found from the dependence of the spectra on the temperature. Finally, various details of the spectra offer information regarding the planarity of the molecules, the electronegativities and torsion angles of substituents, the orbital energies of the π-electrons, and the positions of the energy terms of the molecule (cf. Section V).

II. EPR Spectrometers

The EPR spectra of organic radicals always give a g factor of approximately 2; the absorption lines are from 17 milli-oersted to about 3 oersted wide, and are often very weak. The recording instruments used must therefore combine high sensitivity with high resolving power. In all commercially available EPR instruments, the sample is irradiated with microwaves of frequency ν_0, while being exposed to a magnetic field H which varies linearly with time. The microwave energy absorbed when H is equal to the field strength given by the resonance condition (2) is measured. To obtain increased sensitivity, an alternating field $H_1 \cos 2\pi\nu_1 t$, the amplitude of which is small in comparison with the width of the absorption line, is superimposed on the field H. The magnitude of the resulting signal is proportional not to the height of the absorption curve, but to its slope; consequently the recorded curve is not the absorption curve itself, but its derivative.

Spectrometers with $\nu_0 \simeq 9000$ Mc/s (X band), $\nu_1 \simeq 100$ Kc/s, and magnets with pole diameters of 12 to 30 cm have proved useful for the study of organic radicals [*]. With good EPR equipment, it is possible to detect 2×10^{11} unpaired spins at a line-width of 1 oersted [2]. For a mean effective

[1] This is shown, for example, in a collection of spectra started in 1962, which already contains 1200 articles on EPR spectroscopy: NMR, NQR, and EPR Literature Service: Butterworth, London, and Verlag Chemie, Weinheim/Bergstr.

[*] The orbital angular momentum is assumed to be quenched, since this is the case for most free radicals. Small residual contributions of orbital magnetism are taken into account by the factor g.

[1a] *F. Schneider* and *K. Möbius*, Z. Naturforsch. *18b*, 1111 (1963).

[*] The larger magnets do not give increased sensitivity or resolving power. They are used only when more room is required between the pole shoes of the magnet, as for simultaneous optical measurements.

[2] Instruments of this kind are marketed *e.g.* by AEG (Germany), Decca (U.K.), and Varian (U.S.A.).

sample volume of 0.1 ml, therefore, free radicals can be detected at concentrations as low as 10^{-8} to 10^{-9} mole/l, except when polar solvents such as water are used [3]. The resolving power $H_0/\Delta H$ is about 10^5, *i.e.* about 30 milli-oersted. Since the EPR spectra of organic radicals have total widths of about 30 to 50 oersted, the maximum number of resolvable lines is about 1000.

The temperature of the sample in commercial spectrometers can be varied between −170 and +300 °C [4], and auxiliary equipment is available for working at the temperature of liquid helium. For the investigation of short-lived radicals, *Stone* and *Waters* [5] developed a mixing technique that permits the detection of radicals with lifetimes of only 1 msec. Short-lived ion-radicals are produced in an electrolytic cell in the resonator itself [5a]. The instruments can be used to the best advantage only if all factors that lead to broadening of the lines are eliminated, and it is particularly important to ensure that all solutions are free from oxygen [6, 7].

III. The Generation of Free Radicals and the Application of EPR Spectroscopy

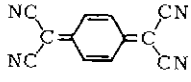
1. Stable Radicals

A general survey of EPR studies on free radicals containing π-electron systems can be obtained from publications by *Ingram* [8], *Blois* [9], *Symons* [10], *Adams* [11], *Kivelson* [12], and *Foster* [13].

Notable advances have recently been made in the EPR investigation of triplet states, particularly in connection with donor-acceptor complexes. In triplet state molecules, two electron spins are coupled to give a resultant spin of S = 1, whereas in biradicals such as those derived from *p*-substituted polyphenyls, the two unpaired electrons are so far apart that interaction between them is very weak, and the spins orient themselves independently of each other in the magnetic field.

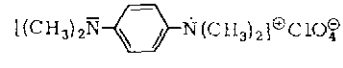
Owing to the strong spin-orbital interaction of the two electron spins in triplet states, the energy levels are split even in the absence of a magnetic field, so that the levels $m_s = \pm 1$ are separated from the level $m_s = 0$. As a result of this zero-field splitting the two fine-structure lines due to EPR transitions $\Delta m_s = \pm 1$ are strongly anisotropic, and often can be observed only in oriented triplet molecules built into host single crystals [14]. The fine-structure lines are greatly broadened in solutions or glasses, and have so far only rarely been observed [15]. However, triplet states can also be detected in randomly oriented molecules by transitions in which $\Delta m_s = \pm 2$, which occur at half values of the magnetic field (double g factor) [16]. Although weaker in intensity, these transitions are relatively isotropic, since they do not involve the level $m_s = 0$. This technique, which does not require the use of host single crystals, has already been used for the EPR-spectroscopic investigation of excited triplet states in phosphorescent hydrocarbons [17]. However, the triplet ground state of methylenes and nitrenes has also been confirmed by EPR measurements, *e.g.* on diphenylmethylene and phenylnitrene ($C_6H_5-\dot{N}:$) [15].

An interesting conversion between singlet, doublet, and triplet states is shown by solid organic charge-transfer complexes which often have the character of ion-radical salts. These complexes are formed from strong electron


(1)

acceptors (A), such as 3,6-bis-(dicyanomethylene)-1,4-cyclohexadiene *(1)* or tetracyanoethylene, and electron donors (D) such as $(C_6H_5)_3PCH_3$, $(C_6H_5)_3AsCH_3$, or Cs [17a].

The magnetic properties of these complexes change from doublet paramagnetism (S = 1/2), through triplet paramagnetism (S = 1), to diamagnetism (S = 0) when the temperature is decreased from about 400 °K, through 200 °K, to only a few °K; at the same time, the electrical conductivity falls from semiconductor values to insulator values. The ion-radical salts of the paramagnetic *N,N,N',N'*-tetramethyl-*p*-phenylenediamine cation, such as Wursters Blue perchlorate *(2)*, are also representatives of these donor-acceptor complexes [18].


(2)

In the case of strong donors and acceptors, electron transfer takes place, so that the structure D^+A^- contributes to the ground state, and paramagnetic properties are to be expected even in the complexes of diamagnetic components A and D. EPR measurements by *Chestnut* and *Phillips* [19] indicate that the radical ions are so close together in the DA crystals that the spins of the unpaired electrons couple in pairs. The temperature-dependence of the EPR signal intensity shows that the ground state of the DA complex is a singlet, and that the triplet state can be excited simply by

[3] *F. Schneider*, Z. Instrumentenkunde *71*, 315 (1963); *72*, 11 (1964).

[4] *W. Heinze*, AEG-Mitt. *53*, 284 (1963).

[5] *T. J. Stone* and *W. A. Waters*, J. chem. Soc. *1964*, 213.

[5a] *A. H. Maki* and *D. H. Geske*, J. chem. Physics *30*, 1356 (1959).

[6] *K. H. Hausser*, Naturwissenschaften *11*, 251 (1960).

[7] *K. Möbius*, Z. angew. Physik *17*, 534 (1964).

[8] *D. J. E. Ingram*: Free Radicals. Butterworths, London 1958.

[9] *M. S. Blois*: Free Radicals in Biological Systems. Academic Press, New York 1961.

[10] *M. C. R. Symons* in *V. Gold*: Advances in Physical Organic Chemistry. Academic Press, London 1963.

[11] *R. N. Adams*, J. electroanalyt. Chem. *8*, 151 (1964).

[12] *D. Kivelson* and *C. Thomson*, Annu. Rev. physic. Chem. *15*, 197 (1964).

[13] *H. Foster*, Analytic. Chem. *36*, 266 R (1964).

[14] *C. A. Hutchison jr.* and *B. W. Mangum*, J. chem. Physics *34*, 908 (1961).

[15] *W. A. Yager*, *E. Wasserman*, and *R. M. R. Cramer*, J. chem. Physics *37*, 1148 (1962).

[16] *J. H. van der Waals* and *M. S. de Groot*, Molecular Physics *3*, 190 (1960).

[17] *G. v. Foerster*, Z. Naturforsch. *18a*, 620 (1963).

[17a] *D. B. Chesnut* and *P. Arthur jr.*, J. chem. Physics *36*, 2969 (1962).

[18] *D. D. Thomas*, *H. Kaller*, and *H. M. McConnell*, J. chem. Physics *39*, 2321 (1963).

[19] *D. B. Chestnut* and *W. D. Phillips*, J. chem. Physics *35*, 1002 (1961).

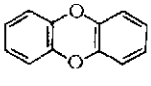
heating. Thus the radical ions dimerize in the ground state. The thermally excitable triplet states are identified by transitions in which $\Delta m_s = \pm 1$ and $\Delta m_s = \pm 2$. In solvents with sufficiently high dielectric constants, the strong DA complexes dissociate into free ion-radicals [20].

2. Unstable Radicals

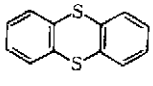
The odd alternant hydrocarbons, such as triphenylmethyl, possess an odd number of π-electrons even in the neutral state, and are therefore paramagnetic. In even alternant hydrocarbons, on the other hand, the spins of the π-electrons are all paired in the neutral state; paramagnetic radical-ions can, however, be produced by the insertion or withdrawal of an electron without appreciably affecting the structure of the molecule [*].

"Free" solvated radical ions are best produced by electrolysis in aprotic solvents of high dielectric constant such as acetonitrile and dimethylformamide [7,21], in which the electron distribution is not affected by solvent effects or by the counter-ion. This method has been used to produce radical ions from unsubstituted hydrocarbons [21], heterocyclic compounds [22–24], quinones, phenols, and carbonyl, nitro, methyl, and amino compounds [25–32] for EPR-spectroscopic investigation. Radical-trianions have even been produced from tetracene and pentacene by electrolysis, and identified by EPR spectroscopy [33].

Radical cations of π-electron systems are usually obtained by dissolving the substances in concentrated sulfuric acid. This often leads to protonation of the aromatic compounds, but radical cations can also be produced by electron withdrawal from many condensed aromatic hydrocarbons such as anthracene, and from condensed heterocyclic compounds such as dibenzo-*p*-dioxin *(3)* [34] or thianthrene *(4)* [24], particularly if oxidizing agents such as H_2O_2 or SO_5^{2-} are added to the sulfuric acid. In nitrogen heterocycles such as pyrazine or phenazine, both nitrogen atoms are protonated in acidic media, with formation of diamagnetic dications. Reduction of these dications with $Na_2S_2O_4$ leads to the introduction of electrons to form radical ions carrying a single positive charge. Radical cations are also obtained from aliphatic and aromatic compounds by electron withdrawal when the solutions contain Lewis acids such as aluminum trichloride or antimony pentachloride [24,35,36].

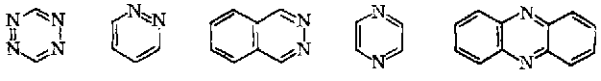


(3)

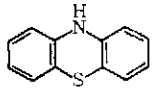


(4)

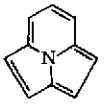
Radical-anions containing π-electron systems are usually obtained by the reduction of neutral molecules with alkali metals in dimethoxyethane or tetrahydrofuran. Owing to the low dielectric constants of these solvents, the radical-anions and alkali metal cations are often present as ion pairs at room temperature. Using the small lithium atom, however, the EPR spectra of "free" solvated radical anions, *e.g.* the anions of polyphenyls and polyacenes [37–40], and of their methyl, nitro, cyano, and carbonyl derivatives [41–44], can also be observed at low temperatures. The cyclopropane radical-anion [45], the tropyl and cyclooctatetraenyl radicals [46,47], and the radical-anions of polyazines [*e.g. (5a)–(5e)*] [48,49], phenothiazines *(6)* [50], and cy-



(5a) *(5b)* *(5c)* *(5d)* *(5e)*



(6)



(7)

[20] *R. L. Ward*, J. chem. Physics *39*, 852 (1963).

[*] Alternant hydrocarbons contain two classes of C-atoms, starred (*) and unstarred (o). Each C-atom of one class possesses only neighbors of the other class. In even alternant hydrocarbons, the number of starred C-atoms is equal to the number of unstarred C-atoms. The odd alternant hydrocarbons contain one extra carbon atom, which is assigned to the starred class.

[21] *K. Möbius*, Z. Naturforsch., in press.

[22] *E. W. Stone* and *A. H. Maki*, J. chem. Physics *39*, 1635 (1963).

[23] *S. Odiot* and *F. Tonnard*, J. Chim. physique 382 (1964).

[24] *H. J. Shine*, *C. F. Dais*, and *R. J. Small*, J. org. Chemistry *29*, 21 (1964).

[25] *E. W. Stone* and *A. H. Maki*, J. chem. Physics *36*, 1944 (1962).

[26] *C. Corvaja* and *G. Giacometti*, J. Amer. chem. Soc. *86*, 2736 (1964).

[27] *R. Dehl* and *G. K. Fraenkel*, J. chem. Physics *39*, 1793 (1963).

[28] *N. Steinberger* and *G. K. Fraenkel*, J. chem. Physics *40*, 723 (1964).

[29] *I. Bernal* and *G. K. Fraenkel*, J. Amer. chem. Soc. *86*, 1671 (1964).

[30] *P. H. Rieger*, *I. Bernal*, *W. Reinmuth*, and *G. K. Fraenkel*, J. Amer. chem. Soc. *85*, 683 (1963).

[31] *M. T. Melchior* and *A. H. Maki*, J. chem. Physics *34*, 471 (1961).

[32] *D. H. Geske*, *J. L. Ragle*, *M. A. Bambenek*, and *A. L. Balch*, J. Amer. chem. Soc. *86*, 987 (1964).

[33] *K. Möbius* and *M. Plato*, Z. Naturforsch. *19a*, 1240 (1964).

[34] *T. N. Tozer* and *L. D. Tuck*, J. chem. Physics *38*, 3035 (1963).

[35] *W. I. Aalbersberg*, *G. J. Hoijtink*, *E. L. Mackor*, and *W. P. Weijland*, J. chem. Soc. (London) *1959*, 3055.

[36] *K. Fukui*, *T. Kawamura*, *T. Masuda*, and *K. Morokuma*, Tetrahedron Letters *1964*, 433.

[37] *H. Nishiguchi*, *Y. Nakai*, *K. Nakamura*, *Y. Deguchi*, and *H. Takaki*, Rev. physic. Chem. Japan *32*, 57 (1963).

[38] *H. Nishiguchi*, *Y. Nakai*, *K. Nakamura*, *K. Ishizu*, *Y. Deguchi*, and *H. Takaki*, J. chem. Physics *40*, 241 (1964).

[39] *P. H. H. Fischer*, *K. H. Hausser*, and *H. A. Staab*, Z. Naturforsch. *19a*, 816 (1964).

[40] *J. R. Bolton* and *G. K. Fraenkel*, J. chem. Physics *40*, 3307 (1964).

[41] *J. R. Bolton* and *A. Carrington*, Molecular Physics *4*, 497 (1961).

[42] *R. L. Ward*, J. chem. Physics *32*, 410 (1960).

[43] *A. Carrington* and *P. F. Todd*, Molecular Physics *6*, 161 (1963).

[44] *P. B. Ayscough* and *R. Wilson*, Proc. chem. Soc. (London) *1962*, 229.

[45] *K. W. Bowers* and *F. D. Greene*, J. Amer. chem. Soc. *85*, 2331 (1963).

[46] *J. dos Santos-Veiga*, Molecular Physics *5*, 639 (1962).

[47] *H. L. Strauss*, *T. J. Katz*, and *G. K. Fraenkel*, J. Amer. chem. Soc. *85*, 2360 (1963).

[48] *R. L. Ward*, J. Amer. chem. Soc. *84*, 332 (1962).

[49] *C. A. McDowell* and *K. F. G. Paulus*, Molecular Physics *7*, 541 (1964).

[50] *M. Bruin*, *F. Bruin*, and *F. W. Heineken*, J. org. Chemistry *29*, 507 (1964).

clazines such as *(7)* [51] have also been obtained with alkali metals. Aromatic free radicals can be obtained in tetrahydrofuran by the addition of butyl-lithium to the solution [52] or by reduction with sodium dithionite in basic media [53] [*]. Radical-anions have been produced from aromatic nitro compounds and ketones by reduction with zinc or glucose in alkaline alcoholic or aqueous solutions [54]. EPR measurements have also been carried out on radical-anions of aromatic hydrocarbons and heterocyclic compounds produced by the action of alkali or alkaline earth metals in liquid ammonia [55].

Using the redox system $TiCl_3 + H_2O_2$, short-lived radicals of organic substances can be produced *via* the radicals $\cdot OH$ and $\cdot O_2H$ [56]. In this way it has been possible, using flow systems in which the solutions are mixed in the microwave resonator itself, to carry out EPR investigations on short-lived radicals, produced during the oxidation of alcohols or during the polymerization of *e.g.* acrylic acid [57]. Many short-lived aryloxy and arylamino radicals, which are formed during the oxidation of phenols or aromatic amines in aqueous solution by cerium(IV) sulfate in sulfuric acid, have been studied with the aid of an EPR mixing chamber [5, 58]. The hydrazine radical-ion $N_2H_4^+$, which is formed on oxidation of hydrazine with cerium(IV) ions, has recently been identified by the flow method [59].

We shall mention only a few of the physical methods of producing free radicals. The pyrolysis of dinaphthyl and diphenyl disulfides leads to the formation of arylsulfenyl radicals Ar–S· [60]; the cyclopentadienyl radical is formed during the pyrolysis of dicyclopentadienyliron (ferrocene) or azo- and hydrazobenzene [61]. Free radicals have been produced by ultraviolet irradiation of solutions of nitrobenzenes [54, 62], nitromethanes [63], benzophenones [54, 64], and the methyl, ethyl, and benzyl derivatives of diquaternary bipyridyl [65], and identified by EPR spectroscopy. EPR measurements on γ-irradiated substances have been mainly confined to high-polymeric plastics such as polyethylene [66, 67] and polypropylene [68]; the identification of the radicals formed was facilitated by the anisotropy of the hyperfine structure of samples oriented by stretching. Free radicals have been produced by the irradiation of oriented polyethylenes [69] and vinyl polymers [70] with electrons, and the kinetics of their recombination were studied. EPR measurements have also been carried out on amino acids irradiated with 1 MeV electrons [71]. The radical produced by the irradiation of benzene with electrons at 77 °K has been identified by EPR measurements as the odd alternant hydrocarbon cyclohexadienyl [72].

Fessenden and *Schuler* [73] have carried out EPR investigations on the structure and reaction kinetics of 21 dissolved alkyl and cycloalkyl radicals as well as on vinyl, methylvinyl, butenyl, allyl, and cyclohexadienyl radicals produced by irradiation with 2.8 MeV electrons.

IV. The Theory of Electron Paramagnetic Resonance

1. Hyperfine Structure

The analysis of EPR hyperfine structure spectra of π-electron radicals is particularly important in organic chemistry. The hyperfine structure of an electron-resonance line is due to interaction between the magnetic momenhet of t unpaired electron and the magnetic moments of neighboring atomic nuclei. The theory of this interaction was developed by *Fermi* [74] and by *Abragam* and *Pryce* [75]. It is necessary to differentiate between anisotropic and isotropic hyperfine interactions. The anisotropic interaction gives a hyperfine structure that depends on the orientation of an axis of the molecule with respect to the external magnetic field [76]. The

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[51] *F. Gerson* and *J. D. W. van Voorst*, Helv. chim. Acta *46*, 2257 (1963).

[52] *H. W. Brown* and *R. C. Jones*, J. chem. Physics *37*, 1571 (1962).

[53] *P. L. Kolker* and *W. A. Waters*, J. chem. Soc. (London) *1964*, 1136.

[*] Butyl-lithium exists in tetrahydrofuran as the ion pair $C_4H_9^-Li^+$. The butyl anion supplies the electrons for the reduction, being itself converted into octane. In the case of pyrene (R), for example, the redox reaction in which the radical-anion (R^-) is formed by uptake of an electron is as follows:

$$2\ C_4H_9^- \rightarrow C_8H_{18} + 2e$$
$$2\ R + 2e \rightarrow 2\ R^-$$
$$2\ C_4H_9^- + 2\ R \rightarrow 2\ R^- + C_8H_{18}$$

Depending on the temperature, R^- associates more or less strongly with Li^+.

[54] *P. B. Ayscough* and *F. P. Sargent*, Proc. chem. Soc. (London) *1963*, 94.

[55] *A. Maximadshy* and *F. Dörr*, Z. Naturforsch. *19b*, 359 (1964).

[56] *W. T. Dixon* and *R. O. C. Norman*, J. chem. Soc. (London) *1963*, 3119.

[57] *H. Fischer*, Z. Naturforsch. *19a*, 866 (1964).

[58] *F. R. Hewgill*, *T. J. Stone*, and *W. A. Waters*, J. chem. Soc. (London) *1964*, 408.

[59] *J. Q. Adams* and *J. R. Thomas*, J. chem. Physics *39*, 1904 (1963).

[60] *P. J. Zandstra* and *J. D. Michaelsen*, J. chem. Physics *39*, 933 (1963).

[61] *P. J. Zandstra*, J. chem. Physics *40*, 612 (1964).

[62] *R. L. Ward*, J. chem. Physics *38*, 2588 (1963).

[63] *B. H. J. Bielski* and *R. B. Timmons*, J. physic. Chem. *68*, 347 (1964).

[64] *G. A. Russell* and *E. J. Geels*, Tetrahedron Letters *20*, 1333 (1963).

[65] *C. S. Johnson jr.* and *H. S. Gutowsky*, J. chem. Physics *39*, 58 (1963).

[66] *D. Libby* and *M. G. Ormerod*, J. physic. Chem. Solids *18*, 316 (1961).

[67] *H. Kashiwabara*, Japan J. appl. Physics *2*, 523 (1963).

[68] *H. Fischer* and *K. H. Hellwege*, J. Polymer Sci. *56*, 33 (1962).

[69] *M. Kashiwagi*, J. chem. Physics *36*, 575 (1962).

[70] *H. Fischer*, *K. H. Hellwege*, *U. Johnson*, and *P. Neudörfl*, Kolloid-Z. *195*, 129 (1964).

[71] *G. Schoffa*, J. chem. Physics *40*, 908 (1964).

[72] *H. Fischer*, J. chem. Physics *37*, 1094 (1963).

[73] *R. W. Fessenden* and *R. H. Schuler*, J. chem. Physics *39*, 2147 (1963).

[74] *E. Fermi*, Z. Physik *60*, 320 (1930).

[75] *A. Abragam* and *M. H. L. Pryce*, Proc. Roy. Soc. (London) A *205*, 135 (1951).

[76] *S. M. Blinder*, J. physic. Chem. Solids *33*, 748 (1960).

hyperfine splitting due to isotropic interaction, on the other hand, is independent of orientation, and is proportional to the unpaired spin density $|\psi(K)^2$ at the position of the nucleus in question, as given by Eq. (3)

$$a = \frac{8\pi}{3} \frac{|\mu_K|}{I} |\psi(K)|^2 \qquad (3)$$

where μ_K is the magnetic moment and I the total spin quantum number of the nucleus.

The anisotropic hyperfine structure is studied by recording the spectra of radicals in single crystals as a function of the orientation of the crystal axes with respect to the magnetic field [77]. In polycrystalline samples, a statistical average is taken over the hyperfine structure lines. This leads to distortion of the lines to an extent depending on the ratio of the anisotropic interaction. Nevertheless, it is often possible to determine all the isotropic and anisotropic hyperfine structure constants by accurate analysis of the line form [76, 78–84]. Most hyperfine structure investigations on π-electron radicals, however, are carried out in solution. The rotational frequency of the molecules is greater than the frequency of the anisotropic hyperfine interaction, so that, on a time average, only the isotropic hyperfine interaction contributes to the splitting. The positions of the individual components of the spectra obtained for N nuclei are:

$$H_{res}(m_{I_1}, m_{I_2}, \cdots m_{I_N}) = H_0 + a_1 m_{I_1} + a_2 m_{I_2} + \cdots + a_N m_{I_N} \qquad (4)$$

where

$$m_{I_i} = -I_i, -I_i + 1, \cdots + I_i, \; i = 1, \cdots N .$$

In Eq. (4), H_0 is the field strength in the center of the spectrum, a_i is the isotropic splitting constant of the i-th nucleus as given by Eq. (3), and I_i is the total spin of the i-th nucleus (*e.g.* for protons, I = 1/2). The individual m_{I_i} values correspond to the $2I_i + 1$ equally probable orientations of the magnetic dipole of a nucleus with respect to the external field (EPR selection rule: $\Delta m_I = 0$ for a strong field $H_0 \gg a$).

Analysis of the observed spectrum on the basis of Eq. (3) and (4) [1a] gives the unpaired spin densities $|\psi(K_i)|^2$ for all the atomic nuclei in the molecule that make a measurable contribution to the hyperfine splitting. *McConnell* [85] and *Jarrett* [86] have shown that the spin density $|\psi(P)^2$ on a ring proton of an aromatic ring system, and hence also its isotropic splitting factor a_i [in accordance with Eq. (5)], is

$$a_i^H = Q \cdot \rho_i^\pi \qquad (5)$$

proportional to the π-electron spin density ρ^π on the adjacent carbon atom. The proportionality constant Q is about 28 oersted [*]. According to *Colpa* and *Bolton* [87] the effect of an excess charge ε_i^π on the i-th carbon atom of a radical-ion is taken into account by an equation of the form (6) (for values of Q and K, see

$$a_i^H = (Q + K \cdot \varepsilon_i^\pi)\rho_i^\pi \qquad (6)$$

Table 1). Considerable changes in the Q factor can, however, also arise through changes in the hybridization of the atomic orbitals of the C atom in question as a result of steric disturbances [88].

In addition to the hyperfine structure due to protons, hyperfine structure lines due to the isotope ^{13}C (natural abundance about 1 %) have also been observed in the spectra of many organic radicals [89, 90]. In the case of the stable paramagnetic $[NO(SO_3)_2]^{2-}$ ion, in addition to the familiar triplet splitting due to the ^{14}N nucleus (abundance 99.64 %, nuclear spin I = 1), it has also been possible to observe doublet splitting due to ^{15}N-nuclei (abundance 0.34 %, I = 1/2) and quartet splitting due to the sulfur isotope ^{33}S (abundance 0.74 %, I = 3/2) [91].

2. Calculation of π-Electron Spin Densities

π-Electron spin densities can be calculated from measured isotropic splitting constants with the aid of Eq. (5) or (6). A comparison of these "experimental" spin densities with theoretical values not only permits identification of the radical under examination, but also provides information regarding its structure and symmetry properties (deviation from planarity, rotational isomerism, *etc.*). For this reason we shall now give a brief description of the usual methods [92, 93] of calculating theoretical spin densities.

a) The LCAO–MO – Hückel Approximation (HMO Method)

The π-system is treated separately from the σ-system. The π-electrons move in molecular orbitals ψ_j (MO), which can be represented as linear combinations (7) of

[77] Colloque Ampère 1964, Bordeaux.

[78] *D. E. O. Reilly*, J. chem. Physics *29*, 1188 (1958).

[79] *D. Kivelson*, J. chem. Physics *33*, 1094 (1960).

[80] *R. Neiman* and *D. Kivelson*, J. chem. Physics *35*, 156, 162 (1961).

[81] *R. Levèbvre*, J. chem. Physics *35*, 762 (1961).

[82] *H. Sternlicht* and *H. M. McConnell*, J. chem. Physics *33*, 302 (1960).

[83] *H. Sternlicht*, J. chem. Physics *33*, 1128 (1960).

[84] *E. L. Cochran, F. J. Adrian*, and *V. A. Bowers*, J. chem. Physics *34*, 1161 (1961).

[85] *H. M. McConnell*, J. chem. Physics *24*, 764 (1956).

[86] *H. S. Jarrett*, J. chem. Physics *25*, 1289 (1956).

[*] Since the signs of splitting constants can only rarely be determined from EPR measurements, we can disregard the negative sign of Q given by the theory.

[87] *J. P. Colpa* and *J. R. Bolton*, Molecular Physics *6*, 273 (1963).

[88] *I. Bernal, P. H. Rieger*, and *G. K. Fraenkel*, J. chem. Physics *37*, 1489 (1962).

[89] *K. Markau* and *W. Maier*, Z. Naturforsch. *16a*, 636 (1961).

[90] *M. Karplus* and *G. K. Fraenkel*, J. chem. Physics *35*, 1312 (1961).

[91] *J. J. Windle* and *A. K. Wiersema*, J. chem. Physics *39*, 1139 (1963).

[92] *A. Streitwieser jr.*: Molecular Orbital Theory. Wiley, New York 1961.

the atomic orbitals φ_r (AO) of the n carbon $2p_z$ atomic orbitals.

$$\psi_j = c_{j1}\varphi_1 + c_{j2}\varphi_2 + \cdots + c_{jn}\varphi_n \tag{7}$$

The probability of finding a π-electron in the j-th molecular orbital at the r-th C-atom is given by the square of the orbital coefficient c_{jr}. The c_{jr} values are determined such that the total energy of the π-system is a minimum. Neglecting explicit π-electron interactions (Coulomb and exchange interactions) and overlap of the atomic orbitals, this leads to a homogeneous set of equations of the form

$$\begin{aligned} &c_{j1}(\alpha_1 - E_j) + c_{j2}\beta_{12} + \cdots + c_{jn}\beta_{1n} = 0 \\ &\vdots \\ &c_{j1}\beta_{n1} \quad + c_{j2}\beta_{n2} + \cdots\cdots c_{jn}(\alpha_n - E_j) = 0, \end{aligned} \tag{8}$$

in which E_j is the energy of a π-electron in the j-th molecular orbital, α_r is the Coulomb integral (a measure of the electronegativity), and β_{rs} is the bond integral (resonance energy) between the C-atoms (or heteroatoms) in positions r and s. For unsaturated hydrocarbons all the α_r values are assumed to be equal ($a_r = \alpha$). The bond integral β_{rs} is assumed to differ from zero only in the case of bonds between adjacent C-atoms, and is then also assumed to be the same everywhere ($\beta_{rs} = \beta$). The energy E_j can then be represented by

$$E_j = \alpha + m_j\beta \tag{9}$$

and the set of equations (8) simplifies to

$$\begin{aligned} &-c_{j1}m_j + c_{j2}\beta_{12}/\beta + \cdots + c_{jn}\beta_{1n}/\beta = 0 \\ &\vdots \\ &c_{j1}\beta_{n1}/\beta + \cdots\cdots\cdots -c_{jn}m_j = 0. \end{aligned} \tag{10}$$

This set of equations no longer contains the undetermined quantities α and β (β_{rs}/β is equal to either one or zero). For complex systems ($n > 10$), it is desirable to use an electronic computer to solve the equations [92] [*].

After all m_j and c_{jr} values ($j, r = 1, \ldots n$) have been calculated, it is still necessary to arrange the electrons correctly in the various energy levels. The arrangement must obey the aufbau principle (including the Pauli principle), according to which the molecular orbitals are filled in order of increasing energy (*i.e.* decreasing m_j value), each orbital accommodating two electrons with opposite spins. The number M of electrons to be accommodated depends on the number of C-atoms (or heteroatoms) and on the charge of the molecule: M = n + ionic charge (see Fig. 1). An unpaired π-electron is thus placed in a certain level with $m_j = m_o$. The unpaired spin density ρ_r^π on the various C-atoms (*i.e.* the probability of finding the unpaired electron on each C-atom) is given directly by the squares of the corresponding c_{or} values (after normalization to $\sum_r c^2_{or} = 1$), as shown in Eq. (11).

$$\rho_r^\pi = c^2_{or} \tag{11}$$

[*] Computer programs in FORTRAN can be obtained from the authors.

[93] *A. D. McLachlan*, Molecular Physics *3*, 233 (1960).

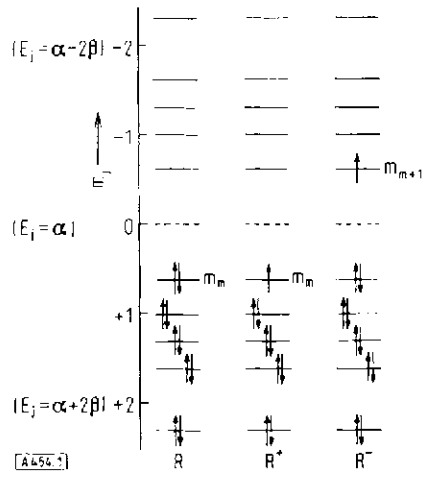


Fig. 1. Arrangement of the π-orbital energy levels and insertion of the π-electrons in naphthalene (10 carbon atoms).

Two or more energy levels (m_j values) often coincide; in these cases, the electrons are inserted in accordance with Hund's rule of maximum spin multiplicity.

It is important for the application of electron paramagnetic resonance to neutral or charged hydrocarbon radicals to differentiate between non-alternant and alternant hydrocarbons. In an even alternant hydrocarbon, the m_j values go in pairs with opposite signs: $m_j = \pm m_1, \pm m_2, \ldots$ The energy levels are therefore symmetrically distributed about the level with $m_j = 0$ ($E_j = \alpha$). The atomic orbital coefficients c_{jr} for $+m_j$ agree, apart from a change of sign on starred positions, with the orbital coefficients for $-m_j$ (pairing theorem [94]). Since, on the basis of the aufbau and Pauli principles, the unpaired electron of the hydrocarbon radical-ions occupies either the highest bonding orbital (smallest positive m_j value; unipositive radical-ion R^+) or the lowest antibonding orbital (smallest negative m_j value; uninegative radical-ion R^-), molecules of this type with opposite charge should have identical spin density distributions. Another consequence of the pairing theorem is the numerical equality of the excess charges ε_r^π for positive and negative ions: $(\varepsilon_r^\pi) = -(\varepsilon_r^\pi)^+$. In Hückel's approximation, moreover, $(\varepsilon_r^\pi)^\pm = \pm\rho_r^\pi$. (For an experimental test of these consequences of the pairing theorem, see Section V.1).

In most odd alternant hydrocarbons, the number of starred C-atoms is one greater than the number of unstarred C-atoms. These molecules are free radicals even in the neutral state. The unpaired electron moves in a molecular orbital with $m_j = m_o = 0$ ($E_o = \alpha$; nonbonding orbital). The corresponding c_{or} values (and spin densities $\rho_r^\pi = c^2_{or}$) can be written directly against the various C positions in the structural formula of the molecule without complicated calculations; in particular, $\rho_r^\pi = 0$ in all the unstarred positions [95].

The effects of different bond lengths, bond deformation, heteroatoms, and hyperconjugation on the spin density distribution can be taken into account in the HMO

[94] *A. D. McLachlan*, Molecular Physics *2*, 271 (1959).

[95] *H. C. Longuet-Higgins*, J. chem. Physics *18*, 265, 275, 283 (1950).

theory by variation of the α and β values for the appropriate positions. The assumption of the HMO theory that β is constant is equivalent to assuming that all the bond lengths are equal. It is known from X-ray studies, however, that the bond lengths in many carbon π-systems vary between 1.33 and 1.52 Å [96,97]. A functional relationship between β_{rs} and the C–C bond length d_{rs} in π-systems has been given by *Longuet-Higgins* and *Salem* [98] in the form (12). In the case of

$$\beta_{rs}/\beta = \exp\left[-(d_{rs}-1.40)/0.311\right] \qquad (12)$$

naphthalene, Eq. (12) gives better results than the simple HMO method [93].

According to *Mulliken* [99] and *Dewar* [100], β_{rs} can be assumed to be related to the torsion angle Θ_{rs} between the 2 p_z orbitals of two adjacent C atoms in positions r and s by:

$$\beta_{rs}/\beta = \cos\Theta_{rs} \qquad (13)$$

By comparing experimental spin densities or m_j values with calculated spin densities or m_j values as a function of Θ_{rs}, it is possible to determine the torsion angle between two or more phenyl rings which cannot lie in the same plane owing to steric hindrance.

Heteroatoms X can be allowed for in the HMO method by suitable modification [Eq. (14)] of the parameters α and β for the appropriate positions. Numerical values

$$\alpha_X = \alpha_C + h_X\beta_{CC}$$
$$\beta_{CX} = k_{CX}\beta_{CC} \qquad (14)$$

of h_X and k_{CX} can be found empirically by fitting the calculated spin densities $\rho^\pi = f(h_X, k_{CX})$ to experimental spin densities [101,102]. However, a number of general principles also apply: for heteroatoms X· that contribute a single electron to the π-system, $h_{X\cdot}$ is approximately equal to the difference in the electronegativities [103] of atoms X· and C [92]. When a heteroatom X: contributes two electrons to the π-system, allowance is made for this by the correction $h_{X:} - h_{X\cdot} \simeq 1$ to 1.5 [92]. Conversely, these rules can also be used to find differences in electronegativity between various atoms in π-systems from empirical h_X values. The numerical values of k_{CX} vary between 0.6 and 1.0 [104].

The EPR spectra of organic free radicals containing substituted methyl groups frequently exhibit hyperfine structure as a result of interaction between the unpaired electron and the methyl protons. This effect is due to direct overlap between the hydrogen 1s-orbitals and the $2p_z$ atomic orbitals of the carbon atoms in the π-system (hyperconjugation), whereby the odd-electron density reaches the protons [92]. The splitting constant of a proton of the i-th methyl group attached to the i-th C-atom of the π-system is given by Eq. (15):

$$a_i^{H(methyl)} = Q\rho_i^\pi \qquad (15)$$

in which $Q \simeq 28$ oersted [105]. The disturbance of the π-electron distribution by a methyl group is allowed for by replacing the three hydrogen atoms of the methyl group by a pseudo-hydrogen atom H_3 and treating the atoms H_3, C_{methyl}, and C_π as heteroatoms [106]. The following h_X and k_{CX} values are generally used: $h_{C_\pi} = 0$ to -0.1; $h_{C_m} = 0.0$ to -0.1; $h_{H_3} = 0.0$ to -0.5; $k_{C_\pi C_m} = 0.7$ to 1.0; and $k_{C_m H_3} = 2.0$ to 2.5 [106–109].

b) McLachlan SCF Approximation

An important disadvantage of the HMO theory is the fact that it disregards the interaction of the π-electrons, although this is partly compensated by the use of effective Coulomb and bond integrals α and β (numerical values of α_{eff} and β_{eff} are not needed for spin density calculations). The π-electron interactions are explicitly taken into account in the self-consistent field (SCF) wave functions [110–116], which permit the removal of spin compensation in the doubly occupied molecular orbitals in free radicals. This depends on exchange energies, which in turn depend on the spin direction. The electrons with α-spin ($\uparrow$) experience on average a weaker repulsion by the unpaired electron than the electrons with β-spin ($\downarrow$); consequently, the two electrons of a Hückel electron pair will move in different molecular orbitals. The unpaired spin density ρ_r^π is then no longer given by the density $(c_{or}^\alpha)^2$ of the unpaired electron alone, but by the excess α-spin density obtained by summation over all the occupied molecular orbitals:

$$\rho_r^\pi = \sum_j^{occ.}\left(c_{jr}^\alpha\right)^2 - \sum^{occ.}\left(c_{jr}^\beta\right)^2 \qquad (16)$$

($\sum^{occ.}$ means summation over all molecular orbitals containing α or β-electrons). This "exchange polarization" of the π-electron core by the unpaired electron makes

[96] *J. M. Robertson*, Proc. Roy. Soc. (London) A *207*, 101 (1951); Organic Crystals and Molecules. Cornell University Press, Ithaca 1953, Ch. 8.

[97] *F. R. Ahmed* and *D. W. J. Cruickshank*, Acta crystallogr. *5*, 852 (1952).

[98] *H. C. Longuet-Higgins* and *L. Salem*, Proc. Roy. Soc. (London) A *251*, 172 (1959).

[99] *R. S. Mulliken*, J. chem. Physics *56*, 295 (1952).

[100] *M. J. S. Dewar*, J. Amer. chem. Soc. *74*, 3345 (1952).

[101] *G. Vincow*, J. chem. Physics *38*, 917 (1963).

[102] *G. Vincow* and *G. K. Fraenkel*, J. chem. Physics *34*, 1333 (1961).

[103] *L. Pauling*: The Nature of the Chemical Bond. Cornell Univ. Press, Ithaca, N.Y., 1960.

[104] *G. W. Wheland*, J. Amer. chem. Soc. *64*, 900 (1942).

[105] *A. D. McLachlan*, Molecular Physics *1*, 233 (1958).

[106] *C. A. Coulson* and *V. A. Crawford*, J. chem. Soc. (London) 2052 (1953).

[107] *R. Pauncz* and *E. A. Haveli*, ibid. *1959*, 1967.

[108] *E. A. Halevi* and *R. Pauncz*, ibid. *1959*, 1974.

[109] *N. Bauman* and *G. J. Hoijtink*, Recueil Trav. chim. Pays-Bas *76*, 841 (1957).

[110] *M. Kotani*, *K. Ohno*, and *K. Kayama* in *S. Flügge*: Handbuch der Physik. Springer, Berlin-Göttingen-Heidelberg 1961. Vol. 37/2, p. 47.

[111] *C. C. J. Roothaan*, Rev. mod. Physics *23*, 69 (1951).

[112] *J. A. Pople*, Trans. Faraday Soc. *49*, 1375 (1953).

[113] *H. C. Longuet-Higgins* and *J. A. Pople*, Proc. physic. Soc. (London) A *68*, 591 (1955).

[114] *J. A. Pople* and *R. K. Nesbet*, J. chem. Physics *22*, 571 (1954).

[115] *A. Brickstock* and *J. A. Pople*, Trans. Faraday Soc. *50*, 901 (1954).

[116] *R. Pariser* u. *R. G. Parr*, J. chem. Physics *21*, 466, 767 (1953).

possible negative spin densities, when $\sum_{j}^{occ.}(c_{jr}^{\alpha})^2 < \sum_{j}^{occ.}(c_{jr}^{\beta})^2$. However, we still have $\sum_{r=1}^{n}\rho_r^{\pi} = 1$, although we can now have $\sum_{r=1}^{n}|\rho_r^{\pi}| \geq 1$, and hence also $\sum_r' a_r^H = Q\sum_r'\rho_r^{\pi} \geq Q$ (Σ' denotes summation over positions occupied by protons).

According to *McLachlan* [93], the exchange polarization can be accounted for to a first approximation if the Coulomb and bond integrals α and β for the unpaired electron and for the electrons with β-spin are equated again to the corresponding Hückel values, and the Coulomb integral α_r for the other electrons with α-spin are corrected by a quantity given by Eq. (17), in which $\lambda \simeq 1.2$ (constant for all C-atoms). The quantities c_{jr}^{α}

$$\Delta\alpha_r = 2\lambda c_{or}^2\beta \tag{17}$$

for the "paired" electrons with α-spin are thus obtained by solving the eigenvalue problem (10) with $(-m_j + 2.4\, c_{or}^2)$ instead of $-m_j$ in the r-th row, and the spin density ρ_r^{π} is finally found from Eq. (18), in which the summation

$$\rho_r^{\pi} = c_{or}^2 + \sum_j\left[(c_{jr}^{\alpha})^2 - c_{jr}^2\right] \tag{18}$$

must be carried out over all doubly occupied molecular orbitals.

c) Complete SCF Method

The complete SCF method takes into account not only the exchange interaction of the electrons, but also their Coulomb repulsion forces over the whole molecule [117, 118] [*]. No check on the spin densities obtained by this method on the basis of Eq. (6) and covering several molecules has yet been carried out.

[117] *A. T. Amos*, Molecular Physics *5*, 91 (1962).

[118] *M. Plato*, unpublished work.

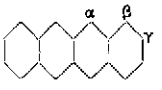
[*] A computer program in FORTRAN can be obtained from the authors.

V. EPR Parameters and Molecular Properties

1. Spin Densities

In the EPR investigation of aromatic hydrocarbon radicals, interest is centered mainly on checking the various approximations of the LCAO–MO method, and particularly, the procedures of *Hückel* and *McLachlan* (see Section IV). As an example, let us consider the even alternant hydrocarbon tetracene. This hydrocarbon forms both an R^+ and an R^- radical-ion, both of which have been detected by EPR spectroscopy [21]. The measured values of the splitting constants are given in Table 1. There are three groups of four protons with identical splitting constants within the groups, *i.e.* in agreement with the postulated structure, the four protons in each group are equivalent. The pairing theorem, according to which R^+ and R^- should have identical spin density distributions, is also verified, although the spectra are not quite identical, owing to the dependence of the splitting constants on the excess charges [Eq.(6)]. The splitting constants calculated from Hückel spin densities and excess charges show good agreement with the experimental values, and are even slightly better, on average, than results obtained by the McLachlan SCF method [119].

Table 1. Experimental and theoretical splitting constants a^H of the negative and positive tetracene radical-ions.



	Position	exper. a^H [Oe] [21]	ρ^{π} [119]		ε^{π} [119]		$a^H = (Q + K\varepsilon^{\pi})\rho^{\pi}$ [Oe]	
			Hückel	*McLachlan*	*Hückel*	*McLachlan*	*Hückel* Q = 31.7 Oe K = 18 Oe [21]	*McLachlan* Q = 24.4 Oe K = 17 Oe [21]
R^-	α	4.16	0.147	0.196	−0.147	−0.099	4.28	4.46
	β	1.43	0.056	0.067	−0.056	−0.046	1.72	1.58
	γ	1.16	0.034	0.022	−0.034	−0.046	1.05	0.52
R^+	α	4.97	0.147	0.196	+0.147	+0.099	5.05	5.11
	β	1.65	0.056	0.067	+0.056	+0.046	1.84	1.69
	γ	1.01	0.034	0.022	+0.034	+0.046	1.08	0.55

The Hückel theory breaks down, however, in the case of the recently detected allyl radical $\overset{1}{C}H_2{=}\overset{2}{C}H{-}\overset{3}{C}H_2\cdot$ [73]. The experimental spin densities are $|\rho_1^{\pi}| = |\rho_3^{\pi}| = 0.58$ and $|\rho_2^{\pi}| = 0.16$, whereas the Hückel theory gives the values $\rho_1^{\pi} = \rho_3^{\pi} = 0.5$ and $\rho_2^{\pi} = 0.0$. In this case, the McLachlan method is more successful in predicting a high negative spin density of $\rho_2^{\pi} = -0.19$ ($\lambda = 1.06$) on the central C-atom.

With a few exceptions, negative spin densities always occur where the Hückel theory predicts a spin density of zero. The principal positions in which this is the case are the unstarred (inactive) positions in the neutral odd alternant hydrocarbon radicals (*e.g.* allyl, triphenylmethyl, and perinaphthenyl), but

[119] *T. C. Sayetta* and *J. D. Memory*, J. chem. Physics *40*, 2748 (1964).

it also occurs at protonated positions in a few even alternant radical-ions (*e.g.* in biphenyl, pyrene, and phenanthrene) [93].

Whereas the hyperfine structure spectra of condensed aromatic hydrocarbon radicals show a constant overall splitting of approximately 30 oersted, an overall hyperfine splitting of less than 10 oersted was found in the case of the pentaphenylcyclopentadienyl radical [120].

Since the only explanation of this anomaly is that the unpaired spin density is forced onto the unprotonated five-membered ring, it must be assumed that the phenyl rings are largely twisted out of the plane of the five-membered ring. This assumption also seems justified in view of the mutual hindrance of the phenyl rings (interaction of the hydrogen atoms) in the completely planar model.

The steric hindrance of the two phenyl rings of biphenyl by the four ortho hydrogen atoms also leads to twisting about the central C -C bond. Comparison of the measured value of the splitting ratio a_{para}/a_{ortho} with the calculated ratio of the spin densities $\varrho_{para}/\varrho_{ortho} = f(\Theta)$ has shown that the angle between the planes of the two phenyl rings is $38 \pm 2°$ [21].

It has been shown by EPR spectroscopy that rotation of the CHO group in *p*-nitrobenzaldehyde is hindered [121]. If rotation about the C_{ring}–CHO bond were free, there should be at the most three different splitting constants; four different splitting constants are however observed. This is explained by assuming that the two *ortho* ring protons are no longer equivalent, owing to the influence of the CHO group. From the difference in the splitting constants, the rotational frequency of the CHO group is estimated to be, at most, 10^6 sec^{-1}.

The terephthalic aldehyde anion gives a hyperfine structure spectrum [122] that can be reconstructed only if we assume the presence of two types of molecule A and B, each containing three pairs of equivalent protons. The concentration ratio of the two types of molecules has been found, from the intensity ratio of the two superimposed spectra, to be $c_A/c_B = 1.40$. On the basis of spin density calculations with variation of α and β for heteroatoms, A and B have been identified as the planar *trans*- and *cis*-rotamers of the terephthalic aldehyde anion. Since $c_A > c_B$, the *trans*-rotamer is the more stable of the two.

In the case of the phthalic aldehyde anion, three rotamers (*meso*, *endo*, and *exo* forms) are possible. It can be concluded, however, simply from the absence of a central line from the hyperfine structure spectrum, that the *meso* form predominates over the other rotamers by a concentration ratio of at least 16:1 [123].

Geske et al. [32] and *Rieger et al.* [124] have described very detailed EPR studies on the steric effects in anion-radicals of aromatic nitro compounds. When the nitro groups in mononitro and symmetrically substituted dinitro radical-anions are rotated out of the plane of the ring, the nitrogen splitting constants increase considerably, while the splitting constants of the ring protons decrease. In 2,6-dimethyl-1,4-dinitrobenzene, for example, the nitrogen splitting constant of the 1-nitro group, which is hindered by the two methyl groups, is only 0.14 oersted, whereas that of the 4-nitro group is 5.7 oersted.

The theoretical calculation of spin densities and π-orbital energies are valid for isolated molecules. Since, however, the EPR measurements are not generally carried out on gaseous, *i.e.* free organic radicals, environmental factors must be taken into account in comparing theoretical and experimental results. It is known since 1962 [25] that the hyperfine splitting constants of organic radicals in different solvents can vary by up to a few oersted. A survey of the experimental results shows that the solvent-dependence of the splitting constants is particularly pronounced in the case of radicals containing functional groups, whereas unsubstituted aromatic radicals show practically no solvent effects. It is clear from measurements on quinones [25], nitro compounds [125,126], and ketones [127] that the changes in the splitting constants (and hence in the spin densities) are particularly large on passing from aprotic to protonic solvents. In addition to the normal electrostatic interaction, which leads to solvation of the radicals, there is evidently also a much stronger interaction between the radicals and the solvent molecules, involving hydrogen bonds. Thus free solvated radicals are obtained in extremely anhydrous aprotic solvents such as acetonitrile or dimethylformamide. *Gendell*, *Freed*, and *Fraenkel* [128, 128a] have shown that the experimentally observed solvent-dependence of the splitting constants can be theoretically explained by postulating localized complex formation between the solvent and the functional groups in the radical. The redistribution of the spin density is then allowed for if the electronegativity, *i.e.* the Coulomb integral α, of the hydrogen-bonded atom carrying the lone pair of electrons is modified as a matching factor for the particular solvent.

2. g Factors

In addition to the hyperfine structure, a radical is also characterized by the g factor. Since the π electrons are firmly coupled to the plane of the molecule by the strong intramolecular fields, their orbital momentum is almost completely quenched, so that the g factors of all organic radicals differ by at most 1 % from the g factor of the free electron, $g_o = 2.002319$. Within a class of molecules, in fact, the g factors often differ only in

[120] *D. C. Reitz*, J. chem. Physics *34*, 701 (1961).

[121] *A. H. Maki* and *D. H. Geske*, J. Amer. chem. Soc. *83*, 1852 (1961).

[122] *A. H. Maki*, J. chem. Physics *35*, 761 (1961).

[123] *E. W. Stone* and *A.H.Maki*, J.chem.Physics *38*, 1999 (1963).

[124] *P. H. Rieger* and *G. K. Fraenkel*, J. chem. Physics *39*, 609 (1963).

[125] *J. Q. Chambers*, *T. Layloff*, and *R. N. Adams*, J. physic. Chem. *68*, 661 (1964).

[126] *J. Pannell*, Molecular Physics *7*, 599 (1964).

[127] *G. R. Luckhurst* and *L. E. Orgel*, Molecular Physics 8, 117 (1964).

[128] *J. Gendell*, *J. H. Freed*, and *G. K. Fraenkel*, J. chem. Physics *37*, 2832 (1962).

[128a] *J. H. Freed* and *G. K. Fraenkel*, J. chem. Physics *38*, 2040 (1963).

the 5th decimal place; consequently, the identification of radicals demands that the g factors be determined very accurately. The g factors can be found directly in accordance with the resonance condition (2) from the ratio of the microwave frequency ν_0 and the resonance field strengths H_0 found from the proton resonance frequency ν_p [Eq. (19)] [21]; alternatively, they can be

$$g = F \cdot \nu_0/\nu_p;\ (F = 3.042000 \pm 5 \times 10^{-6}) \times 10^{-3} \qquad (19)$$

found in relation to the known g factors of standard samples [129] from the difference in the resonance field strengths [Eq. (20)].

$$g = g_s(1-\delta H/H_{0s}) \qquad (20)$$

The deviations $\Delta g = (g-g_0)$ from the g factor of the free electron are due to a residual spin-orbital coupling, resulting in an admixture of excited states, which contain a triplet state in the σ system, with the ground state. Δg can be represented to a first approximation by an equation of the form (21) [130] in which λ is the

$$\Delta g = \text{const} \cdot \left[-\lambda\left(\frac{1}{\Delta E_1}-\frac{1}{\Delta E_2}\right)\right] \qquad (21)$$

spin-orbital coupling parameter of the atoms of which the molecule is composed. ΔE_1 (< 0) is the energy difference between the π-level containing the unpaired electron and the highest fully occupied bonding σ-level, whilst ΔE_2 (< 0) is the energy difference between this π-level and the first antibonding excited σ^*-level. Depending on whether $|\Delta E_1| < |\Delta E_2|$ or $|\Delta E_1| > |\Delta E_2|$, the measured g factors will be greater or smaller than the g factor of the free electron, so that the sign of Δg can be used for the term analysis. The limitations of the approximation (21) for Δg have been discussed by *Stone* [131]. Eq. (21) predicts a steady increase in the g factor with increasing λ of a substituent (cf. Table 2).

Table 2. Spin-orbital coupling parameters λ [132] and experimental g factors [133] of *p*-benzosemiquinone radicals.

p-Benzosemiquinone radical	Substituent	λ [cm^{-1}]	g
Unsubstituted	O	152	2.00468
Tetrachloro	Cl	587	2.00568
Tetrabromo	Br	2460	2.00875
Tetraiodo	I	5060	2.01217

For hydrocarbons, $\lambda = 28$ cm^{-1}, so that the difference between the g factors of unsubstituted π-electron radicals and the value for the free electron fall in the range $2.0025 \leqslant g \leqslant 2.0027$.

In the $AlCl_3$-catalysed alkylation of benzene (Friedel-Crafts reaction), which had formerly been assumed to proceed by a completely ionic mechanism, EPR spectroscopy has revealed the occurrence of free-radical intermediates [134], the g factors of which were always about 2.0025 ± 0.0001, irrespective of the alkylating agent. The radicals are therefore hydrocarbon radicals, and contain no oxygen or chlorine.

Grignard reactions have also been assumed to proceed by an entirely ionic mechanism. Free radicals have, however, been detected by EPR spectroscopy when Grignard compounds such as C_6H_5MgBr were added to aromatic and aliphatic ketones such as benzophenone and hexamethylacetone in tetrahydrofuran [134a].

The free radical formed during the reaction of diphenylpicrylhydrazyl with t-butyl hydroperoxide has recently been identified, by analysis of the hyperfine structure, as diphenylnitrogen oxide [135]; the large g factor (2.0058) and the fact that it agreed with the g factor of an authentic sample of diphenylnitrogen oxide provided important evidence of the identity of the reaction product.

Stone [131] has shown that the deviation of the g factors of aromatic hydrocarbon radicals from the value g_0 are systematic in nature, and bear a linear relationship to the π-orbital energy of the unpaired electron. If E_π in Hückel's approximation is expressed by constant Coulomb and bond integrals, then

$$\Delta g = A + B \cdot m_o \qquad (A, B = \text{constant}) \qquad (22)$$

Here m_o is the Hückel energy coefficient of the lowest half-occupied orbital, *i.e.* $m_o = m_m > 0$ for even alternant radical-cations, $m_o = m_{m+1} < 0$ for radical-anions, and $m_o = 0$ for neutral odd alternant radicals (cf. Fig. 1). Figure 2 shows the deviations Δg of the g factors (experimental error $\pm 2 \times 10^{-6}$) of some positive and negative aromatic radical-ions as a function of m_o [21]. The required linearity of the relationship between Δg and m_o is satisfactorily fulfilled, the slope and intercept of

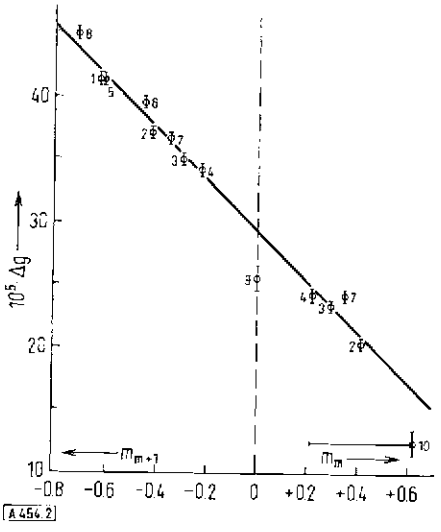


Fig. 2. Change in the g factor of aromatic radicals as a function of the Hückel energy coefficient m_o of the lowest half-occupied π-orbital ($m_o = m_{m+1} < 0$ for R^-, $m_o = m_m > 0$ for R^+).
(1) naphthalene$^\ominus$, (2) anthracene$^{\ominus/\oplus}$,
(3) tetracene$^{\ominus/\oplus}$, (4) pentacene$^{\ominus/\oplus}$,
(5) phenanthrene$^\ominus$, (6) pyrene$^\ominus$,
(7) perylene$^{\ominus/\oplus}$, (8) biphenyl$^\ominus$,
(9) triphenylmethyl. (10) pentaphenylcyclopentadienyl

[129] *K. Scheffler* and *H. B. Stegmann*, Ber. Bunsenges. physik. Chem. *67*, 864 (1963).
[130] *H. M. McConnell* and *R. E. Robertson*, J. physic. Chem. *67*, 7 (1957).
[131] *A. J. Stone*, Molecular Physics *6*, 509 (1963).
[132] *D. S. McClure*, J. chem. Physics *17*, 905 (1949).
[133] *M. S. Blois jr.*, *H. W. Brown*, and *J. E. Maling* in [9], p. 117.
[134] *J. Q. Adams* and *S. W. Nicksic*, J. Amer. chem. Soc. *84*, 4355 (1962).
[134a] *K. Maruyama*, Bull. chem. Soc. Japan *37*, 897 (1964).
[135] *K. Möbius* u. *F. Schneider*, Z. Naturforsch. *18a*, 428 (1963).

the fitted line being $-(20.3 \pm 0.7)\times10^{-5}$ and $(29.8 \pm 0.4)\times10^{-5}$ respectively.

A number of the points do not lie on the straight line. In the cases of the biphenyl radical-ion and the pentaphenylcyclopentadienyl radical, this deviation can be explained as resulting from the non-planarity of the molecules. A torsion angle of $31 \pm 8°$ has been found for the biphenyl radical-anion, whereas the five phenyl rings in pentaphenylcyclopentadienyl are almost perpendicular to the plane of the 5-membered ring [21]. (The m_o range shown is bounded on the left by the torsion angle 0° and on the right by the angle 90°). Thus electron paramagnetic resonance offers two methods of finding the torsion angles of radicals in solution: from the hyperfine structure on the one hand, and from the g factor on the other.

All neutral odd alternant hydrocarbon radicals, such as triphenylmethyl, should have the same g-factor deviation $\Delta g = 29.8\times10^{-5}$, since $m_o = 0$. Even after the twisting has been taken into account in the Hückel approximation, the points 9 and 10 still fall well below the fitted line obtained from the values for radical-ions. This confirms what has been found by experience, *i.e.* that the Hückel molecular orbital theory gives practically the same results for radical-ions as the SCF theory, whereas the HMO approximation is too crude for neutral radicals.

It should also be mentioned that Δg can be determined without laborious theoretical calculations by measurement of the polarographic half-wave potential $U_{1/2}$. For aromatic hydrocarbons, Δg bears a linear relationship to $U_{1/2}$, as indicated in Eq. (23) ($U_{1/2}$ measured in volts *versus* a saturated calomel electrode) [21]. It is

$$\Delta g = (27.8 \pm 0.5)\times10^{-5} - (5.6 \pm 0.2)\times10^{-5}\, U_{1/2} \qquad (23)$$

therefore possible to construct a calibration curve which gives the g factors to an accuracy of about 10^{-5} from the known half-wave potentials, even in the case of radical ions, such as the singly charged positive benzene and naphthalene ions, that have not yet been studied by EPR spectroscopy.

3. Line Widths

Absolute line widths and the small line-width variations occasionally observed in hyperfine structure spectra generally give little information regarding structure. In the case of the dinitrodurene anion, however, the marked variation in the line width in the EPR spectrum has been taken to indicate steric hindrance between the methyl groups and the nitro groups [136]. Examples are also known in which anomalous line-width variations are caused by rotational isomerism [137–140].

[136] *J. H. Freed* and *G. K. Fraenkel*, J. chem. Physics *37*, 1156 (1962).

[137] *J. R. Bolton, A. Carrington*, and *P. F. Todd*, Molecular Physics *6*, 169 (1963).

[138] *E. de Boer* and *E. L. Mackor*, J. Amer. chem. Soc. *86*, 1513 (1964).

[139] *J. H. Freed* and *G. K. Fraenkel*, J. chem. Physics *40*, 1815 (1964).

[140] *A. Carrington*, Molecular Physics *5*, 425 (1962).

4. Intensities

In considering the intensities, it is necessary to distinguish between the relative intensities of individual lines, which are important to the evaluation of the hyperfine structure [1a], and the total intensity of the spectrum. The intensity of the spectrum is measured by the area A under the absorption curve, and is obtained from the recorded curve by double integration. The area depends on the number N_o of absorbing centers, the spin quantum number S, the absolute temperature, and several constants of the apparatus [8] as shown by the proportionality (24). The relative concentrations of radicals in two samples can be found from the ratio A_1/A_2.

$$A \quad N_o S(S+1)/T \qquad (24)$$

In compounds containing paramagnetic ions of transition metals, it is often difficult to establish the valence state of the metal ion. This problem can be solved in many cases with the aid of the EPR spectrum, since the relaxation times of the various valence states are very different. For example, the absorption line for Fe^{2+} is so wide at room temperature that it cannot be detected, whereas Fe^{3+} gives an easily observable spectrum. Even when the relaxation times are approximately equal, however, the valence state can still be calculated from the intensity of the EPR spectrum, since the intensity is proportional to $S(S + 1)$. The spin quantum number of Nb^{4+} is $S = 1/2$, whereas that of Nb^{2+} is $S = 3/2$; at equal Nb concentrations, therefore, the intensities of the spectra are in the ratio of 1:5.

The kinetics of reactions in which radicals are formed or consumed can be studied by the time-dependence of the intensity. This technique has been particularly useful in biological reactions [141], in polymerization [57], and in photochemical reactions [73]. It is possible to measure lifetimes down to a few msec. *Fessenden* [142] has described various experimental methods which can be used to follow fast reactions of this type. This author measured the lifetime at −170 °C (τ = 7.3 to 7.5 msec) of the ethyl radical, which was formed by irradiation of ethane with 2.8 MeV electrons. The activation energy of the recombination reaction was also calculated from the temperature-dependence of τ, the value obtained being 830 cal/mole.

It is often important to know whether free radicals play any part in a given reaction at all. This is the case particularly in biochemical problems in which the course of the reaction has not yet been established. The EPR spectra of free radicals formed during metabolic processes, for example, generally consist of a single wide line at $g \simeq 2$, so that quantitative information can be obtained only from the width and intensity of the line [143].

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[141] *I. Yamazaki* and *L. H. Piette*, Biochim. biophysica Acta *50*, 62 (1961).

[142] *R. W. Fessenden*, J. physic. Chem. *68*, 1508 (1964).

[143] *K. G. Zimmer, W. Köhnlein, G. Hotz*, and *A. Müller*, Strahlentherapie *120*, 161 (1963).

Formation of a 2-Thiocyanatopyrimidine from a 1-Amino-2-thioxo-1,2-dihydropyrimidine and Dimethylformamide/$POCl_3$

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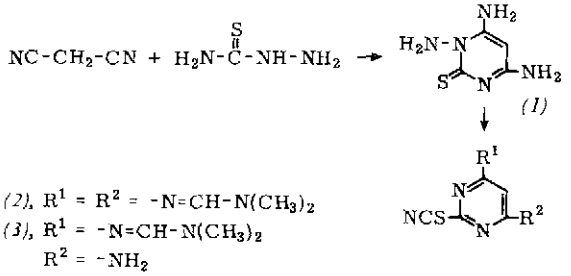
Condensation of malonodinitrile with thiosemicarbazide in 2 M ethanolic sodium ethoxide gives 1,4,6-triamino-2-thioxo-1,2-dihydropyrimidine *(1)*, m.p. 261 °C (decomp.), in 34 % yield. Treatment of *(1)* for 2 h at room temperature with the dimethylformamide/$POCl_3$ complex [1] leads to 4,6-bis(dimethylaminomethyleneamino)-2-thiocyanatopyrimidine *(2)* in 65 % yield. This compound melts at 130–131.5 °C and is isolated by addition of the reaction mixture to crushed ice, adjustment of the pH to 10 with 6 N sodium hydroxide, rapid filtration, and recrystallization of the dried precipitate from acetone/hexane.

The structure of *(2)* was indicated by its elemental composition, by a strong infrared absorption band at 2172 cm^{-1} characteristic of the –SCN grouping, and by its chemical reactions. For example, *(2)* was converted by either benzylamine at 95 °C or 1 N sodium hydroxide at room temperature or refluxing 2 M ethanolic ammonia into 4,6-diamino-2-mercaptopyrimidine [2]. Hydrolysis of *(2)* with cold 0.5 N hydrochloric acid gave 4-amino-6-dimethylaminomethyleneamino-2-thiocyanatopyrimidine *(3)*, m.p. 198.5–199 °C, whereas hydrolysis with 6 N hydrochloric acid at 100 °C gave barbituric acid. Hydrolysis with 4 N acetic acid at room temperature afforded 4,6-bisformylamino-2-thiocyanatopyrimidine *(4)*, m.p. 249 °C (decomp.). Treatment of 1.0 g of *(2)* with 4 g of chlorine in 15 ml of acetic acid gave rise to 4,6-diamino-2,5-dichloropyrimidine in 71 % yield [3].



(2), $R^1 = R^2 = -N{=}CH{-}N(CH_3)_2$
(3), $R^1 = -N{=}CH{-}N(CH_3)_2$, $R^2 = -NH_2$
(4), $R^1 = R^2 = -NH{-}CHO$

We consider that the reaction of *(1)* with the dimethylformamide/$POCl_3$ complex involves initial formation of the 1,4,6-tris(dimethylaminomethyleneamino) compound [4]. The $(CH_3)_2N{-}CH{-}N$-group on N-1 could then cyclize with the thioxo sulfur on C-2 to form a thiadiazole ring; loss of dimethylamine followed by cleavage of the N–N bond could then yield *(2)*.

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[1] *Z. Arnold* and *A. Holy*, Collect. Czechoslov. chem. Commun. *27*, 2886 (1962).

[2] *W. Traube*, Liebigs Ann. Chem. *331*, 64 (1964).

[3] *E. C. Taylor* and *P. Drenchko*, J. Amer. chem. Soc. *74*, 1101 (1952).

[4] Reaction of 4,5-diamino-6-fluoropyrimidine with dimethylformamide/$POCl_3$ gives rise to 4,5-bis(dimethylaminomethyleneamino)-6-fluoropyrimidine: *A. G. Beaman* and *R. K. Robins*, J. med. pharmac. Chem. *5*, 1067 (1962).

Formation of Phenylcarbenes by Photolysis of Phenyloxiranes

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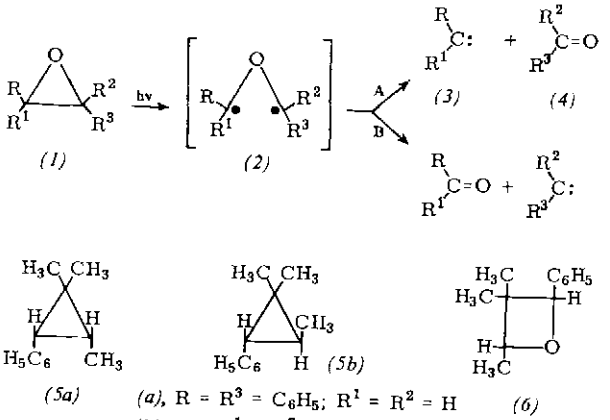
We have found that photolysis [2] of *trans*-stilbene oxide *(1a)* [3] in 2-methylbut-2-ene leads to a 1:1 mixture of *cis*-*(5a)* and *trans*-2,2,3-trimethyl-1-phenylcyclopropane *(5b)* in 90 % yield [4]. In addition, the oxetane derivative *(6)* [5], which is formed by addition of benzaldehyde to the solvent, was isolated.

The cyclopropane derivatives *(5a)* and *(5b)* were also obtained on photolysis [2] of tripbenyloxirane *(1b)* [3] in either 2-methylbut-2-ene/benzene or 2-methylbut-2-ene alone. However, here the main products were tetraphenylethane and the oxetane *(6)*.

These reactions apparently all involve the diradical *(2)*, which decomposes preferentially by Route A to the carbene *(3)* plus the carbonyl compound *(4)*.



(1) *(2)* *(3)* *(4)*

(5a) *(5b)* *(6)*

(a), $R = R^3 = C_6H_5$; $R^1 = R^2 = H$
(b), $R = R^1 = R^2 = C_6H_5$; $R^3 = H$
(c), $R = R^1 = R^2 = R^3 = C_6H_5$

Photolysis of tetraphenyloxirane *(1c)* [3] in methanol/benzene gives benzhydrol methyl ether in almost 100 % yield. *Kirmse* and *Horner* [6] have previously used alcohols to trap aryl carbenes.

All products were separated by gas chromatography and identified by comparison with authentic samples [7].

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[1] We gratefully acknowledge financial support from the Army Research Office (Durham) N.C. (U.S.A.).

[2] The solutions were carefully degassed and irradiated for 10 h at 40 °C. The radiation source was an air-cooled Rayonet Chamber Reactor (from the Southern New England Ultraviolet Co., Middletown, Conn. (U.S.A.) containing sixteen 8-watt low-pressure mercury lamps.

[3] *A. C. Cope*, *P. A. Trumbull*, and *E. R. Trumbull*, J. Amer. chem. Soc. *80*, 2844 (1958).

[4] *G. L. Closs* and *R. A. Moss*, J. Amer. chem. Soc. *86*, 4042 (1964).

[5] *G. Büchi*, *C. G. Inman*, and *E. S. Lipinsky*, J. Amer. chem. Soc. *76*, 4327 (1954).

[6] *W. Kirmse*, *L. Horner*, and *H. Hoffmann*, Liebigs Ann. Chem. *614*, 19 (1958); *W. Kirmse*, ibid. *666*, 9 (1963).

[7] We thank Prof. *G. Closs*, University of Chicago (U.S.A.) for copies of the infrared spectra of *(5a)* and *(5b)*.

Preparation of Heavy Metal Halides in Anhydrous Acetic Acid

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Institut für Anorganische Chemie der Universität Saarbrücken (Germany)

If pure acetyl chloride is added slowly (about 0.2 ml per min) to 100 ml of a 0.1 M solution of lead acetate in anhydrous acetic acid, minima in the specific conductivity of the solution are observed at Pb:Cl molar ratios of 1:1 and 1:2 corresponding to the formation of lead acetate chloride and lead dichloride, respectively.

$$(CH_3COO)_2Pb + CH_3COCl \rightarrow (CH_3COO)PbCl + (CH_3CO)_2O$$

$$(CH_3COO)PbCl + CH_3COCl \rightarrow PbCl_2 + (CH_3CO)_2O$$

Pure lead acetate chloride can he prepared by interrupting the reaction at the first conductivity minimum. The colorless precipitate is filtered off, washed with anhydrous acetic acid, and dried over solid sodium hydroxide in a vacuum desiccator. In this way, lead acetate chloride monoacetic acid-solvate $(CH_3COO)PbCl \cdot CH_3COOH$ is obtained in over 90 % yield. This product releases its acetic acid of crystallization at 120 °C to give lead acetate chloride $(CH_3COO)PbCl$, which decomposes at about 270 °C to basic lead chloride Pb_2OCl_2.

Lead acetate bromide can be obtained similarly at 60 °C and decomposes at about 300 °C to lead oxide bromide. Solvated lead acetate hromide is not formed under these conditions. Lead acetate iodide cannot be made in this way.

The iodides PbI_2, AgI, HgI_2, $Ag_2(HgI_4)$, CuI, and CdI_2 are all highly insoluble in anhydrous acetic acid and can be obtained in quantitative yields by adding a stoichiometric amount of acetone plus the calculated amount of iodine in acetic acid dropwise to solutions of the acetates of these metals in anhydrous acetic acid at 70–80 °C. Silver iodide is precipitated even without addition of acetone.

$$n\,CH_3COCH_3 + n\,I_2 + (CH_3COO)_nM \rightarrow MI_n + n\,CH_3COCH_2I + n\,CH_3COOH$$

The precipitation of lead iodide is very slow at room temperature (30 % conversion after 40 h), but the rate can be almost doubled by passing an alternating current (220 volts between Pt or Ag electrodes) through the solution containing acetic acid, acetone, iodine, and lead(II) acetate. The current density increases to a maximum of 3.3 amp/dm² during the first 3 h and then falls to about 1.6 amp/dm² during the next 30 h.

Thermochromic $Ag_2(HgI_4)$ is obtained at 70–80 °C from a 2:1.3 mixture of silver and mercury acetates. The yellow modification of HgI_2 is formed from mercury(II) acetate alone in anhydrous acetic acid at 118.1 °C. Crystals about 0.5 mm long are obtained which can be kept for a few days (metastable) if quenched rapidly to room temperature.

This new method is especially suitable for the preparation of cadmium iodide. A solution of iodine in acetic acid is added dropwise to a hot solution of $Cd^{2\oplus}$ in acetic acid/acetone until the color of the iodine persists. The yield is quantitative and the product is very pure.

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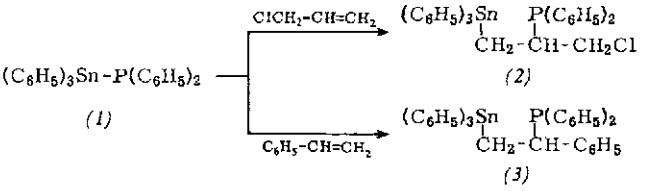
Addition of Diphenyl(triphenylstannyl)phosphine to Multiple Bonds

By Dr. H. Schumann, Dr. P. Jutzi, and Prof. Dr. Max Schmidt

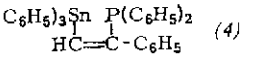
Institut für Anorganische Chemie der Universität Marburg (Germany)

Diphenyltriphenylstannylphosphine *(1)* [1] reacts with allyl chloride or styrene in boiling benzene to afford 3-chloro-2-diphenylphosphino-1-triphenylstannylpropane *(2)*, m.p. 39 °C, or 2-diphenylphosphino-2-phenyl-1-triphenylstannylethane *(3)*, m.p. 59 °C, respectively.



Reaction of phenylacetylene with even a great excess of *(1)* stops at the stage 2-diphenylphosphino-2-phenyl-1-triphenylstannylethylene *(4)*, m.p. 45 °C.

After the solvent has been distilled off, compounds *(2)*, *(3)*, and *(4)* crystallize readily (by scratching) from pentane and can be recrystallized from benzene/pentane. Before this crystallization, unchanged *(1)* is oxidized by prolonged stirring in air to the insoluble triphenyltin diphenylphosphinate which is filtered off.



(4)

We assume a free-radical reaction mechanism, by analogy with hydrostannylation [2]. This is in line with the considerable increases in yield that result on addition of small amounts of azobisisobutyronitrile:

(2): 26 % → 65 %; *(3)*: 16 % → 68 %; and *(4)*: 21 % → 78 %.

Mixtures of isomers were not found in these reactions, even on use of chromatography. The structures given follow from the consideration that the bulky triphenylstannyl group will add preferentially at the terminal-carbon end of the double bond. NMR spectroscopy gave no structural indication. The extraordinarily high solubility of *(2)*, *(3)*, and *(4)* in benzene, pyridine, and carbon disulfide nevertheless did not suffice to permit detection of the Sn- and P-linked protons on aliphatic carbon atoms in ^1H–NMR spectra alongside the 25 or 30 protons of the phenyl nuclei. Moreover, the Sn– and P–NMR spectra were extremely complicated by numerous couplings and could not be interpreted.

Received: July 12th, 1965 [Z 50/876 IE]
German version: Angew. Chem. 77, 912 (1965)

[1] *H. Schumann, H. Köpf,* and *M. Schmidt,* J. organomet. Chem. 2, 159 (1964).

[2] *W. P. Neumann,* Angew. Chem. 76, 849 (1964).

N-Methyl-3,4,5-tricyanopyridinium Perchlorate, a Pyridinium Salt of Extremely High Electron Affinity [1]

By Prof. Dr. K. Wallenfels and Dipl.-Chem. W. Hanstein

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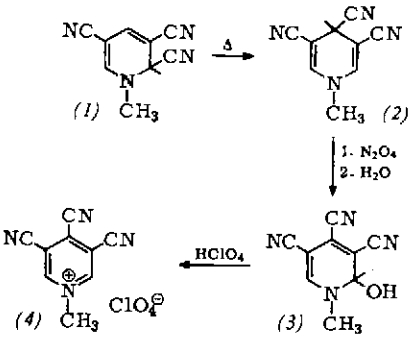
The anion affinity of pyridinium salts is greatly increased by the introduction of electron-attracting substituents [2]. The phenomenon is most readily examined by measuring the equilibrium constants of the reaction

$$\overset{\oplus}{Py} + \overset{\ominus}{CN} \rightleftharpoons PyCN$$

for the various pyridinium derivatives. The redox potentials of the pyridinium salt/dihydropyridine system are directly proportional to the logarithms of the cyanide ion affinities. We have synthesized a pyridinium salt *(4)* of extremely high

anion and electron affinity by the following route. 3,5-Dicyanopyridine is fused and methylated with methyl *p*-toluenesulfonate for 4 h at 110 °C. The *N*-methylpyridinium

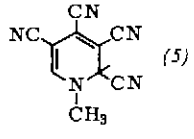


p-toluenesulfonate (90 % yield) is treated with KCN to give the 2-cyanide adduct *(1)* in 80 % yield, which when heated in the melt at 125 °C or in dimethylformamide at 150–160 °C, is converted in 95 % yield into the 4-isomer *(2)*. The latter is suspended in carbon tetrachloride and oxidized for 12 h at 25 °C (90 % yield) with excess N_2O_4. The solvent and reagent are removed in vacuum, the residue is stirred with water, and the *(3)* formed filtered off. Compound *(3)* is then dissolved in acetonitrile, and $HClO_4$ and ether are added. The perchlorate *(4)* crystallizes in the form of long thin needles in 70 % yield.

The *N*-methyl-3,4,5-tricyanopyridinium cation *(4)* is a strong π-acid. It forms intensely colored charge-transfer complexes with anisole (red, λ_{max} = 475 mμ), hexamethylbenzene (red, 505 mμ), and pyrene (green, 620 mμ). The salt *(4)* reacts as a Lewis acid with 2 moles of 9-fluorenol in acetonitrile within 12 h at 25 °C to yield di-9-fluorenyl ether (9 %) and the adduct *(3)*.

Anisole is acetylated in acetonitrile in the presence of the salt *(4)* to give 34 % *p*-methoxyacetophenone, which was isolated as the 2,4-dinitrophenylhydrazone.

The cation *(4)* combines with hydroxide and cyanide ions to form the adducts *(3)*, pK_a = −14.5 [3], and *(5)*, pK_a = −14.9 [3], respectively, which are both extremely resistant to acids.

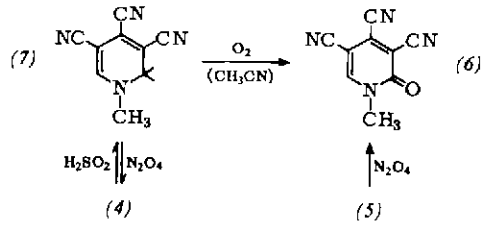


(5)

The salt *(4)* also acts as an oxidizing agent. In the reaction with 9-fluorenol described above, 8 % fluorenone can be isolated in the form of its 2,4-dinitrophenylhydrazone after 6 days at 25 °C. This is therefore the first model system for the enzymatic dehydrogenation of an alcohol by a pyridinium salt.

When solutions of *(4)* and *p*-bisdimethylaminobenzene in acetonitrile are mixed, a deep blue solution is formed in which Wurster's blue can be detected.

So far the primary reduction product formed from the pyridinium salt has not been isolated from any oxidation; it appears to be readily oxidized by oxygen. The product obtained is *N*-methyl-3,4,5-tricyano-2-pyridone *(6)*, which can also be made by oxidation of *(5)* with nitric oxide. The sensitivity of the primary reduction product towards air suggests that it is a pyridyl radical or the dihydropyridine derivative *(7)*. Compound *(7)*, which can be made by reduction of *(4)* in acidic solution, is also converted to the pyridone *(6)* when its solution in acetonitrile is left standing in air. A free pyridyl radical is formed as an intermediate in this oxidation; the hyperfine structure of its characteristic electron-spin resonance spectrum is being investigated. A free radical with a very similar ESR spectrum is produced on reduction of *(4)* with zinc in acetonitrile. The formation of free radicals of this type during the reduction of pyridinium cations containing substituents capable of mesomerism has already been observed [4].



	M. p. [°C]	λ_{max} [mμ]	log ε
(1)	118–120	350	3.95 (CH_3OH)
		246	3.92
(2)	168–169.5	359	3.87 (CH_3OH)
(3)	130–131.5	384	3.93 (H_2O)
		261	3.76
(4)	190–191	313	3.71 ($H_2O/HClO_4$)
(5)	144–150	418	3.84 (CH_3CN)
		263	3.60
(6)	206–207.5	372	3.90 (CH_3OH)
(7)	decomp. above 170 °C	—	—

Received: July 16th, 1965 [Z 37/863 IE]
German version: Angew. Chem. 77, 861 (1965)

[1] The Mechanism of Hydrogen Transfer by Pyridine Nucleotides, Part 27. Part 26: *K. Wallenfels* and *B. Müller-Hill*, Biochem. Z. *339*, 352 (1964).

[2] *K. Wallenfels* and *H. Diekmann*, Liebigs Ann. Chem. *621*, 166 (1959).

[3] The pK values were determined from the pH-dependent intensity of the bands at 384 mμ for *(3)* and 418 mμ for *(5)*.

[4] *K. Wallenfels* and *M. Gellrich*, Liebigs Ann. Chem. *621*, 198 (1959); *E. M. Kosower* and *E. J. Poziomek*, J. Amer. chem. Soc. *86*, 5515 (1964).

Synthesis of Tetrakistrifluorophosphinoiridium Hydride and the Proton Magnetic Resonance Spectra of the Hydrides $HM(PF_3)_4$ (M = Co, Rh, Ir) [1]

By Priv.-Doz. Dr. Th. Kruck and Dipl.-Chem. W. Lang

Anorganisch-Chemisches Laboratorium der Technischen Hochschule München (Germany)

Tetrakistrifluorophosphinoiridium hydride, $HIr(PF_3)_4$, has now been made in 86 % yield analogously to the corresponding derivatives of cobalt [2] and rhodium [3], but using a temperature of 260 °C and a PF_3 pressure of 1000 atm. The new compound is a colorless, mobile, extremely volatile liquid with a choking odor and boils at 95 °C/725 mm; the solid melts at −39 °C. It is surprisingly stable towards heat and starts to decompose only above 245 °C; it is unaffected by air. It dissolves to a small extent in water; its solution is acidic.

$HIr(PF_3)_4$ reacts with potassium amalgam in ether to form potassium tetrakistrifluorophosphinoiridate(−I), $K[Ir(PF_3)_4]$, which crystallizes readily to a colorless solid. This salt can be kept for weeks in dry air and decomposes under nitrogen only above 240 °C. It is readily soluble in ether, acetone, tetrahydrofuran, and water; its aqueous solution is slightly alkaline.

The infrared spectrum of $HIr(PF_3)_4$ vapor [4] contains P–F stretching vibrations at 965 (w–m), 925 (vs), 910 (s, shoulder), and 877 (vs) cm^{-1}. In the spectrum of the tetrakistrifluorophosphinoiridate(-I) these bands are shifted to much longer wavelengths on account of the greater π-bond character of the metal-phosphorus bond, which reduces the double-

bond nature of the P–F bonds; absorptions are observed at 830 (vs) and 811 (s, shoulder) cm^{-1} in acetone. The tetrakistrifluorophosphinoiridate anion is isoelectronic and apparently also isosteric (T_d) with tetrakistrifluorophosphinoplatinum(0) [5].

The proton magnetic resonance spectrum of $HIr(PF_3)_4$ [6] is centered around $\delta = 11.93 \times 10^{-6}$ relative to tetramethylsilane as internal standard. As a result of the coupling of the proton spin with the spins of the four ^{31}P and twelve ^{19}F nuclei, the proton signal is split into 65 lines, some of which lie very close together (see Figure); $J_{P-H} = 31.0 \pm 0.1$ cps, and $J_{F-H} = 14.93 \pm 0.04$ cps. Coupling with the ^{191}Ir and ^{193}Ir nuclei does not occur on account of the high quadrupole moment of these isotopes.

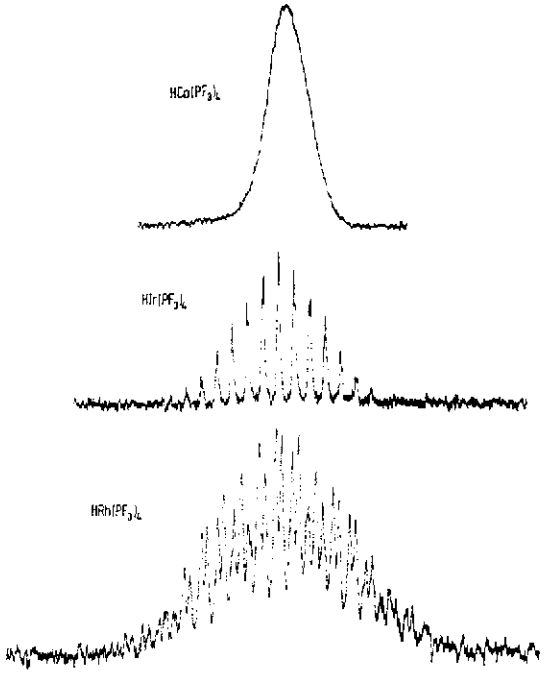


Fig. 1. ^1H—NMR spectra of $HCo(PF_3)_4$, $HRh(PF_3)_4$, and $HIr(PF_3)_4$.

The proton magnetic resonance signal in the NMR spectrum of $HRh(PF_3)_4$ is split into 130 lines since all of the nuclei present in this molecule have a spin quantum number of $^1/_2$. In contrast, despite the comparable quadrupole moments of Ir and Co, the proton signal of $HCo(PF_3)_4$ is merely broadened out over about 130 cps. Measurements at temperatures down to −80 °C gave no indication of any fine structure in the NMR spectrum of $HCo(PF_3)_4$ due to the presence of the P and F nuclei. However, the resemblance of the infrared spectrum of $HCo(PF_3)_4$ and those of $HRh(PF_3)_4$ and $HIr(PF_3)_4$ precludes the possibility that there is any fundamental difference between the structures of these three hydrides.

Received: July 16th, 1965 [Z 30/855 IE]
German version: Angew. Chem. 77, 860 (1965)

[1] Trifluorophosphinometal Complexes, Part XI. — Part X: *Th. Kruck*, *W. Lang*, and *N. Derner*, Z. Naturforsch. *20b*, 705 (1965). We thank the Deutsche Forschungsgemeinschaft and the Badische Anilin- und Sodafabrik for supporting this work.

[2] *Th. Kruck*, *W. Lang*, and *A. Engelmann*, Angew. Chem. *77*, 132 (1965); Angew. Chem. internat. Edit. *4*, 148 (1965).

[3] In collaboration with *N. Derner*.

[4] The infrared spectra were taken on a Perkin-Elmer Model 21 spectrophotometer. — s = strong, vs = very strong, w = weak, m = medium.

[5] *Th. Kruck* and *K. Baur*, Angew. Chem. *77*, 505 (1965); Angew. Chem. internat. Edit. *4*, 521 (1965).

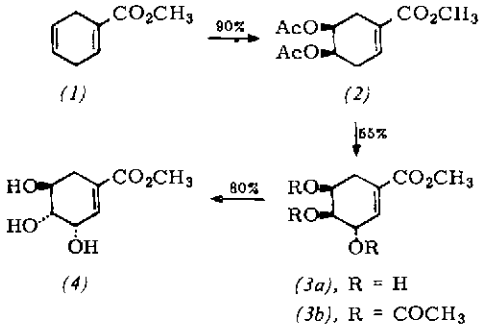
[6] The NMR spectra were kindly measured by Dr. *K. Schwarzhans* on a Varian A60 instrument using the pure liquids at 22 °C and $HCo(PF_3)_4$ at −60 °C.

A Simple Synthesis of Shikimic Acid

By Prof. Dr. R. Grewe and Dipl.-Chem. S. Kersten

Institut für Organische Chemie der Universität Kiel (Germany)

Previous syntheses of shikimic acid [1] gave very poor yields. We have now found that the configuration *(3)* is easy to construct and that it can be rearranged to that of methyl shikimate *(4)*. This method constitutes the first preparatively useful synthesis of shikimic acid. No chromatographic purifications are required at any step: the crystalline methyl esters *(3a)* and *(4)* are obtained directly in high purity and are free from isomers.



The starting material *(1)* is readily obtainable by a diene synthesis from butadiene and methyl propiolate [1]. On treatment with silver acetate plus iodine in aqueous acetic acid [2], *(1)* gives a partially acetylated *cis*-diol, which on heating with 4 % methanolic hydrochloric acid and subsequent treatment with acetic anhydride/pyridine is transformed into methyl 4,5-*cis*-diacetoxycyclohex-1-ene-1-carboxylate *(2)*, b.p. 140 °C/0.005 mm. Treatment of *(2)* successively with *N*-bromosuccinimide for 30 min in refluxing carbon tetrachloride, with excess potassium acetate for 3 h in refluxing acetic acid, and with refluxing methanolic hydrochloric acid leads to *(3a)*, m.p. 155 °C from ethyl acetate. Acetylation of *(3a)* with acetic anhydride/pyridine converts it quantitatively into *(3b)*, b.p. 150 °C/0.005 mm. When *(3b)* is hydrolysed with liquid hydrogen fluoride for 24 h [3] and re-esterified with methanolic hydrochloric acid, (±)-methyl shikimate *(4)*, m.p. 172 °C, is formed.

Received: July 18th, 1965 [Z 31/856 IE]
German version: Angew. Chem. 77, 859 (1965)

[1] For references see *R. Grewe* and *I. Hinrichs*, Chem. Ber. *97*, 443 (1964).

[2] *Woodward*'s adaptation of the Prevost method: *R. B. Woodward* and *F. V. Brutcher*, J. Amer. chem. Soc. *80*, 209 (1958).

[3] *E. J. Hedgeley* and *H. G. Fletcher*, J. Amer. chem. Soc. *84*, 3726 (1962).

The Mechanism of the Formation of Quinones from Monophenols with Dipotassium Nitrosobissulfate

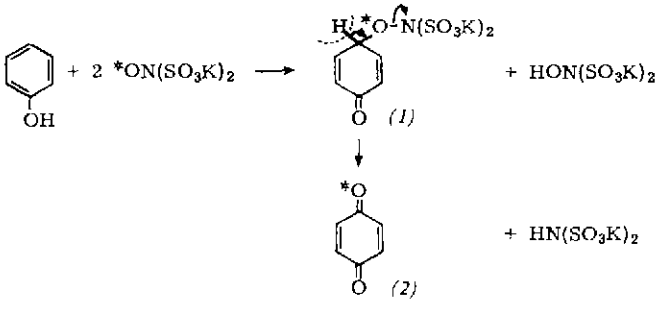
By Prof. Dr. H.-J. Teuber and Dipl.-Chem. K. H. Dietz

Institut für Organische Chemie der Universität Frankfurt/Main (Germany)

Dipotassium nitrosobissulfate $(KSO_3)_2NO$ introduces a new oxygen function in the *ortho*- or *para*-position of phenols. The products formed are a quinone, *e.g. (2)*, plus dipotassium hydroxyimidobissulfate and dipotassium imidobissulfate [1].

If the assumption is correct that quinitrol-like intermediates, *e.g. (1)*, are formed during this reaction, then the new oxygen atom in the quinone *(2)* must be derived from the nitrosobissulfate and not from the solvent (*e.g.* water, alcohol, or acetone) [2]. Oxydation of 2,6-dimethylphenol to 2,6-di-

methyl-1,4-benzoquinone with dipotassium nitrosobissulfate in which the nitroso group was labelled with ^{18}O revealed that the label did in fact recur to 97 % in the new oxygen function of the quinone. The nitroso group does not exchange its oxygen with that of the solvent under the conditions selected. 2,6-Dimethyl-1,4-benzoquinone undergoes a slight, temperature-dependent isotope exchange only above 0 °C.



The formation of *o*-quinones also corresponds to the preceding scheme. However, the labelling, *e.g.* of 3.4-dimethyl-1.2-benzoquinone [3], is somewhat smaller (65–70 %) since the isotope exchange is favored compared with that of *p*-quinones.

Received: July 19th, 1965 [Z 33/858 IE]
German version: Angew. Chem. 77, 913 (1965)

[1] *H.-J. Teuber* and *W. Rau*, Chem. Ber. *86*, 1036 (1953).

[2] The nature of the inorganic by-products of the phenol oxidation indicates that the SO_3 groups do not act as oxygen donor, as was confirmed by labelling experiments.

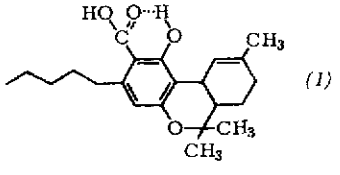
[3] *H.-J. Teuber* and *G. Staiger*, Chem. Ber. *88*, 802 (1955).

Tetrahydrocannabinolcarboxylic Acid, a Component of Hashish [1]

By Prof. Dr. F. Korte, Dipl.-Chem. M. Haag, and Dr. U. Claussen

Organisch-Chemisches Institut der Universität Bonn (Germany)

Hashish extract [2] was separated into 7 fractions by countercurrent distribution using ligroin/methanol/dimethylformamide/water (10:8:1:2 v/v). Fraction VII was separated by a further 550 transfers with the same solvent system into two components, one of which is tetrahydrocannabinolcarboxylic acid *(1)*. This compound is the missing link in the scheme for the biosynthesis of the active principles of hashish [3].



(1)

The pure acid *(1)* could not be crystallized. Its ultraviolet spectrum in cyclohexane contains three maxima at 308 (ε = 4642), 278 (1426), and 223 mμ (1795). The hydroxyl band in its infrared spectrum is broadened owing to hydrogen bonding and occurs at 3600 cm^{-1} (shoulder) and 3500 cm^{-1} (shoulder); the carbonyl absorption is at 1680 and 1655 cm^{-1}. The specific optical rotation of the acid *(1)* is $[\alpha]_D^{20} = -206.8°$ (c = 5.0 in chloroform).

The NMR spectrum [4] of *(1)* has differences from that of tetrahydrocannabinol which characterize the position of the carboxyl group. The protons of the phenolic hydroxyl and the carboxyl group give a broad signal at τ = −1.15 which disappears on shaking *(1)* with D_2O. The signal for the phenolic proton in the spectrum of *(1)* appears at a lower field than that of the corresponding resonance in the spectrum of tetrahydrocannabinol owing to the hydrogen bond between the two *ortho*-substituents. Integration gives values corresponding to one proton each for the benzene ring (τ = 3.86) and for the double bond in the cyclohexene ring (τ = 3.54). The singlet for the olefinic proton is broadened by slight coupling with the single proton on the neighboring carbon atom.

The position of the carboxyl group is also confirmed by the fact that the n-amyl protons next to the benzene ring give rise to a triplet in the NMR spectrum of tetrahydrocannabinol but appear as a multiplet 30 c.p.s. lower in the spectrum of *(1)*. Otherwise the NMR spectrum of *(1)* is identical with that of tetrahydrocannabinol.

The acid *(1)* is rapidly decomposed by light and heat and instantaneously forms red decomposition products on active surfaces, *e.g.* in thin-layer chromatography. Brief treatment with very dilute alkali at room temperature suffices to convert *(1)* into two cannabiscarboxylic acids.

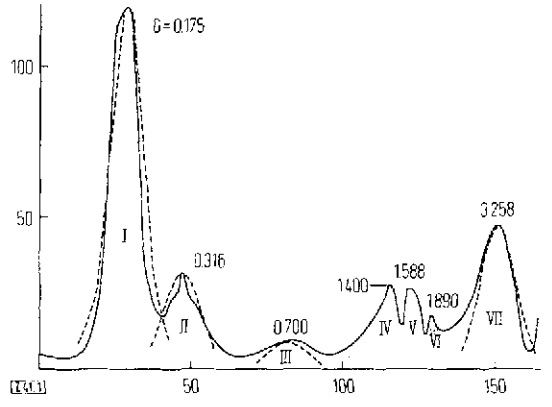


Fig. 1. Distribution of hashish extract: —— experimental curve, –––– theoretical curve. The G-values are the distribution numbers for I: cannabidiolcarboxylic acid, m.p. 45–49 °C, II: cannabidiol, III: cannabinol, IV, V, and VI: tetrahydrocannabinols, VII: tetrahydrocannabinolcarboxylic acid *(1)* and a second substance.
Ordinate: mg of substance; abscissa: fraction number.

Received: July 19th, 1965 [Z 41/866 IE]
German version: Angew. Chem. 77, 862 (1965)

[1] Chemical Classification of Plants, Part 28, and Investigations of Hashish, Part 7. Part 6: *U. Claussen*, *W. Borger*, and *F. Korte*, Liebigs Ann. Chem., in press.

[2] Hashish was pulverized and then homogenized with petroleum ether (b.p. 60–95 °C.) The homogenate was filtered, the residue was extracted repeatedly with petroleum ether and the collected samples were evaporated to dryness at a water aspirator.

[3] *L. Grlic*, Narcotics *16*, (4), 29 (1964).

[4] Measured in CCl_4 at 90 Mc/s with tetramethylsilane as internal standard.

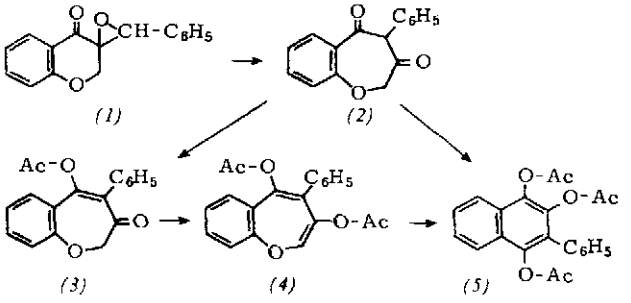
Synthesis of 4-Arylbenzo[b]oxepin Compounds and their Rearrangement to Naphthalene Derivatives

By Dr. Hans Hofmann

Institut für Organische Chemie der Universität Erlangen (Germany)

On treatment of spiro-[4-chromanone-3,2'-(3'-phenyloxirane)] *(1)* [1] with concentrated sulfuric acid or boron trifluoride etherate in benzene or on adsorption on acidic aluminum oxide of activity grade I, a 75 % yield of 4-phenyl-2,3,4,5-tetrahydrobenzo[*b*]oxepin-3,5-dione *(2)*, m.p. 99–101 °C, is formed. This compound is isolated by pouring the mixture into ice-water or removal of the solvents in vacuum, respectively, followed by crystallization from methanol.

The infrared spectrum of *(2)* in KBr or Nujol and its NMR spectrum [2] in $CDCl_3$ indicate that in the solid state and in non-polar solvents it is present in the form of the diketone *(2)* and not as 3,5-dihydroxy-4-phenylbenzo[*b*]oxepin. Acetylation of *(2)* with acetic anhydride in pyridine at *ca.* 20 °C leads to 5-acetoxy-4-phenyl-2,3-dihydrobenzo[*b*]oxepin-3-one *(3)*, m.p. 125–127 °C, which on further acetylation for 24 h at 86–87 °C gives rise to 3,5-diacetoxy-4-phenylbenzo[*b*]-oxepin *(4)*, m.p. 133.5–135 °C.



When *(2)*, *(3)*, or *(4)* are refluxed with sodium acetate in acetic anhydride for 8 h each is converted in good yield into 1,2,4-triacetoxy-3-phenylnaphthalene *(5)* [3].

In view of the oxepin ↔ benzene oxide valence-bond tautomerism [4], it is assumed that a 4,10-epoxy-4,10-dihydronaphthalene is formed by valence-bond tautomerism from *(2)* and *(4)* and by deprotonation of *(3)* and then rearranges to 2,4-diacetoxy-1-hydroxy-3-phenylnaphthalene, which is acetylated to *(5)* [5].

The same reactions were also carried out with spiro{7-methoxy-4-chromanone-3,2′-[3′-(3,4-dimethoxyphenyl)-oxirane]} [1].

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German version: Angew. Chem. 77, 864 (1965)

[1] *O. Dann* and *H. Hofmann*, Chem. Ber. *95*, 1446 (1962).

[2] The NMR measurements were kindly carried out by Dr. *H. Friebolin*, Freiburg (Germany).

[3] *D. Radulescu* and *Ch. Gheorgiu*, Ber. dtsch. chem. Ges. *60*, 186 (1927).

[4] *E. Vogel*, *W. A. Böll*, and *H. Günther*, Tetrahedron Letters *1965*, 609.

[5] *R. Huisgen*, *E. Laschtuvka*, *I. Ugi*, and *A. Kammermeier*, Liebigs Ann. Chem. *630*, 128 (1960) give a similar formulation for the conversion of benzo[*d*]oxepin-2,4-dicarboxylic acid into 2-hydroxy-3-naphthoic acid.

Benzo-1,3-dioxolium Salts

By Prof. Dr. K. Dimroth, Dipl.-Chem. P. Heinrich, and Dr. K. Schromm

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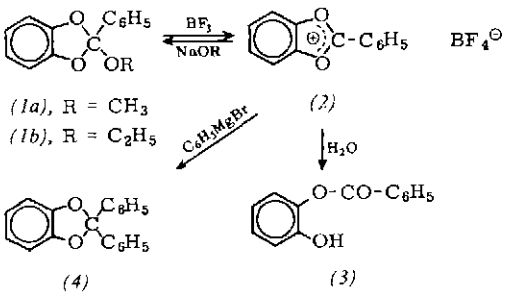
The 1,3-dioxolium cation should as a cyclic 6π-electron system have a certain stability, but in contrast to 1,3-dithiolium salts [1], none of its salts have been reported.

We have now prepared 2-phenylbenzo-1,3-dioxolium fluoroborate *(2)*, the first 1,3-dioxolium salt. The crystalline compound decomposes at 150–160 °C with evolution of gas and formation of a red residue. It is obtained in 60 % yield by treatment of a 2-alkoxy-2-phenylbenzo-1,3-dioxolane *(1a)* or *(1b)* with BF_3 or HBF_4/ether in dichloromethane. The starting material *(1)* is obtained in 68 % yield by heating catechol and a trialkyl orthobenzoate at 170–180 °C. The methoxy compound *(1a)* boils at 112–113 °C/0.5 mm, the ethoxy derivative *(1b)* at 115–116 °C/0.5 mm; both are liquids with an ester-like odor.



Compound *(2)* is readily decomposed by traces of water, which attacks at C-2 and opens the 1,3-dioxolium ring to yield the monobenzoate of catechol *(3)*. Treatment with sodium methoxide or ethoxide reconverts *(2)* into *(1a)* and *(1b)*, respectively, while reaction of *(2)* with phenylmagnesium bromide produces 2,2-diphenylbenzo-1,3-dioxolane *(4)* [2]. The latter reaction can be used to prepare catechol ketals with identical or different residues on C-2.

The NMR spectrum of *(2)* in acetonitrile contains a multiplet at 8.12 ppm and a weakly resolved doublet at 8.70 ppm relative to tetramethylsilane as internal standard. The proton signals in the spectrum of *(2)* are all shifted to lower fields than those in the spectra of *(1)*. The shift is 1.0 ppm for the *ortho*-protons in the 2-phenyl group and about 1.2 ppm for the protons on the benzo moiety, which together with the *meta*- and *para*-protons of the 2-phenyl group give rise to the multiplet.

2-Phenylnaphtho-1,3-dioxolium fluoroborate, m.p. 182 to 187 °C, was prepared analogously to *(2)* and exhibits chemical properties very similar to those of *(2)*.

Received: July 19th, 1965 [Z 32/857 IE]
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[1] *W. R. H. Hurtley* and *S. Smiles*, J. chem. Soc. (London) *1926*, 1821; *L. Soder* and *R. Wizinger*, Helv. chim. Acta *42*, 1733 (1959); *D. Leaver* and *W. A. H. Robertson*, Proc. chem. Soc. (London) *1960*, 252; *E. Klingsberg*, J. Amer. chem. Soc. *84*, 3410 (1962); *E. Campaigne* and *R. D. Hamilton*, J. org. Chemistry *293*, 2877 (1964).

[2] *S. McElvain* and *I. Venerable*, J. Amer. chem. Soc. *72*, 1661 (1950).

Synthesis and Reactions of Diarylmethylcarbonium Ions [1]

By Priv.-Doz. Dr. H. Volz and Dipl.-Chem. H. W. Schnell

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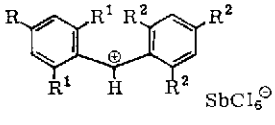
The reaction of diarylmethyl chlorides with antimony pentachloride at room temperature under nitrogen with exclusion of moisture [2] gives the diarylmethylcarbonium salts *(1)*–*(4)* which can be isolated by filtration.



	R	R^1	R^2	Color	Temperature of decomposition [°C]	λ_{max} [mμ] in CH_3NO_2
(1)	H	H	H	canary yellow	97–99	453
(2)	CH_3	H	H	yellow	86–87	459
(3)	CH_3	CH_3	H	carmine red	72–74	465
(4)	CH_3	CH_3	CH_3	red-violet	110–111	522

All the salts give satisfactory C, H, and Cl analyses and react with tropylidene to give the corresponding diarylmethanes and tropylium hexachloroantimonate [3]. The

salts *(1)–(3)* are rapidly decomposed by moisture, but *(4)* can be kept open to the air for several hours since its *ortho*-methyl groups shield the center of the positive charge.

The proton magnetic resonance spectra [4] of *(3)* and *(4)* in dichloromethane with tetramethylsilane as internal standard contain the following signals on the δ-scale: *(3)*, −9.68 (proton on the carbonium carbon), −7.84, −7.69, and −7.33 (benzene ring protons), −7.17 (mesitylene ring protons), and −2.58 (methyl protons); *(4)*, −9.69 (proton on the carbonium carbon), −7.15 (mesitylene ring protons), and −2.50 and −2.43 (methyl protons; relative intensity = 1:2). The methyl proton signals of *(4)* remain unchanged between −60 and +90 °C.

The infrared spectra of *(1)–(4)* in Nujol, Kel–F, or hexachlorobutadiene indicate a strong activation of the C=C vibrations, a reduction in the intensity and shift to higher frequencies in the γ-vibrational region, and a broad and very intense band in the CsBr range at 339 cm^{-1} due to the asymmetric stretching vibrations of the $SbCl_6^{\ominus}$ ion.

The strengths of the carbonium ions as acceptors for chloride ions were determined by reaction with the corresponding di- and triarylmethyl chlorides in carbon tetrachloride and chloroform and measurement of the yields of products. These increase along the series triphenylmethyl$^{\oplus}$<*(4)*<*(1)*,*(2)*<*(3)*. An equilibrium is attained in the reaction of *(4)* with triphenylchloromethane in chloroform which lies to 66–69 % on the side of triphenylmethyl hexachloroantimonate.

The salt *(1)* reacts with ethyl triphenylmethyl ether to yield benzhydryl ethyl ether. The reaction of *(1)* with water or 2 N sodium hydroxide gives mainly dibenzhydryl ether plus some benzhydryl chloride (from internal return of the chloride ion), benzophenone, and diphenylmethane (from hydride transfer between *(1)* and benzhydrol). If the salts are suspended in benzene and shaken with water or 2 N NaOH, *(1)* and *(3)* give diarylchloromethanes as main product together with some bisdiarylmethyl ether by reaction at the interface, but *(4)* yields exclusively dimesitylmethanol.

Aromatic compounds $R-C_6H_5$ are alkylated by *(1)* at room temperature by a Friedel-Crafts reaction *para* to the substituent R; the yields are: R=H, 22–29 %, R=CH_3, 40–42 %, and R=OCH_3, 61–65 %. The reaction of *(1)* with benzhydrol in benzene gives 93 % triphenylmethane, 6 % α,α,α′,α′-tetraphenyl-*p*-xylene, benzophenone, and diphenylmethane. The reaction of the salts with methanol or ethanol produces alkyl diphenylmethyl ethers.

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German version: Angew. Chem. 77, 864 (1965)

[1] Stable Carbonium Ions, Part 5. Part 4: *H. Volz*, Tetrahedron Letters *1964*, 1899.

[2] *H. Volz*, Angew. Chem. *75*, 921 (1963); Angew. Chem. internat. Edit. *2*, 622 (1963).

[3] *H. J. Dauben, L. R. Honnen*, and *K. U. Harmon*, J. org. Chemistry *25*, 1442 (1960).

[4] The spectra were kindly recorded by Dr. *H. A. Brune*.

Preparation of α-Methyl 2,3-O,O′-Isopropylidene-4,6-dideoxymannopyranosid-4-ene

By Dr. J. Lehmann

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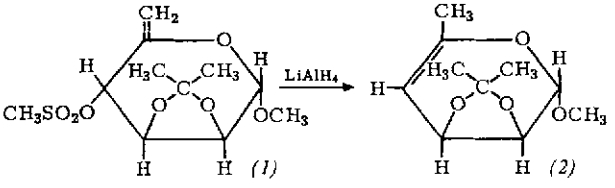
der Universität Freiburg (Germany)

α-Methyl 6-deoxy-2,3-*O*,*O*′-isopropylidenemannopyranosid-5-ene [1] in pyridine was cooled in ice and treated with methanesulfonyl chloride to form the 4-*O*-methanesulfonyl ester *(1)*. The reaction mixture was stirred into a saturated solution of $NaHCO_3$ at 0 °C, and the resultant solution was extracted with chloroform. The organic phase was dried with Na_2SO_4 and the chloroform distilled off. The sirupy residue of *(1)* obtained was processed immediately because it is rather unstable. Reduction with $LiAlH_4$ in ether for 30 min at room temperature gave a mobile oil which contained no sulfur or free hydroxyl groups. The excess $LiAlH_4$ was decomposed with water and the product extracted with chloroform. The extract was washed with water and dried over sodium sulfate, and the chloroform was evaporated off on a water-bath. The residual oil was taken up in low-boiling petroleum ether and the solution washed with water and dried. The solvent was evaporated off and the residue vacuum distilled (b.p. 93–96 °C/13 mm; $[\alpha]_{575}^{25}$ = −193 °, c = 1 in chloroform). The composition and NMR spectrum of the product indicate it to have the structure *(2)*.



The NMR signals for *(2)* at 60 Mc/s in CCl_4 with tetramethylsilane as internal standard are: isopropylidene protons τ = 9.10 ppm (3 H) and 9.02 (3 H); C-6 protons, τ = 8.63 (3 H); C-2 proton, 6.58 (triplet, 1 H); C-3 proton, 6.01 (approximated triplet, 1 H), C-1 proton, 5.90 (doublet, 1 H); C-4 proton, 5.70 (doublet, 1 H) OCH_3 protons, 6.93 (3 H). The coupling constants are $J_{1,2}$ = 5.5 c.p.s., $J_{2,3}$ = 5.5 c.p.s., $J_{3,4}$ = 4 c.p.s., $J_{4,6} \approx 1$ c.p.s., and $J_{3,6} \approx 1$ c.p.s.

Received: July 22nd, 1965 [Z 35/861 IE]
German version: Angew. Chem. 77, 863 (1965)

[1] *J. Lehmann* and *A. A. Benson*, J. Amer. chem. Soc. *86*, 4469 (1964).

Synthesis of α-Methyl [5-^{3}H]-D-Glucoside and β-Methyl [5-^{3}H]-L-Idoside by Hydroboration of Substituted Methyl Glucosidenes

By Dr. J. Lehmann

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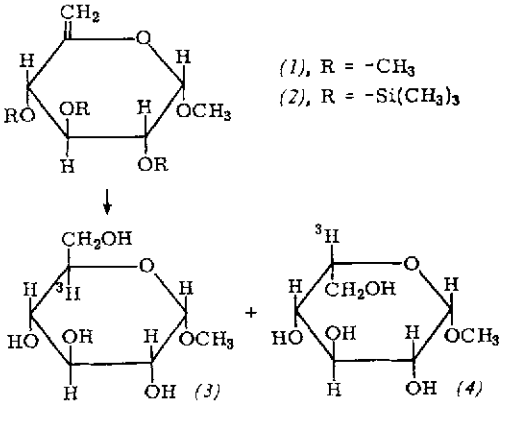
The trimethyl ether *(1)* and tristrimethylsilyl ether *(2)* of α-methyl D-glucopyranosid-5-ene [1] can be hydroborated by passing diborane into their solutions in tetrahydrofuran. This method can be used to achieve specific labelling of sugars with tritium or deuterium.

The reaction of *(1)* and *(2)* with [^{3}H]diborane [2] and subsequent removal of the protective groups lead respectively to 1:2 and 1:0.6 mixtures of α-methyl [5-^{3}H]-D-glucoside *(3)* and β-methyl [5-^{3}H]-L-idoside *(4)*.



For example, *(2)* is hydroborated for 2 h at *ca.* 20 °C and the excess diborane is decomposed with methanol. The solution is evaporated in vacuum to a sirup, which is mixed with

tenfold amounts of methanol and 30 % acetic acid and left for 4 h in order to remove the trimethylsilyl groups. This mixture is then shaken with chloroform, and the aqueous phase is evaporated to a sirup in vacuum. The latter is dissolved in five times its weight of 10 % sodium hydroxide. The solution is cooled in ice, and 10 % of its volume of 30 % hydrogen peroxide is added. After 3 h at room temperature, the sodium ions are removed with a Dowex 50 cation exchanger, and a trace of platinum oxide is added to decompose the excess peroxide. The aqueous solution is evaporated to dryness and the boric acid is removed by repeated distillation with methanol. The residue, which begins to crystallize, is taken up in a little hot ethanol; on cooling, *(3)* crystallizes out. The mother liquor is chromatographed on Whatman No. 4 paper with n-butanol/propionic acid/water (142:71:100 v/v, descending), and the zones of *(3)* and *(4)* at R_f 0.50 and 0.65 are cut out and eluted with water. The overall yield of *(3)* plus *(4)* is 85–90 %. The solution containing *(4)* is concentrated to a sirup and heated for 6 h with 1 N sulfuric acid on a steam-bath. Removal of the acid with an Amberlite IR 45 anion exchanger and concentration of the aqueous solution leads to [5-^{3}H]-L-idosan, which has the same paper- and gas-chromatographic properties as D-idosan [3]. It was proved by degradation [4] of *(3)* that the tritium is located on C-5.

Received: July 22nd, 1965 [Z 36/862 IE]
German version: Angew. Chem. 77, 863 (1965)

[1] *B. Helferich* and *E. Himmen*, Ber. dtsch. chem. Ges. *61*, 1825 (1928).

[2] Here ^{3}H implies a mixture of tritium with ordinary hydrogen.

[3] A sample of methyl α-D-idoside was kindly supplied by Prof. *T. Reichstein*, and a sample of D-idosan triacetate by Dr. *N. K. Richtmyer*.

[4] *H. Simon*, Z. Naturforsch. *18b*, 360 (1963); *H. Simon* and *J. Steffens*, Chem. Ber. *95*, 358 (1962).

Synthesis and Properties of Tantalum Oxide Nitride, TaON

By Prof. Dr. G. Brauer and Dr. J. R. Weidlein

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During the preparation of red tantalum nitride Ta_3N_5 [1] from Ta_2O_5 and NH_3, intermediates of various colors are encountered. We have now found that the changes in color are due to the transient formation of tantalum oxide nitride TaON. This compound is also formed in high purity by heating Ta_2O_5 or Ta_3N_5 in a current of ammonia containing a little moisture at about 800 °C.

Tantalum oxide nitride TaON is a yellow-green solid with $d = 10$ g/cm^3. Its monoclinic crystal structure is probably of the Baddeleyite (zirconium dioxide) type [2]; its lattice parameters are $a = 4.966$, $b = 5.034$, $c = 5.185$ Å, and $\beta = 99.65°$.

Received: July 28th, 1965 [Z 42/868 IE]
German version: Angew. Chem. 77, 913 (1965)

[1] *G. Brauer* and *J. R. Weidlein*, Angew. Chem. *77*, 218 (1965); Angew. Chem. internat. Edit. *4*, 241 (1965).

[2] *D. K. Smith* and *H. W. Newkirk*, Acta crystallogr. *18*, 983 (1965).

Infrared Spectroscopic Investigations on Methylenetriphenylphosphoranes

By Prof. Dr. W. Lüttke and Dipl.-Chem. K. Wilhelm

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For an understanding of the Wittig reaction it is important to know the type of bonding present in methylenetriphenylphosphoranes, and in particular whether the substances are better described by the ylene formula *(1)* or by the ylide formula *(2)*. The type of bonding between the phosphorus and the methylene-carbon should be recognisable on comparison of the P–C stretching frequency in the vibration spectrum with that of methyltriphenylphosphonium ion (P–CH_3 single bond).

$(C_6H_5)_3P{=}CH_2$ *(1)* $\qquad$ $(C_6H_5)_3\overset{\oplus}{P}\ \overset{\ominus}{C}H_2$ *(2)*

We have studied the infrared spectra of methyltriphenylphosphonium iodide *(3)*, methylenetriphenylphosphorane *(4)*, phenacyltriphenylphosphonium bromide *(5)* and phenacylidenetriphenylphosphorane. In order to recognize the P–C stretching frequency among the multiplicity of bands [*(4)* has 37 atoms and thus 105 normal vibrations], we labeled the compounds *(3)*–*(6)* in the methylene group with ^{13}C or D. Thereby the frequencies of those vibrations in which the labeled atoms partake are shifted whereas the frequencies of all the other vibrations of the molecule remain almost unchanged [1]. The labeled compounds were crystallized and were examined spectroscopically as suspensions in Nujol with careful exclusion of air and moisture. Table 1 shows the results. These indicate that the PC bond orders

Table 1. P–C stretching frequencies [cm^{-1}] for compounds *(3)*–*(6)*.

	^{12}C	^{13}C	D
(3) $Ph_3P^{\oplus}CH_3I^{\ominus}$	787	776	763
(4) Ph_3PCH_2	899	884	832
(5) $Ph_3P^{\oplus}{-}CH_2{-}CO{-}PhBr^{\ominus}$	823	–	784
(6) $Ph_3PCH{-}CO{-}Ph$	887	857	?

of the methylenephosphoranes *(4)* and *(6)* are only slightly higher than those of the corresponding quaternary salts *(3)* and *(5)*.

Among P–O and P–N compounds, substantially larger differences are found between compounds with single and double bonds than among the P–C compounds (Table 2).

Table 2. Bond frequencies [cm^{-1}] for compounds with single or double bonds between phosphorus and oxygen, nitrogen, or carbon.

	X = O [2]	X = NH [3]	X = CH_2
P=X	1270–1170	1350–1200	900
	X = OH [4]	X = NH_2 [5]	X = CH_3
P–X	950–1000	870–750	790–775

The remarkably small differences in frequency of the P–C vibrations of methylenephosphoranes and the corresponding quaternary salts show that the bond between phosphorus and methylene-carbon in methylenephosphoranes has only slight double-bond character. With the equation for a diatomic harmonic oscillator, the following force constants were calculated from the P–C frequencies: *(3)*, 3.6 mdyne/Å; *(4)*, 4.9 mdyne/Å. From *H. Siebert*'s rules [6] a rough estimate leads to 1.3 for the bond order in *(4)*. Thus, if one assumes resonance between the ylene form *(1)* and the ylide form *(2)* of methylenephosphoranes, then according to the spectroscopic findings the latter form preponderates.

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German version: Angew. Chem. 77, 867 (1965)

[1] *R. Kübler*, *W. Lüttke*, and *S. Weckherlin*, Z. Elektrochem. *64*, 650 (1960); *S. Weckherlin* and *W. Lüttke*, ibid. *64*, 1228 (1960); *R. Kübler* and *W. Lüttke*, Ber. Bunsenges. physik. Chem. *67*, 2 (1963); *S. Weckherlin* and *W. Lüttke*, Tetrahedron Letters *1964*, 1711; *G. Schroeder*, Diploma Thesis, Universität Göttingen 1964.

[2] *M. Halman* and *S. Pinchas*, J. chem. Soc. (London) *1958*, 3264.

[3] *W. Wiegräbe*, Dissertation, Universität München, 1964.

[4] *L. C. Thomas* and *R. A. Chittenden*, Spectrochim. Acta *20*, 467 (1964).

[5] *H. Sisler* and *N. L. Smith*, J. org. Chemistry *26*, 611 (1961).

[6] *H. Siebert*, Z. anorg. allg. Chem. *273*, 170 (1953).

The 2,2,2-Trichloroethyl Group as a Protecting Group for Phosphate in the Synthesis of Mononucleotides

By Dr. F. Eckstein

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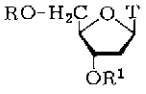
In order to avoid the formation of diesters during the preparation of mononucleotides, the nucleoside to be phosphorylated is condensed with a primary phosphate whose ester group is readily split off. We found that 2,2,2-trichloroethyl phosphate, $CCl_3CH_2OPO(OH)_2$ *(1)* [1], is stable in acidic and alkaline media and can be cleaved by reduction. This ester is obtained by reaction of 2 moles of 2,2,2-trichloroethanol with 0.1 mole of tristriethylammonium phosphate for 2.5 h at 60 °C in 2 moles of trichloroacetonitrile as condensing agent [2] and isolated by converting the free acid into its cyclohexylammonium salt, which is recrystallized from a 1:1 dioxane/ethanol mixture. The cyclohexylammonium salt of *(1)* melts at 194–199 °C; the yield is 46%.



(2), R = H, $R^1 = CH_3CO-$

(3), R = H, $R^1 = C_6H_5CO-$

(2a), R = $-PO(OH)OR^2$, $R^1 = CH_3CO-$

(3a), R = $-PO(OH)OR^2$, $R^1 = C_6H_5CO-$

(4), R = $-PO(OH)_2$, $R^1 = CH_3CO-$

(5), R = $-PO(OH)_2$, $R^1 = H$

(6), R = $-PO(OH)OR^2$, $R^1 = H$

$R^2 = -CH_2CCl_3$, T = Thymyl

Either 1 mole of 3′-*O*-acetylthymidine *(2)* or 1 mole of 3′-*O*-benzoylthymidine *(3)*, m.p. 96–100 °C, was condensed with 2.5 moles of *(1)* in the presence of 5 moles of dicyclohexylcarbodiimide in pyridine for 72 h at room temperature. Chromatography on a layer of silica gel [PF 254, Merck, Darmstadt (Germany)] 0.2 mm thick with chloroform/methanol (6:4 v/v) yielded the esters *(2a)* and *(3a)* in 90 and 75% yield, respectively. The cyclohexylammonium salt of *(2a)* melts at 120–124 °C, that of *(3a)* at 236–238 °C. The ester *(2a)* is also obtained in 80% yield by condensation of 1 mole of 3′-*O*-acetylthymidine-5′-phosphoric acid *(4)* with 5 moles of trichloroethanol in the presence of 5 moles of dicyclohexylcarbodiimide in pyridine for 72 h at room temperature.

Condensation of 1 mole of thymidine-5′-phosphoric acid *(5)* and 21 moles of trichlorethanol with 10 moles of dicyclohexylcarbodiimide in pyridine for 72 h at room temperature afforded a 52% yield of the ester *(6)*, whose cyclohexylammonium salt melts at 207–210 °C.

The 2,2,2-trichloroethyl nucleoside phosphates are stable in pyridine in the presence of a fivefold molar excess of dicyclohexylcarbodiimide. The protective group can be split off by reduction with Cu/Zn for 5 h in 80% acetic acid at room temperature or for 1 h at 50 °C in dimethylformamide. The free acid is isolated in the form of its pyridinium salt using Merck I ion-exchange resin. Spectrophotometric estimations showed that the compounds *(2a)* and *(6)* give the mononucleotides *(4)* and *(5)* in yields of 80–90%.

Received: August 2nd, 1965 [Z 53/879 IE]
German version: Angew. Chem. 77, 912 (1965)

[1] *E. Cherbuliez, A. Gabbai, H. Probst, A. Yazgi*, and *J. Rabinowitz*, Helv. chim. Acta *45*, 2282 (1962).

[2] *F. Cramer* and *G. Weimann*, Chem. Ber. *94*, 996 (1961).

Heterosiloxanes of Zinc and Cadmium

By Dr. F. Schindler, Priv.-Doz. Dr. H. Schmidbaur and cand. chem. U. Krüger

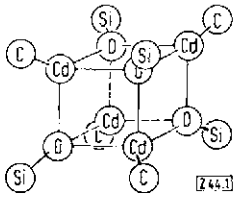
Institut für Anorganische Chemie der Universität Marburg (Germany)

We have synthesised compounds containing the hitherto unknown structural units Si–O–Zn and Si–O–Cd by treating dimethylzinc and dimethylcadmium, respectively, with trimethylsilanol. Methane is evolved rapidly and quantitatively from the ethereal solutions, even at room temperature; subsequent vacuum sublimation leads to tetramethylzinc-*(1)* and tetramethylcadmium-siloxane *(2)* in high yields:

$$CH_3ZnCH_3 + HOSi(CH_3)_3 \rightarrow CH_4 + \underset{(1)}{CH_3ZnOSi(CH_3)_3}$$

$$CH_3CdCH_3 + HOSi(CH_3)_3 \rightarrow CH_4 + \underset{(2)}{CH_3CdOSi(CH_3)_3}$$

Compounds *(1)* and *(2)* form colorless crystals which dissolve readily in organic solvents that contain no active proton. Surprisingly they are tetrameric in such solvents. The ^1H-NMR spectrum of *(1)* in CCl_4 contains only two sharp bands, of relative intensity 1:3. In the analogous spectrum of *(2)* the satellites due to $^1H-C-^{111}Cd$ and $^1H-C-^{113}Cd$ coupling can be detected symmetrically around the signal of the Cd-methyl groups. On the basis of these results and of the corresponding infrared data (see Table) a cubane structure of point group 4 is assumed, in which the metal and the oxygen atoms, each having coordination four, occupy the corners of a – perhaps somewhat distorted – cube. *Coates et al.* [1] recently obtained similar results for alkylzinc alkoxides RZnOR. X-Ray investigations to confirm the proposed structure are in progress.



[Z 44/1]

	$[CH_3ZnOSi(CH_3)_3]_4$	$[CH_3CdOSi(CH_3)_3]_4$
Sublimation temp.	125 °C/1 mm	135 °C/1 mm
Decomp. temp.	150 °C	145 °C
^1H NMR [a]		
δ (CH_3Si)	−9.5	−8.0
δ (CH_3M)	+35.0	+18.2
$J(^1H-C-^{111}Cd)$	–	±80.5
$J(^1H-C-^{113}Cd)$	–	±84.0
IR [b]		
ν (Si–O)	862 cm^{-1}	869 cm^{-1}
ν (Si–C)	676 cm^{-1}	680 cm^{-1}
ν (M–C)	541 cm^{-1}	442 cm^{-1}
ν (M–O)	437 cm^{-1}	409 cm^{-1}

[a] At 60 Mc/s and 35 °C in CCl_4 with tetramethylsilane as internal standard.
[b] In Nujol.

Received: August 4th, 1965 [Z 44/871 IE]
German version: Angew. Chem. 77, 865 (1965)

[1] *G. E. Coates* and *D. Ridley*, J. chem. Soc. (London) *1965*, 1870.

Methyl(trimethylsiloxy)mercury and Dimethyl(trimethylsiloxy)thallium

By Priv.-Doz. Dr. H. Schmidbaur and Dr. F. Schindler

Institut für Anorganische Chemie der Universität Marburg (Germany)

The reaction of diorganylmetals with silanols, which has been used for the synthesis of heterosiloxanes of zinc and cadmium [1], is not suitable for preparation of siloxane derivatives of

bivalent mercury containing the grouping Si–O–Hg. We found, however, that compounds of this type are readily accessible by treatment of organomercury halides with alkali silanolates in tetrahydrofuran (1 h at 65 °C):

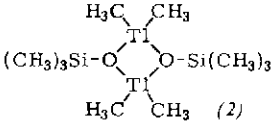
$$(CH_3)_3Si{-}O{-}Na + CH_3Hg{-}Cl \rightarrow NaCl + (CH_3)_3Si{-}O{-}HgCH_3 \quad (1)$$

Compound *(1)* forms colorless, sublimable crystals [2], m.p. 52 °C, is very soluble in organic solvents, and is monomeric in benzene, in contrast to the results for $(CH_3)_3Si{-}O{-}ZnCH_3$ and $(CH_3)_3Si{-}O{-}CdCH_3$ for which a four-fold molecular weight has been found. The acceptor strength of mercury is clearly less than that of zinc or cadmium.

Dimethyl(trimethylsiloxy)thallium, the first heterosiloxane with a Si–O–Tl group, has been prepared analogously from $(CH_3)_3SiONa$ and dimethylthallium chloride:

$$(CH_3)_3Si{-}O{-}Na + (CH_3)_2Tl{-}Cl \rightarrow NaCl + (CH_3)_3Si{-}O{-}Tl(CH_3)_2 \quad (2)$$

This compound forms colorless, sublimable crystals *(2)*, m.p. 98–100 °C, that dissolve in organic solvents where they are dimeric. In this respect they resemble the analogous heterosiloxanes of aluminium, gallium, and indium [3–5].



(2)

	$(CH_3)_3SiOHgCH_3$	$(CH_3)_3SiOTl(CH_3)_2$
Subl. temp.	50 °C/1 mm	90 °C/1 mm
IR [a]		
ν(Si–C)	673 cm^{-1}	668 cm^{-1}
ν(M–C)	552 cm^{-1}	533 cm^{-1}
ν(Si–O–M)	903/484/470/312 cm^{-1}	922/408/311 cm^{-1}
NMR [b]		
δ CH_3Si	−2.0 } 3:1	+7.2 } 3:2
δ CH_3M	−45.0 [c] }	−51.5 [d] }
$J(^1H{-}^{13}C)Si$	117	116
$J(^1H{-}C{-}^{29}Si)$	6.65	6.6
$J(^1H{-}C{-}M)$	196.5	371/368

[a] In Nujol.
[b] In CCl_4 at 60 Mc/s with tetramethylsilane as internal standard.
[c] Accompanied by $^1H{-}C{-}^{199}Hg$ satellites.
[d] Completely split into two doublets by $^1H{-}C{-}^{203}Tl$ and $^1H{-}C{-}^{205}Tl$ coupling.

Received: August 4th, 1965 [Z 45/870 IE]
German version: Angew. Chem. 77, 865 (1965)

[1] *F. Schindler, H. Schmidbaur*, and *U. Krüger*, Angew. Chem. 77, 865 (1965); Angew. Chem. internat. Edit. 4, 876 (1965).

[2] Compound *(1)* forms tetragonal crystals whose unit cell, of approximate dimensions a = 9.1 and b = 14.0 Å, contains eight molecules (*E. Hellner* and *A. Dittmar*, personal communication).

[3] *H. Schmidbaur*, Angew. Chem. 77, 169, 206 (1965); Angew. Chem. internat. Edit. 4, 152, 201 (1965).

[4] *H. Schmidbaur*, J. organometal. Chem. 1, 28 (1963).

[5] *H. Schmidbaur* and *M. Schmidt*, J. Amer. chem. Soc. 84, 1069 (1962).

Organometallic Derivatives of Iminotriphenylphosphorane

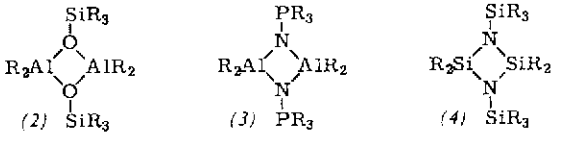
By Priv.-Doz. Dr. H. Schmidbaur, cand. chem. G. Kuhr, and cand. chem. U. Krüger

Institut für Anorganische Chemie
der Universität Marburg (Germany)

Iminotriphenylphosphorane [1] reacts with trimethylaluminum in diethyl ether at room temperature with evolution of methane. (Iminotriphenylphosphorane)dimethylaluminum *(1)* can be isolated in high yield by evaporation of the solvent and recrystallization from cyclohexane.

$$(CH_3)_3Al + HN{=}P(C_6H_5)_3 \rightarrow CH_4 + (CH_3)_2Al{-}N{=}P(C_6H_5)_3 \quad (1)$$

The compound *(1)* forms colorless crystals which slowly disintegrate in moist air. Vapor pressure osmometric determinations of molecular weight show it to be dimeric in benzene solution. Its ^1H–NMR spectrum contains a multiplet for phenyl hydrogen and a singlet due to methyl hydrogen, the ratio of the areas (2.5:1) corresponding with theoretical requirements. In the infrared spectrum, as in the NMR spectrum, analogies to the isoelectronic aluminosiloxanes *(2)* [2] can be seen. Thus structure *(3)* can be assumed for *(1)*, so that now three isostructural isosteres are known, with structures *(2)* [2], *(3)*, and *(4)* [3], respectively. (Iminotriphenylphosphorane)dimethylgallium *(5)* and



(2) *(3)* *(4)*

the indium analogue *(6)* can be prepared similarly from iminotriphenylphosphorane and trimethylgallium or -indium, respectively. Compound *(5)* is also dimeric but *(6)* is less strongly associated. Spectroscopically they resemble the aluminium compound *(1)*.

The isosteres *(7)*–*(9)* which are important for comparative spectroscopic study are all dimeric; they are obtained from the trimethylmetal etherates and triphenylsilanol with evolution of methane:

$$2\,(CH_3)_3M{\cdot}O(C_2H_5)_2 + 2\,HO{-}Si(C_6H_5)_3 \rightarrow 2\,CH_4 + [(CH_3)_2M{-}O{-}Si(C_6H_5)_3]_2$$

(M = Al, Ga, In)

	M.p. [°C]	^1H–NMR [c.p.s.] [a]	
		δ CH_3	δ C_6H_5
(1) $[(C_6H_5)_3P{=}N{-}Al(CH_3)_2]_2$	272	+80.3	−448
(5) $[(C_6H_5)_3P{=}N{-}Ga(CH_3)_2]_2$	238	+52.5	−444
(6) $[(C_6H_5)_3P{=}N{-}In(CH_3)_2]_{1.5}$	230–232	+50.0	−445
(7) $[(C_6H_5)_3Si\ O{-}Al(CH_3)_2]_2$	196–198	+71.5	−449
(8) $[(C_6H_5)_3Si{-}O{-}Ga(CH_3)_2]_2$	177–182	+34.4	−447
(9) $[(C_6H_5)_3Si{-}O{-}In(CH_3)_2]_2$	154–157	+26.8	−446

[a] At 60 Mc/s in CCl_4 with tetramethylsilane as internal standard. Negative values for lower fields.

Received: August 4th, 1965 [Z 46/873 IE]
German version: Angew. Chem. 77, 866 (1965)

[1] Triphenylphosphine imide (iminotriphenylphosphorane) is isosteric with triphenylsilanol.

[2] *H. Schmidbaur*, Angew. Chem. 77, 169, 206 (1965); Angew. Chem. internat. Edit. 4, 152, 201 (1965); J. organometal. Chem. 1, 28 (1963).

[3] *W. Fink*, Chem. Ber. 96, 1071 (1963); *P. Geymayer* and *E. G. Rochow*, Angew. Chem. 77, 618 (1965); Angew. Chem. internat. Edit. 4, 592 (1965).

Preparation of Pyrimidines from Cyanic Esters and CH-Acidic Compounds

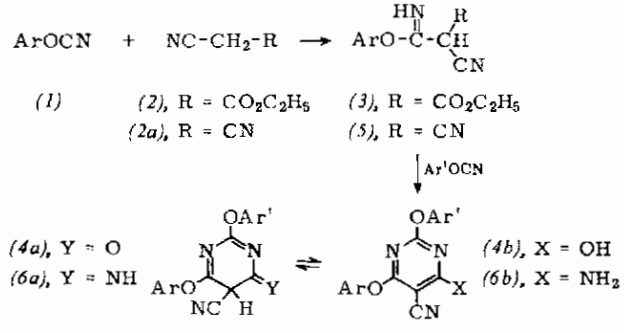
By Dr. E. Grigat and Dr. R. Pütter

Wissenschaftliches Laboratorium der Zwischenproduktenabteilung, Farbenfabriken Bayer AG., Leverkusen (Germany)

The formation of a pyrimidine derivative *(4)* as a by-product was once observed [1] in the reaction of aryl cyanates *(1)* with ethyl β-cyanoacetate *(2)* to make aroxyiminomethylcyanoacetic esters *(3)*. We have now found [2] that *(4)* is ob-

tained as the main product when *(3)* made according to [1] is mixed in acetone at room temperature with 1 mole of *(1)*, 1 mole of triethylamine is then added, and the mixture heated for a short time at 50 °C. If the reaction is carried out in one step, *i.e.* 2 *(1)* + *(2)* → *(4)*, the yield is lower. When two different cyanates are used, two isomeric hydroxypyrimidine derivatives *(4)* are obtained depending on the sequence in which the esters are taken. The products *(4)* precipitate in the form of their triethylammonium salts and can be converted into the free pyrimidines by acidification. The form *(4a)* predominates in the resultant tautomeric mixture; this is indicated by the strong carbonyl bands in the infrared spectra of *(4)*, which are absent in the spectra of their salts.

An analogous cyclization leading to aminopyrimidines *(6)* occurs on treatment of 1 mole of malonodinitrile *(2a)* with 2 moles of ethyl cyanoacetate. Here too *(5)* is first prepared according to [1] and then transformed with *(1)* with addition of triethylamine into *(6)* under conditions similar to those used for the preparation of *(4)*. With two different cyanates *(1)* two isomeric aminopyrimidine derivatives are obtained analogously.



Ar	Ar'	*(4)*, Yield [%]	*(4)*, M.p. [°C]
4-CH_3—C_6H_4	C_6H_5	63	176–178 [b]
C_6H_5	4-CH_3—C_6H_4	68	131–132 [b]
4-Cl—C_6H_4	4-Cl—C_6H_4	57 [a]	205–208 [b]
4-CH_3—C_6H_4	4-CH_3—C_6H_4	20 [a]	293–296
		(6), Yield [%]	*(6)*, M.p. [°C]
Cl_3C—CH_2	Cl_3C—CH_2	86 [a]	181–182
2,4-$(CH_3)_2C_6H_3$	2,4-$(CH_3)_2C_6H_3$	31 [a]	222–224
4-CH_3CO—C_6H_4	C_6H_5	87	257–259
C_6H_5	4-CH_3CO—C_6H_4	52	226
4-Cl—C_6H_4	C_6H_5	78	259–261
C_6H_5	2-H_3CO_2C-C_6H_4	75	204
C_6H_5	5-Quinolyl	68	238–239
5-Quinolyl	C_6H_5	85	286
2-CH_3O—C_6H_4	Cl_3C—CH_2	45	210–211

[a] One-step synthesis. [b] M.p. of triethylammonium salt.

Received: August 5th, 1965 [Z 55/882 IE]
German version: Angew. Chem. 77, 913 (1965)

[1] *E. Grigat, R. Pütter*, and *E. Mühlbauer*, Chem. Ber., in press.
[2] German Patent Application F 46709 IV/12p (July 23rd, 1965); F 46739 IVd/12p (July 27th, 1965), Farbenfabriken Bayer AG.; inventors: *E. Grigat* and *R. Pütter*.

Triscyclopentadienylplutonium

By Prof. Dr. F. Baumgärtner, Prof. Dr. E. O. Fischer, Dr. B. Kanellakopulos, and Dipl.-Chem. P. Laubereau

Kernforschungszentrum Karlsruhe
Anorganisch-Chemisches Laboratorium der Technischen Hochschule München and
Lehrstuhl für Radiochemie der Universität Heidelberg (Germany)

By treatment of plutonium with chlorine and CCl_4 at 880 °C we obtained pure, emerald-green $PuCl_3$ (isolated by sublimation), which reacts further in a melt with $Be(C_5H_5)_2$ at *ca.* 70 °C.

The moss-green compound *(1)* is the first pure cyclopentadienyl complex of a transuranium element. After removal of the excess of $Be(C_5H_5)_2$ by sublimation, *(1)* was isolated in

$$2\ PuCl_3 + 3\ Be(C_5H_5)_2 \rightarrow 2\ Pu(C_5H_5)_3 + 3\ BeCl_2 \qquad (1)$$

more than 60% yield in a high vacuum at 140–165 °C on a water-cooled finger. The product is free from chloride ions and extremely sensitive to air. It is attacked by argon-saturated water with evolution of gas, and by air-free 1 N HCl or by 18% nitric acid with formation of a blue solution of Pu^{3+}.

Compound *(1)* remains unchanged for weeks at room temperature under an inert gas; it begins to sinter at 180 °C and decomposes above 195 °.

Infrared spectra determined for polycrystalline samples in Nujol/polytetrafluoroethylene prove the presence of symmetrical five-membered rings [characteristic bands at 779/793 cm^{-1} (γ_{CH}), 841 cm^{-1}, 1007 cm^{-1} (δ_{CH}), 1447 cm^{-1} (ω_{CC}), 3100 cm^{-1} (ν_{CH})]. From the positions and intensities of the bands, as well as the absence of appreciable absorption at 1100 cm^{-1}, it can be concluded that the linkage between the metal and the cyclopentadienyl ligands has strong ionic character.

Received: August 7th, 1965 [Z 47/872 IE]
German version: Angew. Chem. 77, 866 (1965)

Ionization of Benzylmagnesium Chloride

By Dr. H. F. Ebel and Dr. R. Schneider

Organisch-Chemisches Institut der Universität Heidelberg

Triphenylmethylmagnesium chloride [1] and bromide [2] are colorless in ether or in the crystalline state. This contrasts to the triphenylmethyl compounds of the alkali metals which exhibit a red color due to the $(C_6H_5)_3C^-$ anion, thereby showing that they are ionophores. The lack of ionization in $(C_6H_5)_3C$ MgX led to the conclusion [3] that magnesium alkyls are not ionized to any measurable extent.

We have found that benzylmagnesium chloride, prepared from benzyl chloride and magnesium in ether, can be caused to ionize. On addition of tris(dimethylamino)phosphine oxide, $OP(NMe_2)_3$ [4], the colorless ethereal solution assumes the red color of the benzyl anion, which is characteristic of benzylsodium even in the absence of the phosphine oxide [5]. Depending on the concentrations, a white precipitate may be observed before the color develops. The solution can be decolorized, with evolution of heat, by adding an equivalent amount of benzophenone or benzyl chloride [6]. Addition of much water and evaporation of the ether phase then allows isolation of 1,1,2-triphenylethanol (67%) and bibenzyl (65%), respectively. With benzyl-lithium we have also found for the first time [7] a strong solvatochromic effect (red shift on addition of $OP(NMe_2)_3$ [5]). This compound usually is yellow to orange, even in the presence of tetramethylethylenediamine [8], and may be assumed to form contact ion pairs with partial covalent character [9] under normal conditions.

Received: October 7th, 1965 [Z 74/895 IE]
German version: Angew. Chem. 77, 914 (1965)

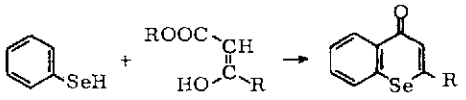
[1] *J. Schmidlin*: Das Triphenylmethyl. Ferdinand Enke, Stuttgart 1914, p. 128.
[2] *M. Gomberg* and *W. E. Bachmann*, J. Amer. chem. Soc. *52*, 2455 (1930).
[3] *E. G. Rochow, D. T. Hurd*, and *R. N. Lewis*: The Chemistry of Organometallic Compounds. Wiley, New York 1957, p. 82.
[4] The strong complexing power of this solvent was first recognized by *H. Normant et al.*, Bull. Soc. chim. France *1965*, 1881, and earlier papers.
[5] A spectrophotometric investigation is in progress.
[6] In ether alone there is no reaction.
[7] Such an effect has been sought without success: cf. *R. Waack* and *M. A. Doran*, J. physic. Chem. *67*, 148 (1963).
[8] *G. G. Eberhardt* and *W. A. Butte*, J. org. Chemistry *29*, 2928 (1964).
[9] *H. F. Ebel*, Tetrahedron *21*, 699 (1965).

Synthesis of 1-Selenochromones [1]

By Dr. F. Bossert

Pharmazeutisch-Wissenschaftliche Abteilung
der Farbenfabriken Bayer AG., Werk Elberfeld (Germany)

We have prepared 1-selenochromones *(1)* by condensation of selenophenol and β-keto esters with polyphosphoric acid. For example, ethyl acetoacetate yields 2-methylselenochromone *(1)*, R = CH_3, m.p. 100 °C, ethyl benzoylacetate yields



(1)

2-phenylselenochromone *(1)*, R = C_6H_5, m.p. 127–128 °C, and ethyl 4-methoxybenzoylacetate yields 2-(*p*-methoxyphenyl)selenochromone *(1)*, R = *p*-$CH_3OC_6H_4$, m.p. 150 to 152 °C.

A mixture of 0.1 mole of selenophenol and 0.12–0.14 mole of β-keto ester is added dropwise over 1 h to 350 g of polyphosphoric acid at about 90 °C, and the mixture is then heated for about 3 h at 90–100 °C and poured onto ice. The product is extracted with ether, and the ether extract is washed with water, dilute sodium hydroxide, and water and then dried. After evaporation of the ether, the crude product is obtained in 40–50% yield and is purified by recrystallization from methanol, ethanol, or benzene/ligroin. The structures of the products were proved by comparing their infrared and NMR spectra with those of the corresponding thio compounds.

Received: August 23rd, 1965 [Z 54/880 IE]
German version: Angew. Chem. 77, 913 (1965)

[1] Cf. *M. Renson*, Bull. Soc. Chim. Belg. *73*, 483 (1964).

Errata

"Formation of Nucleophilic Carbenes from Heterocyclic *N*-Methyl Betaines" by *H. Quast* and *E. Frankenfeld*, Angew. Chem. internat. Edit. *4*, 691 (1965):

The last line of this Communication should read "limiting structure *(2')*".

"Synthesis of 2,5-Dibromo-1,2,4-triazole by Bromination of 1,2,4-Triazole" by *C. F. Kröger* and *H. Frank*, Angew. Chem. internat. Edit. *4*, 434 (1965):

In the title and in the last sentence of this Communication, the name of the compound synthesized should be changed to "3,5-dibromo-1,2,4-triazole".

CONFERENCE REPORTS

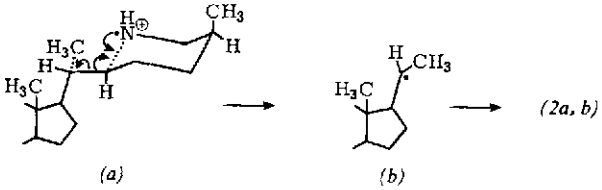
Conference of Chemistry Lecturers in Potsdam

The Conference was held at Potsdam (Germany) on July 5th–8th, 1965. The following is a selection of excerpts from the 108 lectures delivered.

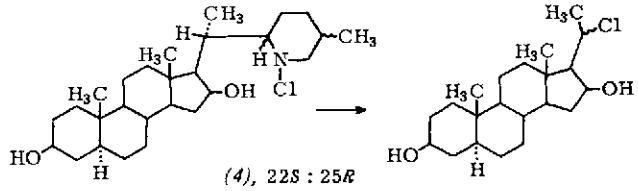
New Photochemical Reactions of Nitrogenous Steroids

G. Adam and *K. Schreiber*, Gatersleben (Germany)

Unlike its (22*R*:25*S*) and (22*S*:25*R*) stereoisomers, (22*S*:25*S*)-*N*-chloro-22,26-imino-5α-cholestan-3β-ol *(1)* does not lead to solanidanol in the Hofmann-Löffler-Freytag reaction induced by ultraviolet irradiation. An unresolvable mixture of the two C-20 stereoisomers of 20-chloro-5α-pregnan-3β-ol *(2a,b)* is obtained instead (in 52% yield) in a degradation reaction taking place when *(1)* is irradiated in trifluoroacetic acid. The same product has also been synthesized from (20*R*)-3β-acetoxy-5α-pregnan-20-ol *(3)*.

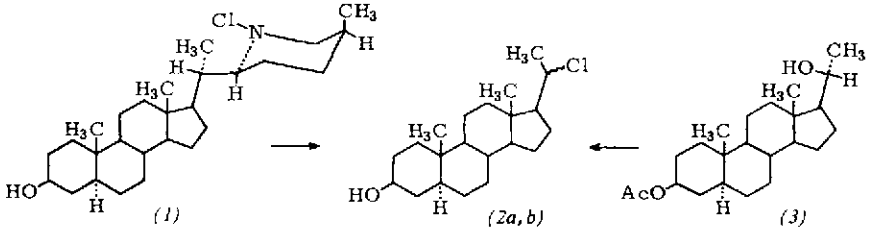


(a) *(b)* *(2a, b)*



(4), 22*S* : 25*R*
(5), 22*S* : 25*S*
(6), 22*R* : 25*S*

(7a,b)



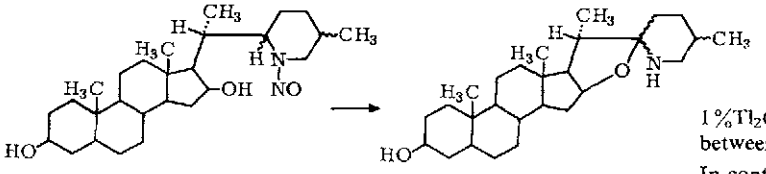
(1) *(2a,b)* *(3)*

According to the free-radical mechanism postulated for this new type of fragmentation, the nitrogen-containing radical ion formed in the photochemical reaction undergoes C–C cleavage *via (a)*, the resulting carbon radical *(b)* being stabilized before it recombines with a chlorine radical to form *(2a,b)*.

When this photolysis is carried out on the 16β-hydroxy-substituted *N*-chloro-22,26-iminocholestanols *(4)–(6)*, degradation is always the principal reaction, leading invariably to the same mixture of C-20 stereoisomeric 20-chloro-5α-pregnan-3β,16β-diols *(7a,b)* in a yield of up to 82%. The resulting mixture can be resolved by column chromatography.

This reaction provides a new route to the degradation of spirosolane alkaloids, leading to the pregnane series in three steps: reduction, *N*-chlorination, and degradation.

Further photochemical investigations with the *N*-nitroso compounds *(8)–(11)* have shown that, instead of degradation, the compounds of this type are cyclized to the corresponding spirosolane alkaloids *(12)–(14)* on ultraviolet irradiation in ethanolic HCl.



(8), 5α, 22*S* : 25*R*
(9), Δ^5, 22*S* : 25*R*
(10), 5α, 22*S* : 25*S*
(11), 5α, 22*R* : 25*S*

(12), 5α, 22*R* : 25*R*
(13), Δ^5, 22*R* : 25*R*
(14), 5α, 22*S* : 25*S*

It has been found in the photolysis of (22*S*:25*R*)-*N*-nitroso-3β,16β-diacetoxy-22,26-imino-5α-cholestane that the photochemical reaction proper consists in the introduction of a $\Delta^{22(N)}$-double bond, followed — in the presence of a free 16β-hydroxyl group — by a spontaneous and stereospecific cyclization to spirosolane.

Preparation and Properties of Silicon Monoxide

H.-H. Emons, Merseburg (Germany)

Vitreous $(SiO)_n$ was prepared [1] from silicon and silicon dioxide. On condensation of SiO vapor on a cold finger, fibrous $(SiO)_n$ is obtained. Even in an atmosphere of argon, the product frequently underwent spontaneous ignition without change in composition, accompanied by lightening of the color. No disproportionation product could be detected in the resulting substance by X-ray analysis.

$(SiS)_n$ was prepared from Si and SiS_2 or CS_2 under vacuum at 850 to 1000 °C. The vitreous substance with a color varying from red to reddish brown obtained on purification by sublimation turns yellow when ground in a mortar, and forms H_2S with water and H_2 with 5% NaOH. The varying appearance of $(SiS)_n$ in metallurgical processes is due to the varying particle size and to impurities.

A three-dimensional, random network structure is assumed for the vitreous $(SiO)_n$ and $(SiS)_n$, the Si atoms or groups of two or more Si atoms being linked *via* oxygen or sulfur by a σ-bond system strengthened by partial $d_\pi p_\pi$ double bonds. An open-chain structure based on rows of Si–Si linkages may be postulated for the fibrous $(SiO)_n$ having unidirectional fracture. The fact that the color of this product becomes lighter on ignition indicates that the chains become detached from each other during this process.

Reactions with Cl_2 and HCl confirm the relative inertness of the vitreous $(SiO)_n$ compared to the more reactive fibrous product.

The "yellow substance" described earlier [1] consists of $(SiO)_n$ and 40 to 50% of silicon and silicon dioxide.

Preparation of Aromatic Nitriles from Alkylaromatic Compounds and Nitric Oxide in the Vapor Phase

E. Fischer, Rostock (Germany)

Alkylaromatic and alkyl-substituted heterocyclic compounds form nitriles with nitric oxide in the presence of catalysts at 650 to 900 °K:

$$2\ RCH_3 + 3\ NO \rightarrow 2\ R{-}CN + 3\ H_2O + 1/2\ N_2$$

(R = aromatic or heterocyclic residue)

The following catalysts were investigated in the reaction with toluene: Ag/carbon, Pd/carbon, Pt/carbon, Re/carbon, $PbSnO_3$, and $PbTiO_3$. The silver catalysts were activated with Tl_2O_3, CaO, or PhO. The highest conversion of toluene into benzonitrile (30 to 42%) was obtained with 7% Ag/1%Tl_2O_3/carbon and $PbTiO_3$/1% Tl_2O_3. The yield varies between 90 and 98%, depending on the temperature.

In contrast to the ammoxidation, the catalytic nitrosation of *p*-xylene into *p*-toluonitrile and of *p*-t-butyltoluene into *p*-t-butylbenzonitrile under suitable conditions leads selectively to the mononitriles.

Benzonitrile is obtained from dialkylaromatics when Pt, Pd, and Ag catalysts containing more than 9% Ag are used above 435 °C.

The concentration of nitric oxide has an important effect. Maximum yields are obtained only when the molar ratio of NO to toluene is 1.5. With a molar ratio of 1.0, the yield amounts at most to 12%, and when the molar ratio is 2.0, the maximum yield falls to 16–25%.

Methyl-substituted heterocyclic compounds, such as 2-methylthiophene or 2-methylfuran can similarly be converted into nitriles. Thus 2-cyanothiophene is obtained in a yield of 85% at 20% conversion of methylthiophene on titanium catalysts at 730 °K.

A residence time of 2.2 to 4.6 sec and a rate of discharge of the liquid products equal to 0.157 to 0.430 h^{-1} represent the best conditions for the vapor phase nitrosation.

Modification of Proteins by the Introduction of Additional Thiol Groups

U. Freimuth and *W. Krüger*, Dresden (Germany)

Thiol groups were introduced into crystalline β-lactoglobulin by the reaction of free ε-amino groups of the latter with acetylmercaptosuccinic anhydride [1] or with *N*-acetylhomocysteine thiolactone [2]. The excess of reagent and the buffer salts can be removed by gel filtration on Sephadex G-25 under milder conditions than by dialysis or ion-exchange chromatography.

Whereas acetylmercaptosuccinyl-β-lactoglobulin appears homogeneous in sedimentation and electrophoresis, *N*-acetylhomocysteinyl-β-lactoglobulin was resolved on Sephadex G-25 into two fractions, one of which was found to be an aggregation product. This result was confirmed by experiments with a reagent labeled with ^{35}S.

The molecules associate rapidly when the thiol groups are removed from acetylmercaptosuccinyl-β-lactoglobulin by deacetylation at pH 10 to 11.

In order to establish whether the introduction of the thiol groups is accompanied by irreversible denaturation, the hydrolysate of the *N*-acetylhomocysteinyl-β-lactoglobulin was tested for lanthionine that may have been formed by disulfide exchange and by nucleophilic attack by the SH^- anions on the disulfide bridges of the protein. However, no lanthionine was detected. The lanthionine analysis was improved considerably by the use of high-voltage electrophoresis, since lanthionine sulfoxide, cysteic acid, homocysteic acid, and methionine sulfone are readily resolved in 1 h in a formic acid/acetic acid buffer (pH 1.9) by the application of about 2000 V.

[1] *H.-H. Emons* and *H. Boenicke*, J. prakt. Chem. *18*, 11 (1962).

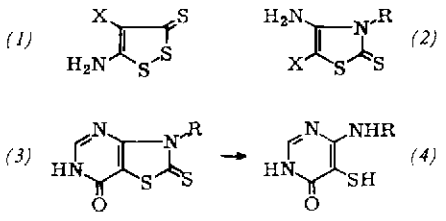
[1] *I. M. Klotz* and *R. E. Heiney*, J. Amer. chem. Soc. *81*, 3802 (1959).

[2] *R. Benesch* and *R. E. Benesch*, Biochim. biophysica Acta *63*, 166 (1962).

Reactions of Carbon Disulfide and Isothiocyanates with Sulfur and Nitriles Containing an Active Methylene Group

K. Gewald, Dresden (Germany)

In the presence of triethylamine at room temperature, the joint action of sulfur and carbon disulfide on nitriles having an active α-methylene group leads to 4-substituted 5-amino-1,2-dithiol-3-thiones *(1)* [1,2]. If isothiocyanates are used instead of carbon disulfide, 3,5-disubstituted 4-aminothiazoline-2-thiones *(2)* are obtained. These compounds can also be prepared by replacing the isothiocyanate by the corresponding primary amine and by carbon disulfide, and by treating these with sulfur and with the nitrile.



X = CN, CO_2R, $CONH_2$
R = Alkyl, Allyl, Phenyl

The compounds of type *(1)*, which are sensitive to strong bases [2], exhibit "trithione properties" (*e.g. S*-methylation) only when the weakly basic amino group is protected by acylation. When compounds of type *(2)*, which are stable to acids and are similarly very weakly basic, are treated with strong bases, the starting materials are reformed by cleavage. The structure of *(2)* can be ascertained *inter alia* by the following reactions: With ethyl orthoformate, the amido derivative of *(2)* (X = $CONH_2$) gives the thiazolopyrimidone *(3)*, which can be cleaved with dilute NaOH to give the mercaptan *(4)*.

Synthesis of Methylenebisphosphorus Compounds

H. G. Henning, Berlin (Germany)

One-stage reactions of bifunctional methylene compounds with two equivalents of a phosphorus compound are unsuitable for the preparation of methylenebisphosphonates or methylenebisphosphinates. The α-monofunctional methylenephosphonates and methylenephosphinates were therefore tested with a view to forming a (P–C–P) linkage. In some cases α-metallated phosphonates and phosphinates (with Na, Na/K, $MgOC_2H_5$, MgCl) could be acetylated, but reactions with ester chlorides of various acids of phosphorus did not lead to the compounds required.

The Michaelis-Arbuzov and the Michaelis-Becker reactions of alkyl α-halogenomethylphosphonates and alkyl α-halogenomethylphosphinates with trivalent phosphorus compounds lead to derivatives that would be expected to result from a nucleophilic attack (a) on the α–C atom and (b) on the ester alkyl group. In the Arbuzov reaction of ethyl ethyliodomethylphosphinate with diethyl ethylphosphonite between 180 and 200 °C, mechanism (a) leads to methylenebis(ethyl ethylphosphinate) in a yield of 69.9%, and mechanism (b) and the action of ethyl iodide liberated in (a) lead to ethyl diethylphosphinate.

In the Michaelis-Becker reaction of the α-halogenomethylalkyl- or α-halogenomethylarylphosphinic acids, the nature of the alkyl or aryl substituent on the phosphorus is also significant. Positive substituents promote elimination of halogen as the anion in accordance with mechanism (a), and inhibit mechanism (b). Negative substituents, on the other hand, promote the alkylating power of the ester [mechanism (b)] and inhibit mechanism (a). Owing to their (+M)-effect, ethoxy groups oppose the withdrawal of electrons from the neighboring groups by the P=O group. Compounds with aromatic substituents do not react in the required manner. In the reaction of ethyl chloromethylethylphosphinate with sodium diethylphosphite, on the other hand, ethyl O,O-diethylphosphonylmethylphosphinate is formed in a yield of 60.9%.

[1] *K. Gewald*, Z. Chem. *3*, 36 (1963).

[2] Cf. *E. Söderbäck*, Acta chim. Scand. *17*, 362 (1963).

Solvent Effects on the Stereospecificity of Halogen Addition to cis- and trans-Stilbenes

G. Heublein, Jena (Germany)

The relative amounts of the diastereoisomers in the addition product of halogens to *cis*- and *trans*-stilbenes, as determined by infrared spectroscopy, is regarded as a measure of the stereospecificity of the reaction.

In non-polar solvents, a halogenonium ion *(1)* is formed, which is stabilized by a partial intramolecular charge redistribution. The reaction is therefore largely stereospecific in favor of *trans*-addition.

In polar solvents, on the other hand, the ionic intermediate is stabilized as a carbonium ion *(2)* by solvation. Internal rotation is possible in the intermediate, and the end-product of the addition is determined by the sterically most favorable conformation of the intermediate, which in this case is the one with distant benzene rings leading to the *meso*-form.

(1) *(2)*

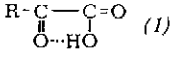
Addition of chlorine to dichloroiodobenzene has shown that, unlike bromine, chlorine is hardly capable of forming a halogenonium ion *(1)* in a non-polar solvent, so that *meso*-dichlorostilbene is formed preferentially with both *trans*- and *cis*-stilbene.

The addition of ICl to *trans*-stilbene in a polar or a non-polar solvent results exclusively in *erythro*-chloroiodostilbene, indicating the formation of an iodonium ion *(1)*.

Intramolecular Acid Catalysis in the Iodination of Keto Acids. Detection of Proton Chelates in Aqueous Solution

G. Hübner, Halle (Germany)

Whereas the halogenation of keto compounds is generally catalysed by acids, the rate of iodination of α-keto acids is independent of the hydrogen-ion concentration [1]. This suggests an intramolecular interaction between the carboxyl and the carbonyl groups, especially since proton chelates of type *(1)* have been detected in non-polar solvents and in



(1)

the vapor phase [2]. In order to separate the inductive effect of the carboxyl group from the hydrogen-bonding effect, aromatic compounds were studied which structurally resemble α-keto acids, but in the *p*-isomers of which the carboxyl or hydroxyl groups have only long-range effects on the carbonyl group. The rates of iodination of *o*-hydroxyacetophenone, *o*-acetophenonecarboxylic acid, and *o*-propiophenonecarboxylic acid were found to be independent of the acid concentration, whereas those of *p*-hydroxyacetophenone and *p*-acetophenonecarboxylic acid were found to be proportional

[1] *A. Schellenberger* and *G. Hübner*, Chem. Ber. *98*, 1938 (1965).

[2] *A. Schellenberger* and *G. Oehme*, Z. physik. Chem. *227*, 112 (1964); *A. Schellenberger*, *W. Beer*, and *G. Oehme*, Spectrochim. Acta *21*, 1345 (1965).

to the acid concentration. It follows that proton chelates can also exist in aqueous solutions, and that the protons protect the carbonyl groups against attack. A certain acidity of the OH groups is probably a prerequisite for such interactions, since phenylacetoin behaves as a simple ketone, although proton chelates can be detected spectroscopically in non-polar solvents. A number of compounds of physiological importance, *e.g.* pyruvic acid, α-ketobutyric acid, and α-ketoglutaric acid exist in the form of proton chelates in aqueous solutions at their spontaneous pH.

Thiocarbamoylphosphines

K. Issleib and *G. Harzfeld*, Halle (Germany)

The formation of thiocarbamoylphosphines depends on the nucleophilicity of the primary or secondary phosphine involved and on the inductive effect of the organic residue of the isothiocynates. Aryl isothiocyanates form thiocarbamoylphosphines $R_2P-C(S)-NHR'$ with aliphatic and aromatic secondary phosphines. Alkyl isothiocyanates, on the other hand, react only with the more strongly nucleophilic aliphatic or cycloaliphatic secondary phosphines to give the corresponding thiocarbamoylphosphines. Being less nucleophilic, diphenylphosphine reacts only with methyl isothiocyanate. Only the use of alkali metal phosphides, MPR_2, provides a general method for the reaction with variously substituted alkyl isothiocyanates. The hydrolysis of such reaction mixtures leads to *N*-alkylthiocarbamoylphosphines, $R_2P-C(S)-NHR'$ with R = C_6H_5-, $C_6H_{11}-$, C_2H_5-, and R' = CH_3-, C_2H_5-, $CH_2=CH-CH_2-$.

Unlike the *N*-arylthiocarbamoylphosphines, the *N*-alkyl derivates form *P*-sulfides$[R_2P(S)-C(S)-NHR']$ with sulfur or by the oxidation of the *P*-oxides.

Whereas the organic groups linked to the phosphorus exert no effect in these reactions, those bound to the nitrogen are highly influential in the reactivity of the lone electron pair on the P-atom. A mesomeric anion *(1)* has now been postulated for the metallated thiocarbamoylphosphines prepared from thiocarbamoylphosphines and phenyl-lithium, or from alkali metal phosphide and isothiocyanate.

$$[R_2P-C(S)-N^{\ominus}R' \longleftrightarrow R_2P-C(S^{\ominus})=NR'] M^{\oplus}$$

(1a) *(1b)*

The existence of this mesomeric anion is indicated by the fact that the reaction with, methanol leads to thiocarbamoylphosphines, pointing to form *(1a)*, whereas the reaction with ethyl iodide results in *S*-ethylisothiocarbamoylphosphines, the substrate being in form *(1b)*.

With secondary phosphines, diisothiocyanates give thiocarbamoylphosphines of the general formula

$R_2P-C(S)-NH-R'-NH-C(S)-PR_2$

R = C_6H_5-, $C_6H_{11}-$; R' = $(C_6H_4)_2-$, $-(CH_2)_6-$

In contrast to methyl isothiocyanate, aryl isothiocyanates react with primary aliphatic and cycloaliphatic phosphines (phenylphosphine does not react), giving bis(thiocarbamoyl)-phosphines, $RP[-C(S)-NHR']_2$, or thiocarbamoylphosphines, $RHP-C(S)-NHR'$. The former are also obtained with dilithium phosphide, Li_2PR, by hydrolysis. The formation of addition compounds between tertiary phosphines and aryl isothiocyanates has not been observed in the case of the biphosphines, R_2P-PR_2, which form thiocarbamoylphosphines in the presence of ethanol.

Preparation and Reactions of Optically Active Aminosilanes

K.-D. Kaufmann and *K. Rühlmann*, Berlin (Germany)

Optically active aminosilanes, $R_3Si^*NR^1R^2$ (R_3Si^* = α-naphthylphenylmethylsilyl, R^1 and R^2 = H, alkyl, or aryl), were prepared from optically active α-naphthylphenylmethylchlorosilane [1,2]. On the basis of optical rotatory dispersion [3], the configuration (−)-R_3Si^*-H has been assigned to the aminosilanes prepared from (−)-R_3Si^*Cl [4].

It follows from this that the nucleophilic substitutions of amines in halosilanes also proceed *via* an S_N2 mechanism, with inversion of configuration at the silicon center. The hydrolysis and the alcoholysis of aminosilanes in polar and non-polar solvents are also accompanied by inversion of configuration. In the conversion of aminosilanes with acid halides into halosilanes and the corresponding amides, inversion of configuration occurs if the steric shielding of the nitrogen atom in the aminosilane is low. Thus the stereochemical yields (inversion) in the reaction of $R_3Si^*NHCH_3$ with *p*-nitrobenzoyl chloride and with phosphorus trichloride are 98 and 83%, respectively. With bulkier substituents at the nitrogen, however, a competing reaction also takes place, accompanied by retention of configuration. Thus the reaction of $R_3Si^*NHC_6H_{11}$ ($C_6H_{11}-$ = cyclohexyl) with *p*-nitrobenzoyl chloride to give R_3Si^*Cl, which is still characterized by the predominance of inversion, leads to a stereochemical yield of only 63%, whereas the reaction of $R_3Si^*N(C_2H_5)_2$ with PCl_3 results in a yield characterized by 61% retention. Similar phenomena have been observed in the reaction of aminosilanes with HCl in non-polar solvents [1].

The reactions of aminosilanes with $LiAlH_4$, giving R_3Si^*H [1], and with solid KOH, giving R_3Si^*OK, proceed predominantly with retention of configuration.

According to these results, inversion of configuration is to be expected in the reactions of aminosilanes if the $d_\pi-p_\pi$ bond between silicon and nitrogen can be ruptured by protons or Lewis acids, whilst retention of configuration occurs whenever this bond can be broken only *via* the formation of a cyclic intermediate.

N-(Iodophenyl)pyridinium Salts

B. Lipke, Berlin (Germany)

In order to study their oxidation reactions, three isomeric *N*-(iodophenyl)pyridinium salts were prepared by *W. König*'s method from cyanogen bromide, pyridine, and the corresponding iodoanilines, and were converted into compounds containing iodine in its higher valence states.

The three isomeric (dichloroiodophenyl)pyridinium salts were prepared by chlorination of the *N*-(iodophenyl)pyridinium salts. Attempts at conversion into the iodoso derivatives were unsuccessful. With the aid of the *N*-(4-iodylphenyl)pyridinium salts, which were prepared from *N*-(iodophenyl)-pyridinium salts by the action of peroxydisulfuric acid, hydroquinone was oxidized to quinone, aniline to azobenzene, and ethanol to acetaldehyde, the reactions being carried out in aqueous acetone at 20 to 50 °C.

At 0 °C, *N*-(4-bromophenyl)pyridinium chloride and *N*-(4-chlorophenyl)pyridinium chloride form adducts with chlorine.

Bonding and Electron Distribution in the I_3^- Ion According to a Three-Dimensional Free-Electron Model

Hans Müller, Jena (Germany)

The three-dimensional free-electron (FE) model suggested earlier [5] can be used for the calculation of bond energies because of the simultaneous treatment of the σ- and π-electrons. In accordance with the $D_{\infty h}$ symmetry group of the

[1] *L. H. Sommer, J. D. Citron*, and *C. L. Frye*, J. Amer. chem. Soc. *86*, 5684 (1964).

[2] *K. Rühlmann, K.-D. Kaufmann*, and *U. Mann*, Z. Chem. *5*, 107 (1965).

[3] *K.-D. Kaufmann, U. Mann*, and *K. Rühlmann*, Z. Chem. *5*, 188 (1965).

[4] Cf. *L. H. Sommer, C. L. Frye, G. A. Parker*, and *K. W. Michael*, J. Amer. chem. Soc. *86*, 3271 (1964).

[5] *H. Müller* and *H. Dunken*, Theoret. chim. Acta *3*, 97 (1965).

linear I_3^- ion, the 22 valence electrons of the molecule-ion are considered to form a force-free electron gas in a cylindrical potential box. Solution of the Schrödinger equation gives the eigenvalues in closed form and tractable eigenfunctions Ψ_{lpn}. The I_3^- ion is a particularly interesting three-center system, since both I_2 and I^- (which may be considered as the components of I_3^-) have complete octets, so that the additional covalent bond in I_3^- is usually described in terms of hybridization, although the excitation $\ldots(5d)^5 \rightarrow \ldots(5d)^4(6s)$ requires 156 kcal/mole, and the bond energy of I_2 is only 35.6 kcal/mole. In the FE model, on the other hand, the formation of I_3^- can be described without recourse to higher orbitals, thus avoiding this difficulty.

As early as 1951, a MO calculation by *Pimentel* [6] succeeded in excluding the higher states, but arrived at an unsatisfactory qualitative result by taking into account only four electrons and assuming that the other 18 valence electrons occupied non-bonding orbitals.

On the basis of the FE model, the ground state of the I_3^- ion is expressed as (R denotes inner electrons):

$$I_3^-[RRR(1\sigma_g)^2(1\sigma_u)^2(2\sigma_g)^2(2\sigma_u)^2(1\pi_u)^4(1\pi_g)^4(3\sigma_g)^2(2\pi_u)^4]\,{}^1\Sigma \quad (1)$$

Weak σ-bonds are deduced for I_3^- from a balance between the bonding orbitals ($1\sigma_g$, $2\sigma_u$, $1\pi_u$) and the antibonding orbitals ($2\sigma_g$, $2\pi_u$), and a bond energy of 25.8 kcal/mole is obtained for the I–I bond. The corresponding electronic distribution is inferred from an FE molecular diagram:

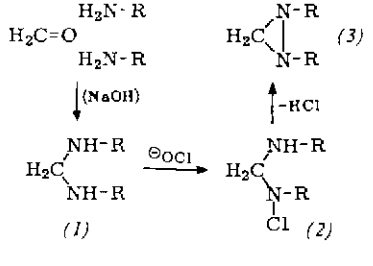
$$1.89\text{–}I\ \underset{3.83}{\overset{1.58}{\underset{1.79}{\quad}}}\ I\text{–}3.38\text{–}I\text{–}1.89 \qquad 3.79$$

whose electronic population $pop_nV = \int g_n D_n(z)dz$ can be calculated from the FE molecular orbitals by the use of the axial density, $D_n(z) = \iint|\Psi_{lpn}|^2\rho d\rho d\varphi$. The aufbau principle following from *(1)* is applicable to linear triisocentric systems, as can be shown on H_3^+, C_3, Si_3, Ge_3, Sn_3, N_3^-, and I_3^-.

Cyclization of 1,1-Diamino Compounds

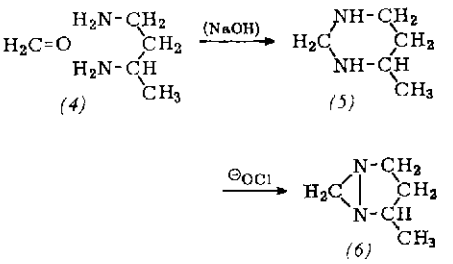
R. Ohme and *P. Dolge*, Berlin (Germany)

Primary aliphatic amines react with formaldehyde leading to hexahydro-1,3,5-triazines. Aminals of formaldehyde are assumed to be the intermediates involved in this well-known reaction. When formaldehyde is condensed with 2 moles of an alkyl amine in a strongly alkaline medium (2N NaOH), the reaction stops at the aminal stage *(1)*.

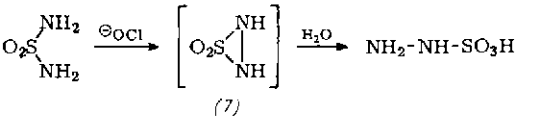


If 1 mole of sodium hypochlorite is then added, *N,N'*-dialkyldiaziridines *(3)* are obtained in good yields *via* the *N*-chloraminals *(2)*. The 1,3-diamine *(4)* can be condensed with formaldehyde in 2 N NaOH, giving a cyclic aminal *(5)*, which is further cyclized into the diaziridine derivative *(6)*, yield 93%, when treated with hypochlorite.

The *N*-substituents in the diaziridine *(6)* are attached in the cis-position, and therefore the compound has a dipole moment of 2.91 D, which is too high for diaziridines.

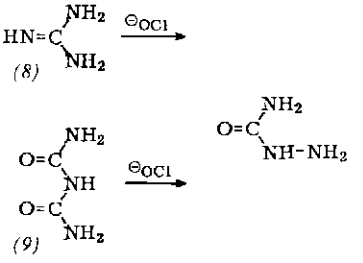


With alkaline hypochlorite, sulfamide forms hydrazinosulfonic acid:



Similarly to the reaction of *N,N'*-dialkylsulfuric acid diamides [1], an S–N–N ring *(7)* may be assumed as intermediate.

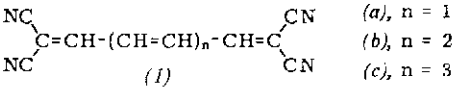
The action of alkaline hypochlorite on guanidine *(8)* and biuret *(9)* leads to semicarbazide (isolated as the *p*-nitrobenzaldehyde semicarbazoen) in a yield of 30–40%.



Synthesis and Properties of Tetracyanopolyenes

Hermann Schmidt and *C. Hamann*, Dresden (Germany)

Tetracyanopolyenes of type *(1)* were prepared, the starting material for *(1a)* and *(1c)* being 1,1,4,4-tetramethoxybut-2-



ene, the bisacetal of maleic dialdehyde. Acid condensation with malononitrile led to *(1a)* in good yield. In the preparation of *(1c)*, the unsaturated bisacetal was first converted by *Kucharov*'s method into 2,4,6-octatriene-1,8-dial, and the latter was then made to react with malononitrile to give *(1c)*. Product *(1b)* was analogously obtained from *trans,trans*-mucondialdehyde bisacetal. Ethyl cyanoacetate, ω-cyanoacetophenone, or barbituric acid can be used as a CH-active compound. Infrared spectroscopy showed all polyenes obtained in this manner to be all-*trans* compounds.

Tetracyanopolyenes behave similarly to tetracyanoethylene in that they form colored π-complexes with aromatic hydrocarbons. In the Diels-Alder reaction, two moles of a diene react with one mole of tetracyanopolyene. They are readily converted into the expected products with nucleophilic reagents (amines, alcohols).

Polycrystalline samples were used to measure the d-c dark conductivity of the polyenes as a function of temperature. This property was found to increase with the number of π-electrons in the compound. The tetracyanopolyenes are n-type semiconductors, their Seebeck coefficients varying linearly with the number of π-electrons in the compound.

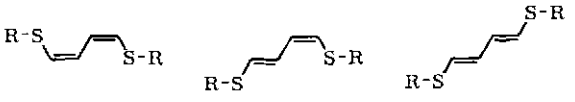
[6] *G. C. Pimentel*, J. chem. Physics *19*, 446 (1951).

[1] *R. Ohme* and *E. Schmitz*, Angew. Chem. *77*, 429 (1965); Angew. Chem. internat. Edit. *4*, 433 (1965).

Syntheses and Reactions of 1,4-Dimercaptobutadienes

W. Schroth, F. Billig, and *H. Langguth,* Leipzig (Germany)

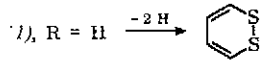
cis,cis-1,4-Bis(dibenzylthio)butadiene *(1)* (R = $-CH_2-C_6H_5$) prepared by the nucleophilic addition of benzyl mercaptan to diacetylene reacts with sodium in liquid ammonia with retention of the double bonds to give the *cis,cis* salt *(1)*, R = Na, which can be *S*-alkylated and *S*-acylated. The multiple bonds



(1) *(2)* *(3)*

also remain intact in the analogous debenzylation of bis-(benzylthio)acetylene into the sodium salt of dimercaptoacetylene (investigations carried out in collaboration with *D. Wallach*). The free dimercaptan *(1)*, R = H, obtained from *(1)*, R = Na, forms the phenylhydrazone of succinaldehyde and thiophene (50% yield) with P_4O_{10}.

The dehydrogenation of *(1)*, R = H, leads to 1,2-dithiin *(4)*, which behaves as an heterocyclic olefin and not as an aromatic compound.



(4)

On ultraviolet irradiation, *(1)*, R = $COCH_3$, undergoes rearrangement, giving the corresponding *cis,trans*-isomer *(2)* and the *trans,trans*-isomer *(3)*, both of which can be hydrolysed and alkylated into sterically uniform derivatives.

Compound *(3)*, R = $COCH_3$, was also obtained from cyclooctatetraene dibromide with potassium thioacetate, by diene synthesis with acetylenedicarboxylic ester, and by the Alder-Rickert fission. Only the *trans,trans*-isomer *(3)*, R = $COCH_3$, reacts with dienophiles under mild conditions because of the possibility of the *cis*-configuration about both double bonds. The diene adducts can be aromatized by the cleavage of thioacetic acid.

The free dimercaptans *(1)*–*(3)*, R = H, exist almost exclusively as enthiols and not as thioaldehydes.

Equilibrium measurements have shown that *cis*-bis(methylthio)ethylene [1] is more stable below 60 °C than the *trans*-isomer (work carried out with *R. Kemmler*).

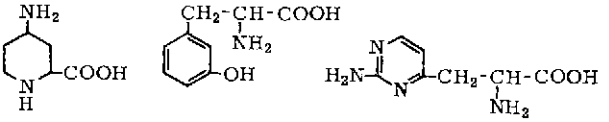
Rare Amino Acids in Plants

H.-R. Schütte, Halle (Germany)

Several non-proteinogenic amino acids have recently been found in plants. The author has investigated 4-aminopipecolinic acid *(1)* extracted from *Strophanthus scandens*, *m*-tyrosine *(2)* extracted from *Euphorbia myrsinitis*, and tingitanin *(3)* obtained from *Lathyrus tingitanus*. The structure of 4-aminopipecolinic acid was established by synthesis and by converting the compound into 4-hydroxypipecolinic acid with sodium nitrite. 4-Aminopipecolinic acid is formed in plants from pipecolinic acid *via* hydroxypipecolinic acid and probably 4-ketopipecolinic acid.

The structure of *m*-tyrosine was elucidated by oxidation reactions, in which *m*-hydroxybenzoic acid was formed together with aspartic acid (on rupture of the benzene ring).

The structure of tingitanin, deduced elsewhere [2] from physical properties, has now been confirmed by synthesis from 2-amino-4-chloromethyl-pyrimidine and ethyl acetaminocyanoacetate. It seems that the biosynthesis of these amino acids proceeds *via* aspartic acid, lysine, homoarginine, and γ-hydroxyhomoarginine.



(1) *(2)* *(3)*

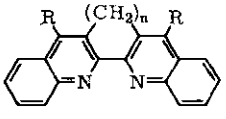
[1] *W. Schroth,* Tetrahedron Letters *1965*, 195, the literature cited therein.

[2] *E. A. Bell* and *R. G. Foster,* Nature (London) *194*, 91 (1962).

The Complexochemical Properties of Bridged 2,2'-Biquinolyls

E. Uhlemann and *P. Thomas,* Leipzig (Germany)

Several new compounds of the type *(1)* were synthesized and used to prepare complexes of various transition metals. Only 1:1 and 1:2 complexes were formed, similarly to other reagents of the cuproin series. Daylight converts the copper(II) complexes of *(1)* into the copper(I) complexes, the rate of the reaction depending on the temperature, solvent, and the intensity of irradiation.



(1), R = H, CH_3, C_6H_5
n = 1, 2, 3

the copper(II) complexes of *(1)* are converted into the copper(I) complexes, the rate of the reaction depending on the temperature, solvent, and the intensity of irradiation.

The strongly colored copper(I) complexes of compounds of type *(1)*, with n = 2, are suitable for the quantitative photometric determination of copper. They can be extracted with isopentanol.

The complexochemical properties of compounds *(1)* (spectra, basicity constants, and the stability of the complexes) are influenced by substituents in the 4,4'-positions and by the length of the 3,3'-methylene bridge. The polarographic reduction of the copper complexes of *(1)* is irreversible. Therefore, only the relative stabilities of these complexes can be estimated.

Reversed-Phase Paper-Chromatographic Separation of Rare Earths

G. Werner, Leipzig (Germany)

In an organic solvent, dinonylnaphthalenesulfonic acid (DNNSA) acts as a liquid cation-exchanger. Chromatography paper can serve as a support for this organic phase, the mobile phase being an aqueous solution (reversed phases). Paper impregnated with DNNSA can be used for the separation of rare earths. If a non-complexing eluent is used, separation is poor, since the rare earths all have approximately the same affinity for the sulfonic acid. When hydrochloric acid is used as an eluent, the mean separation factor of the adjacent rare earths is 1.04. As in the case of sulfonic acid ion-exchange resins, the lighter elements are more strongly fixed than the heavier ones.

In the application of complexing eluents (lactic acid, α-hydroxybutyric acid), the separation factors are determined by the stability of the rare earth complexes. The R_F-values can be correlated with the distribution coefficients of the DNNSA extraction and of the sulfonic acid ion exchange, as well as with the complexing constants of the rare earths with the eluent.

The rare earths were applied to the paper in 5–20 μg samples, eluted, and the paper was developed by spraying with an ammonical alcoholic solution of 0.1% 1-(2-pyridylazo)-2-naphthol. The spots were marked immediately, since they fade very quickly. With the exception of the Eu/Gd, Tb/Dy, and Dy/Ho pairs, any four adjacent elements chosen from La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, and Yb can be separated on a paper chromatogram by the correct selection (in each case) of the concentration and the pH of the eluent, each separation being characterized by constant conditions of elution.

[VB 947/261 1E]
German version: Angew. Chem. 77, 915 (1965)
Translated by Express Translation Service, London

Oxidation in Organic Chemistry

A Symposium on Oxidation in Organic Chemistry was held on March 23rd and 24th, 1965 in the Manchester College of Science and Technology, Manchester (England). Most of the contributions came from scientists in the chemical industry.

From the lectures:

Recent Advances in Metal-Ligand Oxidation Chemistry

J. P. Candlin, G. A. Gamlen, and *J. K. MacKay,*
Runcorn, Cheshire (England)

A necessary condition for electron transfer from or to a metal ion to occur is given by the law of conservation of energy. Thus, for example, the energy absorbed in the rearrangement of a complex so that an electron transfer can occur must be removed again in order to reach the final state. This condition is easy to fulfil in solution owing to the large number of energy levels available. The electron which is transferred must be in a state which is undisturbed by the other electrons in the system, usually an excited state.

If electronegative ligands exert a strong attraction on the electrons of the coordinative σ-bond in a complex, the central atom can take up electrons, and thus a low valence state of the metal atom is stabilized. The withdrawal of electrons into unoccupied or antibonding orbitals is particularly efficient in this respect. The lower the energy of the unoccupied orbital on the ligand, the greater its ability to attract electrons, hence electronegative ligands with vacant orbitals of the π-type, *e.g.* CO and PF_3, stabilize low valence states particularly well.

A third kind of ligand, *e.g.* $OH^{\ominus}$, $F^{\ominus}$, and H_2O, can release sp-electrons into unoccupied orbitals of the metal atom and thus alter the charge density at the metal. The large number of electrons on the central atom then causes the easy release of electrons to oxidizing agents, a process which stabilizes a high oxidation state of the metal.

There are also ligands which stabilize both low and high oxidation states. For instance, $o\text{-}C_6H_4[As(CH_3)_2]_2$ forms complexes with a higher coordination number than that allowed by the rule of the effective atomic number. The excess electrons on the central atom can be readily removed by oxidation. Heterocycles, whose readily polarized π-electron system can both release electrons to and absorb electrons from the central metal atom, are another group of ligands of this type.

The electronic structure of the metal atom also determines in part the occurrence of stable oxidation states. According to the ligand field theory, the five-fold degenerate d-orbitals in octahedral complexes are split under the influence of the ligand field into three orbitals of lower energy and two of higher energy, so that one unpaired electron in Co(II) complexes and two in Ni(II) complexes are in orbitals of higher energy and can therefore be easily released if the ligand field is strong enough. This results in Co(III), Ni(III), and even Ni(IV) as stable oxidation states. Under the influence of the strong ligand field of $CN^{\ominus}$, Fe(III) is a strong oxidizing agent, since the orbitals of low energy are occupied by only five electrons and can readily accomodate one more.

An example of the application of these considerations is the air-drying of a soya oil alkyd film in the presence of a Co(II)-*o*-phenanthroline complex (1:2), which can reduce oxygen to the superoxy stage ($O_2^{\ominus}$), which occupies a free coordination site and initiates the free-radical cross-linking of the oil. The oxygen is reduced to the peroxide stage ($O_2^{2\ominus}$) during this process. The peroxide reduces the Co(III) initially formed back to Co(II). Catalysis by Co(II) is suppressed by a third mole of *o*-phenanthroline. In the presence of a ligand with a lower ligand field, the oxidation of Co(II) to Co(III) with simultaneous formation of superoxide cannot occur. Ligands of higher field strength, *e.g.* $CN^{\ominus}$, prevent the back-reduction to Co(II). The selection of ligands of suitable field strength is therefore of decisive importance for such catalytic processes and even more so for biochemical reactions.

Oxidation of Olefins with Palladium Chloride [1]

J. Smidt, W. Hafner, R. Jira, A. Sabel, J. Sedlmeier, and *R. Sieber,* München (Germany)

The oxidation of olefins to carbonyl compounds by palladium chloride proceeds *via* palladium chloride-olefin complexes. Kinetic investigations showed that the step which initiates the hydrolysis of the complex is an intramolecular reaction of the complexed olefin with a hydroxo ligand on the palladium. Analogous reactions are probably involved in the formation of vinyl acetate and isopropenyl acetate from acetic acid and ethylene or propylene and in the formation of vinyl chloride by thermolysis of $K[C_2H_4PtCl_3]$. Another route that deserves attention is the oxidation *via* π-allyl complexes; sometimes this is the preferred route, *e.g.* with isobutylene or allyl halides. It leads in anhydrous media to allyl compounds, *e.g.* allyl chloride or allyl acetate, but in the presence of water to unsaturated carbonyl compounds, *e.g.* acrolein and its homologues.

Carbonylation of olefins in the presence of palladium chloride also entails olefin or π-allyl complexes. The product composition is not as uniform as in the oxidation of olefins, because carbon monoxide is not a strong nucleophile.

Mechanisms of Oxidation of Organic Compounds by Ions of the Transition Metals

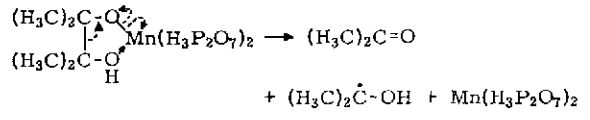
W. A. Waters, Oxford (England)

One prerequisite for many oxidations with ions of transition metals is the intermediate substitution of a ligand of the transition metal ion by the molecule that is to be oxidized in order to make the electron transfer possible or easier. For instance, the oxidation of thiols to disulfides by $K_3[Fe(CN)_6]$ occurs by substitution of a $CN^{\ominus}$ ion by a sulfide residue which releases an electron to the Fe(III), being thereby transformed into a sulfide radical, in preference to a direct transfer of the electron through the hexacyano shell.

$$[RS\text{–}Fe(CN)_5]^{3\ominus} \rightarrow RS\cdot + [Fe(CN)_5]^{3\ominus}$$

[1] Cf. *J. Smidt* et al., Angew. Chem. *71*, 176 (1959); *74*, 93 (1962); Angew. Chem. internat. Edit. *1*, 80 (1962).

Frequently steric factors determine whether a reaction occurs. Simple primary alcohols are not attacked by $Mn[H_3P_2O_7)_3$, but the latter oxidizes pinacol readily to acetone. This reaction proceeds *via* a chelate.



(The broken arrows indicate the transfer of a single electron.)

Some other examples of oxidations by oxometallates in which an intermediate bond between the organic molecule and the metallate ion have been detected are the oxidation of benzaldehyde to benzoic acid and of olefins to glycols by permanganate, the oxidation of alcohols to aldehydes by $HCrO_4^{\ominus}$, and the oxidation of cyclohexanol to cyclohexanone by $[V(OH)_3]^{2\oplus}$. Ester-like intermediates occur during these reactions. When one-electron transfers occur, *e.g.* manganese(VII) → manganese(VI) or vanadium(V) → vanadium(IV), free radicals are often formed as intermediates.

The active form of $Co(ClO_4)_3$ is the cation $[(HO)Co(H_2O)_5]_2^{\oplus}$, which can oxidize primary, secondary, and tertiary alcohols, carboxylic acids, and aromatic hydrocarbons. The products formed are similar to those obtained in other free-radical reactions, *e.g.* the Kolbe synthesis or the Sandmeyer reaction.

Liquid-Phase Oxidation of Organic Compounds with Oxygen

G. H. Twigg, Epsom, Surrey (England)

This reaction has a free-radical chain mechanism; the first products formed usually are hydroperoxides which can react further in various ways.

$$ROO\bullet + RH \rightarrow ROOH + R\bullet$$

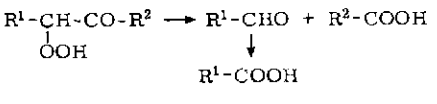
The formation of cumene hydroperoxide in this way is a technically important reaction.

The "hydroperoxide" formed in the oxidation of acetaldehyde is peroxyacetic acid, which reacts with unchanged acetaldehyde to yield a hydroxy peroxyester. The peroxyacetic acid can be isolated from the equilibrium mixture of these three substances. Under the catalytic influence of heavy metal salts, the hydroxy peroxyester rearranges by a non-radical mechanism to two moles of acetic acid. If large amounts of metal salts are present, especially copper salts, the product is acetic anhydride.

$$CH_3{-}CO\bullet + Cu^{2\oplus} \rightarrow CH_3{-}CO^{\oplus} + Cu^{\oplus}$$

$$CH_3{-}CO^{\oplus} + CH_3COOH \rightarrow (CH_3{-}CO)_2O + H^{\oplus}$$

Ketones react more slowly than aldehydes and also yield hydroperoxides according to the same general scheme, but the hydroperoxides often rearrange to acids and aldehydes or ketones. The ketonic products — and even more so the aldehydes — are oxidized further.



Ethers yield hydroperoxides. Alkyl benzyl ethers can be decomposed under the catalytic influence of $Fe^{2\oplus}$ to esters.

When alcohols are oxidized, the carbon atom bearing the hydroxyl group is attacked. The autoxidation of isopropanol to acetone and hydrogen peroxide is a process of technical importance.

$$(CH_3)_2CHOH + HOO\cdot \rightarrow (CH_3)_2\dot{C}{-}OH + H_2O_2$$

$$(CH_3)_2\dot{C}{-}OH + O_2 \rightarrow (CH_3)_2CO + HOO\cdot$$

Numerous products are obtained from the autoxidation of olefins. This is due in part to the resonance of the intermediate allyl radicals formed. 1,4-Diolefins give good yields of hydroperoxides. Epoxides are frequently obtained as the main products when substituted olefins are oxidized.

Under suitable conditions, *e.g.* low oxygen pressures, readily polymerizing olefins such as styrene can yield copolymers with oxygen.

$$ROO\bullet + Ph{-}CH{=}CH_2 \rightarrow ROO{-}CH_2{-}\dot{C}HPh \xrightarrow{O_2} ROO{-}CH_2{-}CHPh{-}O{-}O\bullet\ldots$$

Elevated temperatures are necessary for the oxidation of paraffins because of the absence of activating groups. Tertiary carbon atoms are attacked faster than secondary or primary carbons. The primary products are again hydroperoxides and the major end-products are ketones.

$$R^1OO\bullet + R^2CH{-}OOH \rightarrow R^1OOH + R^2_2\dot{C}{-}OOH$$

$$R^2_2\dot{C}{-}OOH \rightarrow R^2_2C{=}O + HO\bullet$$

$$HO\bullet + R^2_2CH{-}OOH \rightarrow H_2O + R^2_2\dot{C}{-}OOH$$

The amounts of acids formed increase with the time of reaction; the acids are formed by the scheme mentioned above for the oxidation of ketones. The oxidation of butane to acetic acid is an important technical process. Higher paraffins also yield dihydroperoxides, ketonic hydroperoxides, and diketones.

In the presence of boric acid and a limited amount of oxygen, the hydroperoxide is trapped in the form of its peroxyborate, and alcohols can be obtained as reaction products.

Paraffin-Oxygen Reactions at 500–650 °C

R. J. Sampson, Billingham, Durham (England)

The reaction (at low conversions) of ethane with oxygen in a small autoclave at 600–630 °C yielded ethylene (90% of the reacted carbon), H_2O, H_2O_2, H_2, HCHO, CH_4, CO, CH_3CHO, ethylene oxide, and traces of other products. In order to explain these results, a quasi-stationary free-radical chain mechanism was assumed [2]. The main reaction is the abstraction of a hydrogen atom from the ethane by a hydroxyl radical formed from H_2O_2. The oxygen then removes another hydrogen atom from the ethyl radical and converts it into ethylene.

The other products are formed by chain-terminating reactions following chain branching, which includes the formation of the radicals $H\cdot$, $C_2H_5O\cdot$, $H_3O\cdot$, $H_3CO\cdot$, *etc.* Ethylene oxide is formed from ethylene.

Similar autoxidations of propane, n-butane, isobutane, n-pentane, and isopentane were examined at conversions of up to 30%. The principal products were olefins and methane. About 10 moles of oxygenated products such as formaldehyde, acetaldehyde, and methanol plus minor amounts of ethanol, acetone, acrolein, ethylene oxide, propylene oxide, and propionaldehyde and traces of other products were obtained for every 100 moles of paraffin.

The reactivity increases as the number of carbon atoms in the paraffin rises but also depends to a large extent on the structure of the paraffin. At low conversions, propane yields mainly propylene, but as the conversion increases, progressively less propylene but more ethylene and methane are formed. In the same way, n-butane and n-pentane give increasing yields of ethylene, propylene, and methane and decreasing amounts of butylene and pentene. The composition of the mixture of products is considerably different with the iso-paraffins: olefins with one carbon atom less than the initial iso-alkane are the main products, accompanied by olefins with the same number of carbons, methane, ethylene, hydrogen, *etc.*

[2] *R. J. Sampson*, J. chem. Soc. (London) *1963*, 5095.

Oxychlorination

R. B. Richards, Runcorn, Cheshire (England)

Oxychlorination is the reaction of hydrocarbons with hydrogen chloride and oxygen which leads to chlorinated addition and substitution products. Currently it is used mainly for the production of dichloroethane from ethylene, the dichloroethane then being dehydrochlorinated by pyrolysis to vinyl chloride. A modified Deacon catalyst consisting essentially of cupric chloride distributed on pumice as a carrier is used. The rate-determining step in the reaction is:

$$C_2H_4 + 2\,CuCl_2 \rightarrow Cu_2Cl_2 + C_2H_4Cl_2$$

The oxygen mixed with the hydrogen chloride reconverts the cuprous chloride into the cupric salt at 250–300 °C. Free chlorine cannot be detected, and hence the Deacon mechanism, which requires a temperature of 400–450 °C, cannot be in operation with ethylene. However, this mechanism probably does occur during the oxychlorination of paraffins such as ethane, which requires higher temperatures.

Oxidation of Organic Compounds by Sulfur Dioxide under Pressure

A. J. Shipman, Runcorn, Cheshire (England)

Alkylated aromatic compounds are oxidized by excess sulfur dioxide at 250–400 °C and pressures of at least 300 atm to the corresponding aromatic carboxylic acids in 80–90% yield. For example, toluene gives benzoic acid, xylenes give phthalic acids, and pseudocumene gives trimellitic acid. The sulfur dioxide is reduced to sulfur. Aldehydes can be obtained by using smaller amounts of SO_2.

The heat of reaction for the oxidation of a methyl group is about 50 kcal/mole; the activation energy is about 42 kcal/mole. The reaction is accelerated by bromo and iodo compounds but completely suppressed by copper or silver. Solvents exert no effect on the reaction. A free-radical chain mechanism similar to that for the oxidation of hydrocarbons with oxygen is assumed.

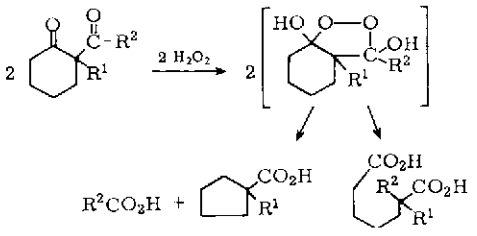
Unsubstituted aromatic compounds, polycyclic hydrocarbons, pyridine, and the picolines do not react with SO_2 under the usual reaction conditions. However, above 450 °C benzene is transformed into biphenyl, diphenyl sulfide, *etc.* Alicyclic compounds are dehydrogenated to aromatics. Non-oxidative reactions occur with other compounds. Olefins copolymerize in the presence of a free-radical sources to yield polysulfones and cyclic sulfones. Alkylene oxides afford cyclic sulfites, and aliphatic alcohols yield ethers.

Some Recent Developments in Organic Oxidations Utilizing Hydrogen Peroxide

G. B. Payne and *J. D. McLure*, Emeryville, Cf. (U.S.A.)

The reactivity of hydrogen peroxide can be augmented by addition to some organic compounds. A suitable adduct is for example peroxyacetic acid. Hydrogen peroxide plus acetonitrile or benzonitrile gives rise to peroxyimidic acids which oxidize olefinic double bonds to epoxides. Since the reactions are carried out in neutral or weakly alkaline solutions, these compounds can be used to make epoxides which are otherwise unobtainable or formed in only low yields, *e.g.* the epoxides of acrolein diethyl acetal, allylcyclohexanone, and 5-hexenone. Unsaturated peroxyimidic acids rearrange to the corresponding epoxy carboxamides.

New, highly effective oxidizing agents for the Baeyer-Villiger reaction are peroxymaleic acid and a reagent consisting of 90% hydrogen peroxide and boron trifluoride etherate. 2-Acylcyclohexanones react with hydrogen peroxide – probably *via* a cyclic peroxide – to yield a cyclopentanecarboxylic acid and a dicarboxylic acid.



Another reaction with activated H_2O_2 is the oxidation of benzene homologues – preferably methyl derivatives have been converted – to phenols and quinones using trifluoroperoxyacetic acid; frequently a shift of the methyl groups is observed.

Polymerization by Oxidative Coupling

A. S. Hay and *J. B. Elliot*, Schenectady, N.Y. (U.S.A.)

Novel polymers with excellent properties are formed by oxidation of 2,6-dimethylphenol with oxygen in the presence of a cupramine complex with the composition, for example, $(R_3N)_2CuCl(OH)$. During the reaction, a phenoxide anion replaces the hydroxyl group in the complex. An electron transfer from the oxygen of the phenoxide ion to the Cu(II) reduces the latter to Cu(I). The resultant phenoxide radical is an intermediate in the formation of the poly(phenylene oxide).

The most suitable amines for the complex are aliphatic tertiary amines containing at least one small alkyl residue, *e.g.* methyl-di-n-octylamine. Other coupling reactions are also possible. When a polymer made from *m*-diethynylbenzene is ignited, its hydrogen burns away with explosive rapidity, but the carbon skeleton remains intact. If a film of the polymer is applied to a solid and then gradually warmed, a conducting carbon film results.

Inhibition of Oxidation

G. Scott, Grangemouth (England)

Inhibition of oxidation is an extension of the induction period of free-radical initiated, mostly autocatalysed oxidation of organic compounds. There are two types of antioxidants. Those which interrupt the oxidation chain are mostly phenols or amines. Their effectiveness is increased by electron-releasing groups (*e.g.* CH_3) and reduced by electron-attracting groups (*e.g.* CN). Their activity is due to their stabilizing or activating effect on the free radicals formed. Steric factors are also important. The second group contains substances which prevent oxidation; here one can differentiate between 1. complexing (chelating) agents which sequester the metal ions that activate peroxides; 2. ultraviolet-light deactivators (2-hydroxybenzophenones), which are rearranged by ultraviolet irradiation to enolic quinones; 3. sulfur compounds such as dithiocarbamic acid, dithiophosphoric acid, and especially dilauryl 3-thiaheptanedioate ("dilauryl thiodipropionate"), which decompose peroxides without giving rise to free radicals. The last compound is used as stabilizer for polypropylene.

[VB 929/243 IE]
German version: Angew. Chem. 77, 867 (1965)

Second Conference of the Federation of European Biochemical Societies

The conference was organized by the Austrian Biochemical Society under the direction of *O. Hoffmann-Ostenhof* and took place in Vienna from April 21st to 24th, 1965. It included three colloquia on "Antibodies to biologically active molecules", "Cyclitols and phosphoinositides", and "Biosynthesis of aromatic compounds", as well as a symposium on the structure and function of ribonucleic acid. Many research papers were also given. About 500 papers were read and some of the results described are reported below.

1. Antibodies to Biologically Active Molecules

M. R. Pollock (England) studied the influence of specific antibodies on the biological activity of bacterial penicillinases produced by wild-type *Bacillus licheniformis* and its mutants. The mutant penicillinase proteins ("muteins") differ from wild-type penicillinase by only one amino acid (point mutation). In the majority of cases, the activity is less than that of natural penicillinase. The "muteins" are precipitated by anti-wild-type penicillinase serum and the activity is then found to have increased almost to that of the precipitate obtained from the wild-type enzyme with the same antiserum. It is thought that the lower activity of the mutein is due to a conformational change resulting from a modification of the primary structure and partly counteracted by reaction with the antibody.

D. Glässer and *M. John* (Germany), by intravenous injection of recrystallized leucine aminopeptidase from bullock's eye lens into mice and rabbits, have produced a several hundredfold increase in the serum level of this enzyme without causing toxic reactions. However, it is impossible to maintain the continuously decreasing level by re-injection. This suggests the formation of antibodies against the active center of the injected leucine aminopeptidase.

An enzyme isolated from mouse salivary gland by *I. Trautschold, E. Werle,* and *A. Schmal* (Germany) was found to resemble kidney renin in its ability to split off Hypertensin I from blood plasma hypertensinogen. Antibodies to this enzyme, produced in the rat, also inactivate mouse kidney renin. Thus the enzymes from the kidney and from the salivary gland have the same specificity range and identical antigen determinants.

2. Cyclitols (Polyhydroxycyclohexanes) and Phosphoinositides

F. Eisenberg, Jr. (U.S.A.) reported on the biosynthesis of inositol in mammals. Experiments on rats point to the testicular tubules as the site of synthesis. The semen contains 1 % inositol, whose function is as yet unknown. Using various forms of ^{14}C-labelled glucose, it was shown that inositol is formed by cyclization from the intact hexose. Glucose-6-phosphate is probably an intermediate product in the biosynthesis and the same is possibly true for *meso*-inositol 1-phosphate.

H. Kindl (Austria) has investigated the biosynthesis of *meso*-inositol in microorganisms and higher plants. Using variously ^{14}C-labelled glucose, he was able to show that *meso*-inositol is formed from intact D-glucose in such a way that C-1 of the glucose becomes C-6 of *meso*-inositol [1]. *Meso*-inositol is possibly metabolized *via* D-glucose 6-phosphate, *meso*-inosose-(2) 1-phosphate and *meso*-inositol 1-phosphate.

[1] *H. Kindl* and *O. Hoffmann-Ostenhof*, Biochem. Z. *339*, 374 (1964).

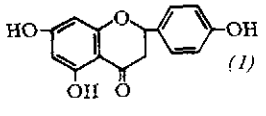
O. Hoffmann-Ostenhof (Austria) reviewed the biosynthesis of other cyclitols. Work carried out to date has shown that the synthesis of all naturally occurring hexahydroxycyclohexanes and their methyl ethers proceeds *via meso*-inositol or a derivative thereof. In *Trifolium incarnatum*, labelled *meso*-inositol is incorporated into D-inositol and the methyl ether D-pinitol. In one species of *Artemisia*, it is incorporated into L-inositol and the methyl ethers L-quebrachitol and L-pinitol, while in *Calicanthus occidentalis*, *meso*-inositol is a direct precursor of scyllitol. An independent biosynthesis for pentahydroxycyclohexanes, *e.g.* L-viburnitol and D-quercitol, cannot be ruled out.

R. M. C. Dawson (England) reported on the metabolism and function of the polyphosphoinositols. Using radioactive phosphorus, it was shown that the phosphate groups of the di- and tri-phosphoinositols, which occur in the brain, are metabolized rapidly. Triphosphoinositols have a greater affinity for calcium than for magnesium. It is suggested that these compounds play a part in controlling the permeation of monovalent ions, especially potassium, across certain regions of the nerve membrane.

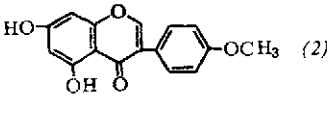
3. Biosynthesis of Aromatic Compounds

S. A. Brown (Canada) reported that over 100 coumarin compounds are known, almost all formed by higher plants. Coumarin itself probably does not exist in the intact cell in the free form but as the phenolic glucoside of *cis-o*-hydroxycinnamic acid. On destruction of the cell this glucoside is hydrolysed by a specific glucosidase and the free phenol is lactonized to coumarin. Using ^{14}C-labelled compounds it was shown that the biosynthesis of coumarin proceeds *via* shikimic acid, phenylalanine, *trans*-cinnamic acid, *trans-o*-hydroxycinnamic acid, *o*-coumaryl glucoside to *o*-coumarinyl glucoside. 7-Hydroxycoumarin and its derivatives also exist in the form of glucosides within the cell. Their biosynthesis takes place *via trans-p*-hydroxycinnamic acid, so that it is necessary to postulate the presence of enzyme systems different from those involved in the synthesis of coumarin itself. This explains why coumarin and 7-hydroxycoumarin are seldom found in association.

H. Grisebach et al. (Germany) found that extracts from chick-pea or parsley can synthesize flavones from cinnamic acid or 7-hydroxycinnamic acid. Using ^{14}C-labelled compounds, it can be shown that in red cabbage plants 5,7,4'-trihydroxyflavanone *(1)* is incorporated unchanged into the cyanidine molecule. In the chick-pea the same compound takes part in



(1)



(2)

the synthesis of biochanin-A (5,7-dihydroxy-4'-methoxyisoflavone) *(2)*. It was shown with *Chaemocyparis obtusa* that the flavanonols are formed by direct oxidation of flavanones and not *via* flavanols. In young tea leaves chalcones are precursors for catechins.

Work by *G. Billek* and *A. Schimpl* (Austria) has confirmed the hypothesis that biosynthesis of all naturally occurring stilbenes proceeds by condensation of a phenylpropane precursor with three acetate groups. These phenylpropane precursors are probably the corresponding cinnamic acids which

are hydroxylated before condensation to form stilbenes. The biosynthesis of 4-hydroxy- and 4-methoxystilbenes remains unsolved. These compounds are said to occur in the Himalayan variety of *Pinus excelsa* but have not been detected in European specimens.

According to *R. Azerad, R. Bleiler-Hill,* and *E. Lederer* (France) the radioactive carbon of [$^{14}CH_3$]-L-methionine is incorporated into position 2 of the naphthoquinone part of vitamin K_2, in cell-free extracts of *Mycobacterium phlei*. ATP and $MgCl_2$ are necessary for this process. [u-^{14}C]-Tyrosine is not incorporated.

M. H. Zenk (Germany) reported on the biosynthesis of C_6–C_1 compounds which are derived from C_6–C_3 compounds such as phenylalanine or cinnamic acid. C_6–C_1 acids result from β-oxidation of C_6–C_3 acids, presumably after these have been hydroxylated or methylated. C_6–C_1 aldehydes, for example vanillin, are also formed from C_6–C_3 compounds and not from the C_6–C_1 acids. Salicyl alcohol is formed particularly readily from *o*-hydroxycinnamic acid with liberation of free acetyl-CoA, which with CO_2 forms malonyl-CoA. This compound forms malonyltryptophan with tryptophan.

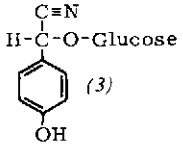
C. Ratledge (Ireland) has shown that in an iron-free medium *Mycobacterium smegmatis* preferentially accumulates salicylic acid. The yield of the latter is increased by addition of shikimic acid. Anthranilic acid, 3,4-dihydroxybenzoic acid, *p*-hydroxybenzoic acid, and *p*-hydroxyphenylacetic acid are also accumulated. Formation of salicylic acid from shikimic acid was postulated. Using cell-free extracts it was, however, possible to establish only the synthesis of anthranilic acid from shikimic acid. A possible mechanism for the anthranilic acid synthesis was put forward, with *N*-pyruvylanthranilic acid as the immediate precursor.

K. Schubert (Germany) was able to show that aromatization of steroids can be brought about with microorganisms. Aromatization is complete with *Mycobacterium smegmatis*, whereas a species of *Norcardia* effects only partial aromatization.

K. Mothes (Germany), in his review of the synthesis of aromatic systems in alkaloids, emphasized that different routes may lead to the same aromatic system in different plants. Thus nicotinic acid may be formed from tryptophan or aspartic acid. The same applies to anabasine and quinoline. Anthranilic acid can arise from shikimic acid but also by degradation of tryptophan. The nitrogen in heterocycles is derived from precursors with amino-acid character and not from ammonia.

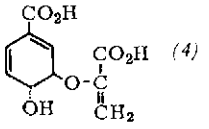
E. W. Underhill and *L. R. Wetter* (Canada) showed that shikimic acid, glucose, and phenylalanine are utilized in the biosynthesis of the aglycone from C_6–C_3 thioglucosides. The maximum incorporation occurred with 3-benzylmalic acid, so that this compound is postulated as an intermediate product in the biosynthesis.

G. H. N. Towers et al. (Canada) suggest that taxiphylline *(3)* (D-*p*-hydroxymandelic nitrile β-D-glucopyranoside) is synthesized from intact tyrosine, since both [^{14}C]- and [^{15}N]-tyrosine are incorporated. β-(*p*-Hydroxyphenyl)lactic acid and smaller quantities of β-(*p*-hydroxyphenyl)serine are also utilized.



(3)

F. Lingens (Germany) demonstrated that accumulation of chorismic acid *(4)* is especially favored when *p*-fluorophenylalanine is added to (try-) mutants of *Saccharomyces cerevisiae* or when 4-methyltryptophan, 6-diazo-5-oxonorleucine, or albizziin (α-amino-β-ureidopropionic acid) are added to (phen$^-$, tyr$^-$) mutants. As a result, the formation of alternative products in other branches of the chain is largely suppressed. [*Phenyl*-^{14}C]-tryptophan was used to investigate the ability of several microorganisms to convert tryptophan into nicotinic acid. In the *phycomycetes*, tryptophan is a starting point for nicotinic acid synthesis when the biosynthesis of lysine proceeds *via* α-aminoadipic acid. However, if lysine is produced from α,ε-*diaminopimelic* acid, tryptophan does not act as a precursor for nicotinic acid.



(4)

P. O. Larsen (Denmark) has studied the biosynthesis of *m*-carboxylated aromatic amino acids in the *Resedaceae*. [1-^{14}C]-Tyrosine was incorporated into L-2-amino-3-(3-carboxy-4-hydroxyphenyl)propionic acid.

4. Ribonucleic Acid – Structure and Function

M. Staehelin (Switzerland) reviewed analytical methods for the elucidation of the structure of transfer-RNA. Preparation of pure t-RNA was accomplished by means of chromatography on Sephadex 200. Isolation of an individual t-RNA can be particularly readily effected by countercurrent distribution. The purity of a fraction is best tested chemically, *viz.* by checking the base composition and by quantitative analysis of the nucleotide sequences, especially of those containing unusual bases.

H. G. Zachau et al. (Germany) have worked out methods for the investigation of the primary structure of serine t-RNA. Fragments formed by degradation of 5–8 mg RNA with pancreas and T_1 ribonuclease were used to elucidate oligonucleotide sequences. The stepwise degradation of RNA with snake venom phosphodiesterase was investigated. Eleven unusual nucleotides were detected in the serine transfer RNA. They are N(2)-dimethyl-Gp, 5-methyl-Cp, rTp, Ip, 2′-*O*-methyl-Gp, 2′-*O*-methyl-Up, three ΨUp and two nucleotides resembling 4,5-dihydro-Up [2].

Sequences of up to 23 nucleotides could he established. Some of the rare nucleotides are closely adjacent in serine t-RNA. Several anticodons were found. The sequences described have little similarity with those of the model proposed by *Cantoni* et al.

D. Grünberger (Czechoslovakia) showed that in growing *Bacillus cereus* cells protein synthesis is inhibited by incorporation of 8-azaguanine into RNA. Incorporation of the different amino acids is not uniformly inhibited; maximum inhibition is found for lysine and glutamic acid. In contrast to findings *in vivo*, the incorporation of amino acids is not inhibited when a ribosomal system from *B. cereus* cells treated with 8-azaguanine is used. However, liberation of the protein formed by the ribosomes into the supernatant is reduced.

S. Ochoa (U.S.A.) showed that hydrogen bonds must be involved in the codon-anticodon interaction, since poly-(5-fluorouridylic acid) or poly-(5-methyluridylic acid) as well as polyuridylic acid bring about polyphenylalanine synthesis in a cell-free system from *E. coli*. In contrast, poly-[*N*(3)-methyluridylic acid] was inactive. This compound does not form a complex with polyadenylic acid.

A further indication of the presence of three nucleotides in one codon was supplied by *H. G. Khorana* (U.S.A.) with the aid

[2] Gp = Guanosine 3′-monophosphate, Cp = Cytidine 3′-monophosphate, rTp = Ribothymidine 3′-monophosphate, Ip = Inosine 3′-monophosphate, ΨUp = Pseudouridine 3′-monophosphate, Up = Uridine 3′-monophosphate.

of a polynucleotide containing a repeating uridylic-cytidylic acid sequence [poly(UC)$_n$]. This polynucleotide induces the cell-free synthesis of a polypeptide with a repeating serine-leucine sequence. Only a codon with an odd number of bases (3,5, *etc.*) is able to form such copolypeptides, since codons with an even number of bases would be identical and could thus produce only homopolypeptides. Even numbers can therefore be ruled out. Experiments with short-chain (poly-A)-nucleotides also lead to formation of polylysine peptides, whose length agrees with the triplet code. Additional experiments showed that messenger-RNA is read from the 5′- to the 3′-end of the chain, while polypeptide formation proceeds from the *N*-terminal to the *C*-terminal end. The polynucleotide

ApApAp · · · · pApApApC

with 17–20 nucleotides brings about synthesis of a polypeptide with 5–6 lysine residues and a *C*-terminal asparagine in a nuclease-free system. Removal of the labelled cytidylic acid residue by periodate oxidation and aminolysis suppresses the incorporation of the asparagine, while that of lysine remains unaffected. This indicates an AAC code for asparagine.

U. Harding and *G. Hartmann* (Germany) recommended a chromatographic technique for the fractionation of transfer-RNA, using a not too fine-grain hydroxyapatite. After adsorption and stepwise elution with phosphate buffer, sharp peaks of the transfer-RNA are obtained. The entire activity is regained in the eluate, with, in the case of phenylalanine, an enrichment of the specific acceptor activity by a factor of 10 to 15.

W. Zillig et al. (Germany) reported on the structure and function of the DNA-dependent RNA polymerase. The enzyme obtained from *E. coli* could be purified by differential ultracentrifugation, chromatography on DEAE cellulose, ammonium sulfate precipitation, and centrifugation in a sucrose density gradient. Electron microscopy leads to a model in which 6 cylindrical sub-units longitudinally surround a central cavity. The enzyme-DNA complex has also been analysed with the electron miscroscope.

M. Bagdasarian and *M. Ombach* (Poland) demonstrated the repression of messenger-RNA synthesis by histidine in (his$^-$) mutants of *Salmonella typhimurium*. Derepressed cultures were obtained by growth in minimal media containing *N*-formylhistidine. On addition of L-histidine one minute before commencement of labelling, a 30–40% decrease in the labelling of the messinger-RNA fraction was observed. An (operator$^-$) mutant of *S. typhimurium* was not repressed by histidine.

5. Miscellaneous

Celina Janion and *D. Shugar* (Poland) reported that hydroxylamine reacts with 5-hydroxymethylcytosine and 5-methylcytosine as well as with cytosine. Since the reaction is accompanied by little change in the ultraviolet spectrum, it has so far been overlooked. The 5,6-double bond is not attacked, but 4-hydroxyamino compounds are formed. In this way the mutagenic action of hydroxylamine on T-phages is explained.

As *D. Yi-Yung Hsia*, *N. Nadler*, and *P. Justice* (Switzerland) were able to show, phenylketonuria patients are able to hydroxylate tryptophan despite their deficiency in phenylalanine hydroxylase. It follows that phenylalanine and tryptophan are not hydroxylated by the same enzyme system, as has been suggested by other authors.

B. Gorzkowski and *Z. Porembska* (Poland) showed that *Helix pomatia* synthesize the pyrimidine ring in the same way as do vertebrates, *i.e.* from carbamyl phosphate and aspartate.

U. Döbereiner and *H. Grisebach* (Germany) showed that the branched sugar apiose [3-*C*-hydroxymethyl-D-glyceroaldotetrose] is metabolically derived from glucose. During synthesis the C-6 atom of glucose is probably split off. The hydroxymethyl group originates from the C-3 or C-4 atom. Decarboxylation of a UDP-4-ketoglucuronic acid and subsequent rearrangement is suggested as the biosynthetic pathway.

T. Klopotowski et al. (Poland) reported on the effect of 3-amino-1,2,4-triazole on *Saccharomyces cerevisiae*. This substance effects accumulation of imidazolylglycerophosphate by inhibition of imidazolylglycerophosphate dehydrase. It is suggested that this inhibitory effect explains the herbicidal action of the compound. [VB 935/247 IE]

German version: Angew. Chem. 77, 921 (1965)

Model Studies on the Mechanism of Microsomal Hydroxylation

Hj. Staudinger and *V. Ullrich*, Gießen (Germany)

In the metabolism of steroids and amino acids and the degradation of foreign substances in organisms, reactions occur involving the substitution of a hydrogen atom by a hydroxyl group. These reactions require molecular oxygen and a reducing agent. Equivalent reactions form the basis of oxidative deamination, dealkylations, *N*-oxidations, and other detoxification reactions. The enzymes which catalyse such reactions are called "mixed-functional oxygenases"; they occur for example in the endoplasmatic reticulum (microsomes) of liver cells.

Model systems were studied to help clarify the mechanism of these oxygenations. A common feature of all such systems is that the oxygen molecule is reduced stepwise with one-electron donors, *e.g.* heavy metal ions such as $Fe^{2\oplus}/P_2O_7^{4\ominus}$, $Fe^{2\oplus}$/EDTA, $Cu^{\oplus}$, $Ti^{3\oplus}$, or $Sn^{2\oplus}$, or organic reducing agents such as reduced flavine, leuco-methylene blue, or the dihydroxyfumarate radical [1]. By examining the hydroxylation products obtained from various substrates it can be shown that two hydroxylation mechanisms can occur simultaneously during the reduction of molecular oxygen [2]. One mechanism proceeds *via* hydroxyl radicals [3], in the other, HOO· radicals are formed first and give rise to an oxygen atom which is inserted directly into the C–H bond in the substrate. By analogy to carbene reactions, this second mechanism might be termed „oxene hydroxylation". This mechanism is operative for example in the hydroxylation of cyclohexane to cyclohexanol and of naphthalene to 1,2-dihydroxynaphthalene. Further reactions typical of the latter mechanism are the oxidative deamination of phenethylamine and the dealkylation of phenacetin. These reactions do not involve hydroxyl radicals. The same products however are also formed by degradation of the compounds by the mixed-functional oxygenases in liver microsomes. These and other parallels make it appear likely that the oxygenations occurring in the microsomes by catalysis with the mixed-functional oxygenases adopt a course similar to that observed in the oxene hydroxylations in the model systems. However, it must be assumed for the enzymatic reactions that some sort of stabilization of the reactive stage of the oxygen atom by iron(III) or copper(II) occurs.

[GDCh-Ortsverband Saar, Saarbrücken (Germany), May 21st, 1965] [VB 936/239 IE]

German version: Angew. Chem. 77, 924 (1965)

[1] *V. Ullrich*, Doctorate Thesis, Universität Gießen, 1964; *Hj. Staudinger* and *V. Ullrich*, Biochem. Z. *339*, 491 (1964).

[2] *Hj. Staudinger* and *V. Ullrich*, Z. Naturforsch. *19b*, 409, 877 (1964).

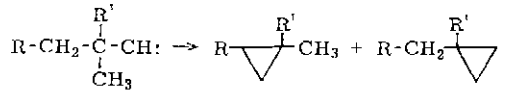
[3] *R. O. C. Norman* and *G. K. Radda*, Proc. chem. Soc. (London) *1962*, 138.

Carbenes and Carbenoid Reactions

W. Kirmse, Marburg/Lahn (Germany)

α-Eliminations [1] and catalytic decomposition of diazo compounds are examples of "carbenoid" reactions [2], which resemble, but are not completely identical with, the reactions of "free" carbenes.

1. The competitive intramolecular insertion reactions of alkylcarbenes, *e.g.*

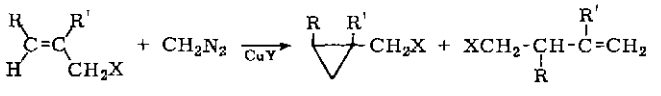


(1) *(2)*

depend largely on steric and polar effects [3]. They therefore afford a sensitive test for the identity of intermediates which have been made in different ways. Diazo decomposition products were compared with products formed by α-elimination of HCl from primary alkyl chlorides with sodium or sodamide ($R-CH_2Cl \rightarrow R-\ddot{C}H$) and by elimination of iodine from 1,1-diiodoalkanes with methyl-lithium, lithium, or magnesium ($R-CHI_2 \rightarrow R-\ddot{C}H$). The results are qualitatively the same, but the α-elimination reactions are more selective, *i.e.* they give a higher ratio *(2)*:*(1)*.

The reaction of *gem*-diiodoalkanes with zinc (the Simmons-Smith reaction) adopts a different course; here the products are mainly olefins formed by alkyl migration.

2. When carried out in the presence of allyl halides, the decomposition of diazomethane catalysed by copper salts yields information on the behavior of "modified methylene". In addition to a stereoselective addition to the double bond – which excludes the possibility of addition of $XCH_2^{\ominus}M^{\oplus}$ [1] – a chain-lengthening reaction also occurs. Labelling with deuterium or CH_3 shows that the formation of homologous halides occurs *via* an allylic rearrangement.



[GDCh-Ortsverband Wuppertal-Hagen, Wuppertal (Germany), May 5th, 1965] [VB 928/238 IE]

German version: Angew. Chem. 77, 923 (1965)

[1] *W. Kirmse*, Angew. Chem. *77*, 1 (1965); Angew. Chem. internat. Edit. *4*, 1 (1965).

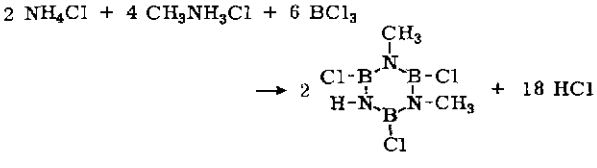
[2] *G. L. Closs* and *R. A. Moss*, J. Amer. chem. Soc. *86*, 4042 (1964).

[3] *W. Kirmse* and *G. Wächterhäuser*, Angew. Chem. *76*, 591 (1964); Angew. Chem. internat. Edit. *3*, 651 (1964).

Substitution and Condensation Reactions of Borazines

V. Gutmann, Vienna (Austria)

Although the reactions and properties of borazines are easier to study on unsymmetrically substituted derivatives, so far mainly the symmetrically substituted derivatives have been studied because they are simpler to prepare. However, unsymmetrically substituted borazines can be prepared using known synthetic methods, *e.g.* the chloroborazine synthesis according to *Laubengayer* [1, 2].



1-Methyl-2,4,6-trichloroborazine, 1,3,5-trimethyl-2,4,6-trichloroborazine, and 2,4,6-trichloroborazine are formed as by-products in this reaction. In order to prevent condensation of these products, the borazines must be alkylated on the boron atoms before separating them. On alkylation with Grignard compounds B–N-linked polyborazines are formed as by-products [2, 3].

Cyclopentadienylborazines are obtained by the reaction of cyclopentadienylmetal compounds with *B*-halogenoborazines [4]. In these derivatives the cyclopentadienyl groups are linked to the boron by localized σ-bonds. The compounds exhibit a strong tendency to polymerize, undergo the Diels-Alder reaction with dienophiles, and combine with organotin hydrides.

Little work has been done so far on polyfluoro and perfluoro derivatives of B–N compounds. β-Fluoroalkylmagnesium halides react with *B*-chloroborazines to give *B*-fluoroborazines [5]. The reaction of polyfluoroalkylamines with BCl_3 leads to *N*-polyfluoroalkyl-*B*-trichloroborazines, but the elimination of HCl in the final step of the reaction is difficult. *N*-Trifluoroethyl-*B*-trichloroborazole (earlier data on this compound [6] could not be confirmed) reacts for instance with perfluoroarylmagnesium halides to give borazines in which all of the ring atoms are substituted by perfluoro-organo residues.

[GDCh-Ortsverband Köln, Köln (Germany), June 18th, 1965] [VB 937/242 IE]

German version: Angew. Chem. 77, 872 (1965)

[1] *C. A. Brown* and *A. W. Laubengayer*, J. Amer. chem. Soc. *77*, 3699 (1955).

[2] *A. Meller* and *R. Schlegel*, Mh. Chem., in press.

[3] *J. J. Harris*, J. org. Chemistry *26*, 2155 (1961).

[4] *V. Gutmann*, *A. Miller*, and *E. Schaschel*, J. organometallic Chem. *2*, 287 (1964).

[5] *A. Meller*, *M. Wechsberg*, and *V. Gutmann*, Mh. Chem. *96*, 388 (1965).

[6] *V. F. Gridina*, *A. L. Klebansky*, and *A. V. Bartashev*, Zh. Osbhch. Khim. *34*, (5) 1401 (1964).

New Developments in the Ionic Polymerization of Cyclic Acetals

K. Weissermel, Frankfurt/Main-Hoechst (Germany)

Polymerization of trioxane in the melt with cationically active catalysts leads to high polymers with oxymethylene repeating units. The polymers contain hemiacetal end-groups and are decomposed by heat. Copolymerization of trioxane with oxacycloalkanes leads to stable polymers. Unstable sequences in these copolymers can be removed by treatment with alkali.

The ability of trioxane to copolymerize with cyclic ethers decreases with the ring size of the ethers. If cyclic acetals are used instead of the cyclic ethers, the size of the ring is of only minor importance, since here the oxonium salts formed as intermediates are easy to split. Cyclic acetals derived from higher aldehydes and cyclic ketals react with polymerizing trioxane with elimination of the aldehyde or ketone component. When trioxane is copolymerized with small amounts of ethylene oxide, the latter is almost entirely incorporated into the polymer chains already after small conversions. Nevertheless, at the end of the polymerization, the ethylene oxide is found to be distributed uniformly throughout all the polymer molecules. This result is explained by transacetalizations between polymer molecules and active chain ends, *i.e.* cleavage and recombination of chain segments occurs throughout the course of the polymerization. This principle can be used to copolymerize almost any formal, *e.g.* polydioxolane, poly-*trans*-quinitol formal, or polyethylene glycol formal, with trioxane to give uniform products.

Another peculiarity of trioxane polymerization observed is a hydride shift at the active chain end which causes the for-

mation of formate and methoxyl end-groups and reduces the molecular weights of the polymers to values lower than those expected.

Copolymerization of trioxane with monomers containing a halogeno and/or a carbonyl group leads to products which can be cross-linked. These are characterized by their increased adhesion to metals and their dyeability.

[GDCh-Ortsverband Braunschweig (Germany), July 12th, 1965] [VB 948/253 IE]
German version: Angew. Chem. 77, 871 (1965)

Crystallization and the Microstructure of High Polymers

H. A. Stuart, Mainz (Germany)

Single crystals of polyethylene may contain folded chains. Lamellar single crystals within the bulk of the material have a disordered surface. From this it is concluded that there are both straight and folded chains present in the solid.

Further observations on stretched polyethylene can be represented essentially by an extended Hess-Kiessig model containing both straight and folded chains. Only part of the lamellar single crystals is pulled out on stretching. After stretching, the straight chains in particular are under considerable stress but relax on annealing, as can be seen from the nuclear magnetic resonance signals.

Since some of the chains in the non-crystalline regions are given a fluid-like motion on annealing, the diffusion constant and swelling (coloring capacity) increase considerably, even though the proportion of crystalline material also increases. Analysis of the small-angle X-ray diffraction pattern by the method of *Bonart-Hosemann* shows that the fibrils in cold-stretched polyethylene merge into large blocks on annealing. The crystals of neighboring fibrils form a macrolattice (paracrystalline layer lattice) which can be observed directly in the electron microscope. The chain mobility in the non-crystalline regions and the ratio of straight to folded chains are important structural parameters which must be given due consideration in the interpretation of physical or technological properties of polyethylenes.

[GDCh-Ortsverband Mainz (Germany), July 1st, 1965]
[VB 940/245 IE]
German version: Angew. Chem. 77, 871 (1965)

Mobility of Molecules Adsorbed on the Surfaces of Solids

R. Haul, Hannover (Germany)

An important property for characterizing the interaction between the surfaces of solids and adsorbed molecules is the residence time of the molecules on the surface. The residence time can be determined from experiments on transient Knudsen molecular flow. For example, the non-stationary flow of argon, krypton, and xenon through a pyrex glass capillary was measured between 80 and 295 °K using ionization manometers. The measurements were made in an ultrahigh vacuum in order to determine the residence times of physisorbed molecules even at a relatively low surface coverage ($\theta = 10^{-3}$ to 10^{-1}).

The adsorption isotherms obtained from the flow experiments are non-linear owing to the energetic heterogeneity of the surface but satisfy the Radushkevich-Dubinin equation. On the basis of these adsorption isotherms, differential residence times $\tau = \tau_0 \cdot e^{E/RT}$ can be calculated. For example, the values found for τ_0 (sec) and E (kcal/mole) at $\theta = 0.01$ were 3×10^{-14} and 3.6 for argon, 1×10^{-13} and 4.4 for krypton, and 1×10^{-13} and 5.5 for xenon. As the coverage of the surface increases, the pre-exponential factor $\tau_0 = 1/\nu_0$ increases by several powers of ten. There is a connection between ν_0 and the activation energy E in the sense of a compensation effect. This phenomenon can be explained by assuming that the molecules do not always leave the surface directly but that some are desorbed only after repeated changes of sites. The same conclusion is arrived at from entropy considerations. The surface mobility of physisorbed molecules can also be derived from studies of material transport in porous media.

[GDCh-Ortsverband Braunschweig (Germany), June 28th, 1965] [VB 943/250 IE]
German version: Angew. Chem. 77, 924 (1965)

The Effect of Particle Size on the Reaction Mechanism of Gases with Solids

W. Feitknecht, Bern (Switzerland)

Finely divided solids react rapidly with gases even at low temperatures. In this way metastable compounds may result, which would not be formed with coarser substances. For reactions of oxygen with metals and metal oxides the following cases were distinguished by X-ray and electron-microscope investigations and kinetic measurements: single-phase reactions I (during the reaction there are no phase boundaries between starting material and product) and two-phase reactions II (the starting material is converted into the end-product along a phase boundary).

Ia. In single-phase surface reactions, only a thin surface layer reacts without phase change.

Example: MnO prepared in a reducing atmosphere at low temperature (particle size 350–1500 Å) takes up considerable amounts of oxygen on careful oxidation at up to 100 °C. The crystal structure (NaCl-type) is not altered since a surface layer (approx. 50 Å) of Mn^{3+} ions with cation defects is formed.

Ib. During single-phase "through" reactions the microcrystals gradually change in composition equally outside and inside. With larger particles a concentration gradient occurs; the mixed phase decomposes to yield starting material and a new phase.

Example: oxidation of Fe_3O_4 to γ-Fe_2O_3 with small particles (< ca. 3000 Å), and to α-Fe_2O_3 with larger particles (> ca. 3000 Å).

IIa. By the layer mechanism, a continuous layer, the growth of which is controlled by diffusion, is formed on the crystal surface. With large specific surface areas, other secondary reactions may take place than occur with small specific surface areas.

Example: finely-divided iron (< ca. 500 Å) + $O_2 \rightarrow Fe_3O_4 \rightarrow \gamma$-$Fe_2O_3$, coarse iron (> ca. 500 Å) + $O_2 \rightarrow Fe$, $Fe_3O_4 \rightarrow Fe$, Fe_3O_4, α-Fe_2O_3.

IIb. By the nucleation mechanism nuclei once formed grow rapidly at the expense of the microcrystal of starting material on which they originated. The reaction is not diffusion-controlled, depends strongly on the pressure of the reacting gas and goes to completion only with finely divided starting material.

Example: oxidation of Mn_3O_4 to Mn_5O_8 with finely divided starting material (size < ca. 1000 Å) and to α-Mn_2O_3 with coarse starting material (particle size > ca. 1000 Å).

[GDCh-Ortsverband Freiburg-Südbaden (Germany), February 19th, 1965] [VB 920/226 IE]
German version: Angew. Chem. 77, 870 (1965)

Color and Constitution of Inorganic Solids

O. Schmitz-DuMont, Bonn (Germany)

According to the crystal field theory, the absorption of light by a coloring cation, *e.g.* $Co^{2\oplus}$, $Ni^{2\oplus}$, or $Cr^{3\oplus}$, after isomorphous incorporation into a host lattice is determined by the strength and symmetry properties of the crystal field in the neighborhood of the colored cation. These parameters de-

pend on the coordination number, the symmetry of the coordination polyhedron, and on the distances between the coloring cation and the coordinating ligands.

To investigate this problem experimentally, oxides (MgO, ZnO, spinels, $MgTiO_3$, or silicates) were used as host lattices. It was found that reduction of the coordination number from 6 to 4 causes a red-shift of the main absorption bands. The same effect is observed if the coloring cation is incorporated in a simple host lattice with only one type of cationic lattice site and the lattice is expanded by isomorphous exchange of larger cations [*e.g.* $Ni_{0.01}Mg_{0.99}TiO_3$ (ilmenite lattice, yellow) → $Ni_{0.01}Cd_{0.99}TiO_3$ (ilmenite lattice, red)]. A bathochromic shift is observed with more complicated lattices only when the isomorphous exchange of larger cations expands the coordination polyhedra containing the coloring cation; this is not always the case. Reduction of the point symmetry in the environment of the coloring cation does not produce any significant bathochromic shift. Since the transition from $Ni_{0.1}Mg_{0.9}O_3$ (regular octahedral coordination) to $Ni_{0.1}Mg_{0.9}TiO_3$ (hexagonally distorted coordination octahedron) results in a large red shift of all three main absorption bands, it was at first concluded that this effect was occasioned by the distortion of the coordination polyhedron. However, further studies on phases of the perovskite type revealed that the hathochromic shift of the bands required the presence of both low-charged cations and high-charged cations on coordinatively equivalent lattice sites. This results in a weakening of the field around the low-charged coloring cations.

These findings can be applied conversely in practice by using light absorption to determine unknown types of coordination and to study localized effects in crystal lattices which cannot be investigated by other methods, *e.g.* X-ray techniques. Apart from uses in crystallography (*e.g.* mixed crystal formation), the changes in the light absorption can also be applied to examine changes in bonding types between coloring cation and coordinated ions or atoms.

[GDCh-Ortsverband Düsseldorf, Düsseldorf (Germany), April 12th, 1965] [VB 926/237 IE]

German version: Angew. Chem. 77, 872 (1965)

Advances in Complexometry

R. Pribil, Prague (Czechoslovakia)

Complexometric titrations can be made selective by masking interfering ions. Thus some colored cations can be converted to colorless or almost colorless complexes, *e.g.* $Fe^{3\oplus}$ with triethanolamine, $Cu^{2\oplus}$ with thioglycollic acid, $Mn^{3\oplus}$ with cyanide, and $Co^{3\oplus}$ with triethanolamine or cyanide. $Zn^{2\oplus}$ and $Cd^{2\oplus}$ can be estimated in admixture using β-mercaptopropionic acid.

Triethylenetetraminehexaacetic acid is a new complexometric titrating agent which forms 1:2 complexes M_2Y with bivalent metals M such as Ga, Pb, Cd, or Zn and 1:1 complexes MY with tri- and tetravalent metals. This reagent is used for analysis of gallium/indium mixtures, *etc.* It can also be used to determine thorium in mixtures with rare earths, or thorium alongside scandium. Analyses of mixtures of rare earths (RE) can be carried out using the following displacement reaction:

$$[RE\text{-}EDTA]^{2\ominus} + Zn^{2\ominus} + PO_4^{3\ominus} \rightarrow REPO_4 + [Zn\text{-}EDTA]^{2\ominus}$$

Only La, Ce, Nd, and Pr are precipitated as their phosphates. Holmium and the higher rare earths remain in solution and are titrated complexometrically.

[GDCh-Ortsverband Nordbayern, Erlangen (Germany), May 14th, 1965] [VB 931/234 IE]

German version: Angew. Chem. 77, 871 (1965)

Structures and Reactions in Molten Salts

W. Bues, Tübingen (Germany)

$BO_3^{3\ominus}$ ions with D_{3h} symmetry can be detected in molten Li_3BO_3 by Raman spectroscopy. Melts with the composition $Li_4B_2O_5$ contain $B_2O_5^{4\ominus}$ ions (C_{2v}) plus $BO_3^{3\ominus}$ and $B_3O_7^{5\ominus}$ ions. This means that $B_2O_5^{4\ominus}$ disproportionates by an electron donor-acceptor mechanism to give $BO_3^{3\ominus}$ and $BO_2^{\ominus}$. The $BO_2^{\ominus}$ ion is short-lived and reacts further in the melt either with $BO_3^{3\ominus}$ to give $B_2O_5^{4\ominus}$ or with $B_2O_5^{4\ominus}$ to give $B_3O_7^{5\ominus}$; since the oxygen atoms in $BO_3^{3\ominus}$ and $B_2O_5^{4\ominus}$ are of equal basicity, the $BO_2^{\ominus}$ reacts non-selectively. The $BO_3^{3\ominus}$ ion can also be detected in melts of $Li_5B_3O_7$ and $Li_6B_4O_9$. The spectra of metaborates, borax, and diboron trioxide can be readily interpreted starting from the short-chained anions: in melts, boron has always the coordination number three. This explains for example the great difference in density between B_2O_3 in the molten and crystalline states; in crystals B_2O_3 has the coordination number four.

Molten $ZnCl_2$, like crystalline $ZnCl_2$, has a space lattice structure with the coordination number four for the zinc. K_2ZnCl_4 melts consist of isolated $ZnCl_4$ tetrahedra, while $KZnCl_3$ melts contain chains of $ZnCl_4$ tetrahedra. Molten mixtures of KNO_3 and $ZnCl_2$ contain the ions $NO_3^{\ominus}$, $ZnCl_4^{2\ominus}$, and $Zn^{2\oplus}$.

The TlCl in molten mixtures of TlCl and $CuCl_2$ can be oxidized to $TlCl_3$ with HCl and oxygen. The $TlCl/TlCl_3/CuCl/CuCl_2$ melt catalyses the chlorination of ethylene to 1,2-dichloroethane. At 280 °C and ratios of oxygen:HCl:ethylene of 1:4:2, 3:8:4, and 1:2:1, the purity of the 1,2-dichloroethane obtained is 99.0, 99.0, and 98.0 %, and the conversion (based on the ethylene) is 26.5, 55.7, and 98.6 %, respectively. A glass tube 80 cm long and 2 cm in diameter with a sealed-in Grade 4 sintered-glass filter can be used to achieve 30 seconds contact time of the gases with 150 g of the melt, which foams intensely.

[GDCh-Ortsverband Giessen (Germany), June 14th, 1965] [VB 939/244 IE]

German version: Angew. Chem. 77, 871 (1965)

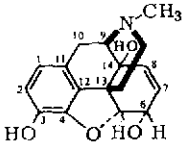
SELECTED ABSTRACTS

The structure of fluorenyl-lithium has studied by *J. A. Dixon, P. A. Gwinner*, and *D. C. Lini* by NMR spectroscopy. When heptane was added to the solutions formed by treating fluorene in tetrahydrofuran (THF) and dimethoxyethane (DME) with lithium, a precipitate of solvated fluorenyl-lithium is formed which does not release its solvent of crystallization even after 48 h at pressure below 1 mm. Solutions of the complexes in perdeuterobenzene give NMR spectra whose integrated signals indicate the compositions RLi·3THF and RLi·1DME (R = 9-fluorenyl). The complexed THF gives signals at higher fields for both the α- and β-protons than free THF. The relative positions of the methyl and methylene proton signals were interchanged in the complexed and free forms. Because of the electron donor/electron acceptor interactions between the cation and the ether molecule, a shift to lower fields would have been expected. The ^7Li resonance occured at higher field strengths (3 ppm for the THF complex) than in aqueous solutions of inorganic lithium salts. It was concluded that the solvated lithium cation lies above the plane of the aromatic carbanion and thus falls within the shielding range of the ring current. / J. Amer. chem. Soc. *87*, 1379 (1965) / -Eb. [Rd 343/552 IE]

The halogenation of aromatic compounds with *N*-bromosuccinimide and *N*-chlorosuccinimide under ionic conditions has been studied by *F. L. Lambert, W. D. Ellis,* and *R. J. Parry*. When 100 ml of the aromatic compound was heated for 1–4 h at 45–90 °C with a mixture of dilute sulfuric acid (200 ml of concentrated H_2SO_4 diluted to 20–66 %) and 0.16 mole of *N*-halogenosuccinimide, nuclearly substituted monohalogeno derivatives are obtained in yields of 64–95 %; practically no higher halogenated or benzyl-substituted products are formed. The use of large amounts of free bromine or chlorine is avoided by this technique. In this way, benzene gives 90 % bromobenzene or 64 % chlorobenzene. Toluene gives 95 % bromotoluene (ratio of *o*-:*m*-:*p*-isomers = 67:2:31) or 93 % chlorotoluene (with similar ratios of isomers). Nitrobenzene yields 70 % bromonitrobenzenes, and chlorobenzene 94 % chlorobromobenzenes, or 80 % dichlorobenzenes. The attacking species may be the protonated *N*-halogenosuccinimide. / J. org. Chemistry *30*, 304 (1965) / –Bi. [Rd 298/507 IE]

A complex with a coordination number of 7 and tungsten-mercury bonds has been made by *M. C. Ganorkar* and *M. H. B. Stiddard*. $HgCl_2$ and $W(CO)_4$(bipy) interact at room temperature in acetone with release of CO [bipy = 2,2′-bipyridyl]; dilution of the reaction mixture with pentane precipitates orange crystals of $W(CO)_3$(bipy)$(HgCl)_2$. The compound is diamagnetic and dissolves in monomeric form in dichloromethane, from which it can be recrystallized. Its solution in nitrobenzene is non-conducting. Its infrared spectrum (in chloroform) contains bands in the C–O stretching frequency range at 2000, 1924, and 1887 cm^{-1}, and is therefore very similar to the spectrum of $W(CO)_3$(bipy)I_2, which compound also contains sevenfold coordinated tungsten(II). The observed shift of the bands to lower frequencies is in accordance with the lower electronegativity of the HgCl ligands. / Chem. Commun. *1965*, 22 / –Gn. [Rd 272/481 IE]

14-Hydroxymorphine and 14-hydroxy-7,8-dihydromorphine, new compounds with analgetic properties, have been synthesized by *U. Weiss*. 14-Hydroxymorphine *(1)* was prepared by reduction of the 6-oxo derivative with $NaBH_4$; its structure



(1)

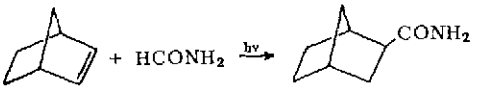
was proved by methylation with diazomethane, which gave the known compound 14-hydroxycodeine. The 14-hydroxy-7,8-dihydromorphine *(2)*, m.p. 249–250 °C, was obtained analogously from 14-hydroxy-7,8-dihydro-6-morphinone. Whereas the analgetic effect of *(1)* is somewhat weaker than that of morphine but of the same duration (*ca.* 2.8 h), *(2)* is twice as effective as morphine (ED_{50} = 1.1 mg/kg in mice) and acts much longer (4 h). / J. med. Chem. *8*, 123 (1965) / –De. [Rd 245/454 IE]

Stable colloids of transition metals in the zerovalent state in ethers (tetrahydrofuran, dimethoxyethane) were prepared by *G. Henrici-Olivé* and *S. Olivé* by slow addition of solutions of VCl_3, $CrCl_3$, $MnBr_2$, $FeCl_3$, $CoCl_2$, or $NiBr_2$ to alkali metal naphthalene ($C_{10}H_8^{\ominus}$ and $C_{10}H_8^{2\ominus}$) solutions (reducing agents) with exclusion of air and moisture. The metallic state is confirmed for Fe and Co by their weak ferromagnetism. The colloid particles are negatively charged. The systems transition-metal colloid/organic halide (*e.g.* CCl_4) are suitable for initiating polymerization of, *e.g.*, methyl methacrylate or styrene. Formally, the radical-producing step is

$$M + CCl_4 \rightarrow M^{\oplus}Cl^{\ominus} + \cdot CCl_3$$

/ Chimia *19*, 46, 47 (1965) / –Ma. [Rd 248/457 IE]

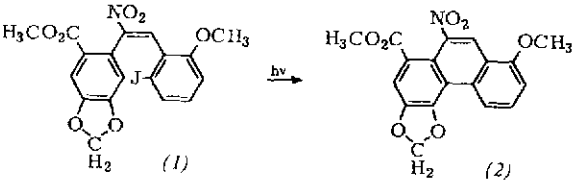
Stereospecific addition of formamide to norbornene was observed by *D. Elad* and *J. Rokach*. Irradiation of a mixture of norbornene, formamide, t-butanol, and acetone for about 1 h with a high-pressure mercury vapor lamp afforded an 87 % yield of norbornane-2-*exo*-carboxamide *(1)*, m.p. 181 to 183 °C; no *endo*-isomer could be detected. Some 2-*exo*-acetonylnorborane was formed in a side reaction, and 2:1 telomers were also produced by the reaction of 2 moles of norbornene with 1 mole of formamide. The photoadduct *(1)*



(1)

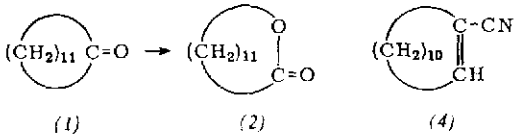
was also formed in sunlight or on prolonged irradiation with ultraviolet light of the mixture without acetone. / J. chem. Soc. (London) *1965*, 800 / –Ma. [Rd 246/455 IE]

A photochemical synthesis of phenanthrene derivatives by photocyclization of substituted 2-iodo-*cis*-stilbenes – similar to the photolysis of aromatic iodo compounds discovered by *Kharasch* – has been described by *S. M. Kupchan* and *H. C. Wormser*. For example, photolysis of 2-iodo-*cis*-stilbene in cyclohexane with ultraviolet light at room temperature leads *via* an intramolecular reaction to phenanthrene in 90 % yield. Analogously, methyl 2′-iodo-*cis*-stilbene-α-carboxylate

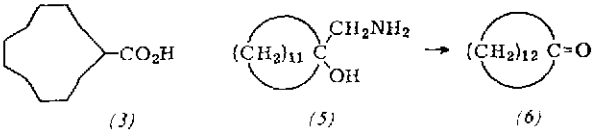


yields 71 % methyl phenanthrene-9-carboxylate, 2′-iodo-α-nitro-*cis*-stilbene affords 40 % 9-nitrophenanthrene, and 2′-iodo-2-methoxycarbonyl-6′-methoxy-4,5-methylenedioxy-α-nitro-*cis*-stilbene *(1)* gives rise to 54 % methyl aristolochiate *(2)*, which on saponification yields the known acid. / Tetrahedron Letters *1965*, 359 / –Ma. [Rd 247/456 IE]

The chemistry of cyclododecanone *(1)* has been studied in detail by *K. Kosswig, W. Stumpf, W. Kirchhoff, W. Dittmann,* and *W. Franke*. Oxidation of *(1)* with peroxyacetic acid in conc. H_2SO_4 at 10 °C leads to the lactone dodecanolide *(2)*, b.p. 130 °C/10–11 mm, in 50 % yield; 1,12-dodecandioic acid is a by-product. H_2O_2 containing 1–2 % SeO_2 transforms *(1)* in t-butanol to cycloundecanecarboxylic acid *(3)*, b.p. 126 to 128 °C, in 32 % yield. Cyclododecanone cyanohydrin can be



(1) *(2)* *(4)*



(3) *(5)* *(6)*

obtained in excellent yield and reacts with $SOCl_2$ in refluxing benzene to give 91 % 1-cyano-1-cyclododecene *(4)*, b.p. 112 to 118 °C, which can be converted into 1-cyclododecene-1-carboxamide, m.p. 84–89 °C, and thence into the free acid, m.p. 120–121 °C. Hydrogenation of *(4)* over acidic catalysts gives 50 % 1-aminomethyl-1-cyclododecanol *(5)*, m.p. 126.6 to 127.7 °C, which rearranges on treatment with HNO_2 to cyclotridecanone *(6)* in 56 % yield. / Liebigs Ann. Chem. *681*, 28, 30, 32 (1965) / –Ma. [Rd 250/459 IE]

An ylide synthesis by pyrolysis is described by *N. E. Miller*. Although ylides normally are made by the reaction of onium salts with strong bases, trimethylsilylmethylenetrimethylphosphorane *(1)*, b.p. 70–75 °C/14 mm, is obtained by heating (trimethylsilylmethyl)trimethylphosphonium chloride to 180 °C *in vacuo*; the product distils off together with

$$(CH_3)_3SI-\overset{\ominus}{C}H-\overset{\oplus}{P}(CH_3)_3 \leftrightarrow (CH_3)_3\overset{\ominus}{Si}=CH-\overset{\oplus}{P}(CH_3)_3 \leftrightarrow (CH_3)_3Si-CH=P(CH_3)_3$$

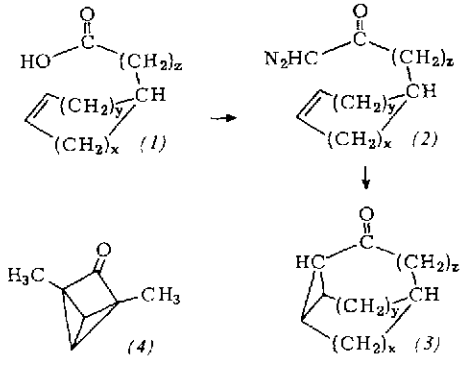
volatile trimethylsilyl chloride, leaving a residue of tetramethylphosphonium chloride. / J. Amer. chem. Soc. *87*, 390 (1965) / –Ma. [Rd 249/458 IE]

Sodium bis-(4-bromophenylsulfonyl)amide is used for identifying organic bases by *E. A. Julian* and *E. M. Plein*. They obtained the amide *(1)* by the reaction of 2 moles of *p*-bromobenzenesulfonyl chloride with NaOH and ammonium chloride. Compound *(1)*, m.p. 232–234 °C, reacts with the

$$Br-C_6H_4-SO_2-\overset{\ominus}{N}-SO_2-C_6H_4-Br\ Na^{\oplus} \qquad (1)$$

salts of primary, secondary, and tertiary amines in ethanol/water (1:1) to give crystalline salts of the sulfonylamide, which can be crystallized from methanol/n-amyl acetate (1:1). These ammonium salts have sharp melting points: for example, the salts of the antihistamines cyclizine, diphenylpyraline, and meclizine melt at 165, 147, and 189 °C, respectively. / J. pharmac. Sci. *54*, 147 (1965) / –De. [Rd 293/502 IE]

Tricyclic ketones *(3)* have been synthesized by *W. v. E. Doering, E. T. Fossel*, and *R. L. Kaye* by copper-catalysed cyclization of cyclo-olefinic diazo ketones *(2)*. Compounds *(2a)–(2f)* are readily obtained from the corresponding carboxylic acids *(1)* by treating the acid chlorides with diazomethane. These diazo ketones *(2)* release nitrogen on warming in inert solvents such as n-hexane or tetrahydrofuran in the presence of copper powder or anhydrous copper salts. Intramolecular cycloaddition of the copper-stabilized keto carbene intermediate onto the olefinic double bond leads to the ketones *(3a)–(3f)*. The reaction could not be conducted photochemically. The method has very broad

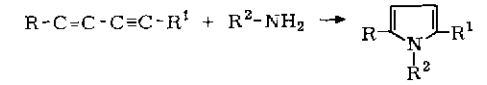


Compound	x	y	z	Yield [%]	B.p. [°C/mm] (m.p. [°C])
(3a)	4	0	1	36	82/0.1
(3b)	2	2	0	47	(126–128)
(3c)	2	2	1	47	(100–102)
(3d)	3	0	1	39	107–111/8.5
(3e)	2	1	0	31	
(3f)	1	1	0	65	75–77/15
(4)	0	0	0	*ca.* 1	(57–58)

scope and has been used to prepare 2,4-dimethyltricyclo-[1,1,1,$0^{2,4}$]pentan-5-one *(4)*, a compound that is remarkable because of its large ring strain [1]. / Tetrahedron *21*, 25 (1965) / –Bi. [Rd 276/485 IE]

[1] *W. v. E. Doering* and *M. Pomeranz*, Tetrahedron Letters *1964*, 961.

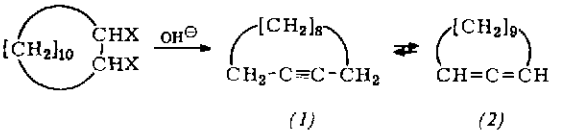
A new pyrrole synthesis starting from butadiyne and its derivatives has been worked out by *K. E. Schulte, J. Reisch*, and *H. Walker*. Pyrrole and 1,2-, 2,5-, and 1,2,5-substituted pyrroles are obtained from butadiyne and mono- or disubstituted butadiynes by reaction with ammonia or primary aliphatic or aromatic amines at 140–160 °C in the presence of catalytic amounts of CuCl; quinoline derivatives are formed as by-products when aromatic amines are used. The reaction proceeds in alcohols, dioxane, or dimethylformamide



R	R^1	R^2	M.p. (B.p.) [°C]	Yield [%]
C_6H_5	C_6H_5	H	143	73
C_6H_5	C_6H_5	CH_3	204	77
C_6H_5	C_6H_5	C_4H_9	113	76
C_6H_5	C_6H_5	*p*-Cl–C_6H_4	217–218	85
C_6H_5	C_6H_5	*p*-$NO_2C_6H_4$	253	70
CH_3	CH_3	CH_3	(176–178)	40

or even without solvent. Instead of the butadiyne, 1-methoxybut-1-en-3-yne, which is more stable, can be used. / Chem. Ber. *98*, 99 (1965) / –Ma. [Rd 259/468 IE]

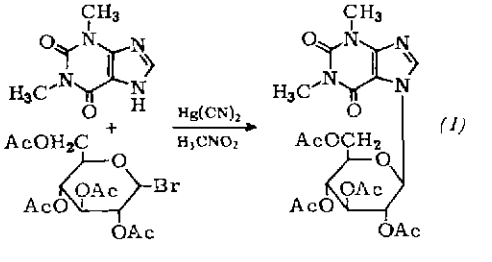
Convenient syntheses of cyclododecyne, cis-cyclododecene, 1,2-cyclododecadiene, and 1,3-cis,trans-cyclododecadiene are described by *W. Ziegenbein* and *W. M. Schneider*. 1,2-Dichlorocyclododecane reacts with alcoholic alkali metal hydroxides at 120–150 °C in an autoclave to give over 70 % cyclododecyne *(1)*. With increasing temperature, 1,2-cyclododecadiene *(2)* is formed in increasing amounts. Hydro-



(1) *(2)*

genation of *(1)* with lithium diisobutylaluminohydride proceeds selectively to *cis*-cyclododecene. 1,3-*cis*,*trans*-Cyclododecadiene is obtained in good yield on pyrolysis of 1,2-bisacetoxycyclododecane at 500 °C/20 mm. It is also formed, together with *cis*- and *trans*-cyclodecene as by-products, from 1,2-dibromocyclododecane and quinoline. / Chem. Ber. *98*, 824 (1965) / –Ma. [Rd 286/495 IE]

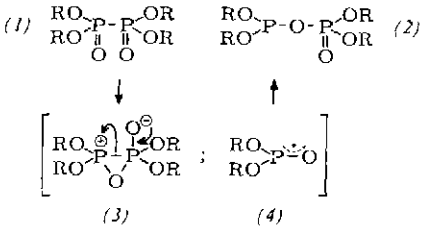
A new synthesis of nucleosides and analogous compounds has been achieved by *N. Yamaoka, K. Aso*, and *K. Matsuda* by condensation of heterocyclic imino compounds such as acylaminopurines, chloropurines, theophylline, *N*(6)-benzoylcytosine, or benzimidazole with acylglycosyl halides in nitromethane in the presence of hydrogen halide acceptors, *e.g.* Ag_2O, $Hg(CN)_2$, $Hg(CN)_2$, $Zn(CN)_2$, AgCN, or KCN. The components are heated for several hours over Drierite with



(1)

exclusion of moisture, and the crystalline acylated nucleosides are obtained directly. For example, 7-(2′,3′,4′,6′-tetra-*O*-acetyl-β-D-glucopyranosyl)theophylline *(1)*, m.p. 167 °C from ethanol, is obtained in 94 % yield. / J. org. Chemistry *30*, 149 (1965) / –De. [Rd 292/501 IE]

Thermal isomerization of a P(V) to a P(III) compound was observed for the first time by *J. Michalski*, W. *Stec*, and *A. Zwierzak*. When tetraalkyl hypophosphates *(1)* are heated for 3–4 h at 190–200 °C, large amounts (up to 60 %) of tetraalkyl esters of mixed anhydrides of phosphoric and



(3) *(4)*

phosphorous acids *(2)* are formed. The isomerization probably occurs *via* a dipolar cyclic phosphonium structure *(3)* or a free radical *(4)*. / Chem. and Ind. *1965*, 347 / –Ma.

[Rd 251/460 IE]

An acidity function H_- in the alkaline region has been set up by *E. C. Steiner* and *J. M. Gilbert* for dimethyl sulfoxide as solvent. The basic medium consisted, for instance, of

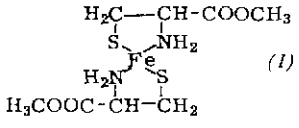
$$H_- = pK_{IH} + \log ([I^\ominus]/[IH])$$

$CH_3SOCH_3/CH_3SOCH_2^\ominus K^\oplus$, sometimes containing water or methanol up to a molarity of 0.4. The equilibrium indicator acid IH/indicator anion $I^\ominus$ was measured by spectrophotometry. The basicity of the medium is defined by

$$H_- = -\log (a_{H^\oplus} \gamma_{I^\ominus}/\gamma_{IH})$$

The H_- function represents an extension of Hammett's acidity function to alkaline, *i.e.* deprotonating, solutions. When pK_{IH} is known, it can be used to determine the value of the H_- function or hence the acidity of a new indicator. By reducing the content of water or methanol, one can advance stepwise to the hitherto unknown acidity constants of less and less acidic indicators. The H_- scale was extended to 12 pK units and is connected to the conventional pH scale by the most acidic indicators used. Precise pK values could be given for the first time for some C–H acids in $(CH_3)_2SO/CH_3OH/CH_3OK$ buffer solutions, *e.g.* indene (pK = 18.2), fluorene (20.5), and triphenylmethane (27.2). / J. Amer. chem. Soc. *87*, 382 (1965) / –Eb. [Rd 274/483 IE]

The iron(II)-cysteine complex in ferredoxin was studied by *E. Bayer*, *W. Parr*, and *B. Kazmeier*. The iron(II) complex *(1)* of methyl cysteinate was prepared as a model compound. The agreement of the spectroscopic data of *(1)* and ferredoxin (λ_{max} = 280 and 390 μm and 285 and 390 mμ, respectively) makes it appear likely that the arrangement of the iron(II) ions in ferredoxin is similar to that in *(1)*. The hydrogen



(1)

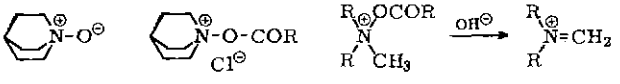
sulfide liberated on acidification of ferredoxin is not linked as inorganic sulfide but is produced by an Fe(II)-catalysed β-elimination of sulfur from the cysteine in the peptide. The methyl *N*-benzoylcysteinate and methyl cysteinate ester used as models behave like ferredoxin in this respect. The benzoyl compound releases H_2S even in the absence of $Fe^{2\oplus}$ on acidification, but methyl cysteinate reacts only in the presence of iron, which therefore exerts a catalytic effect. Pure apoferredoxin was made be splitting off the iron from the complex with α,α'-bipyridyl in a solution containing sodium dithionite. In the presence of $Fe^{2\oplus}$, the apoferredoxin exhibited complete activity in enzymatic tests. / Arch. Pharmaz. *298*, 196 (1965) / –Hö. [Rd 371/580 IE]

Tetrakis-8-hydroxyquinolyltin(IV), a chelate with the coordination number 8, is described by *K. Ramaiah* and *D. F. Martin*. It was made from diphenylbis-8-hydroxyquinolyltin(IV) and excess 8-hydroxyquinoline by cleavage of the phenyl-tin bond at 300 °C. The brick-red substance, m.p. 400 °C, was purified by washing it with ether and toluene and subsequent vacuum sublimation. The properties of the compound are those expected of a chelate with 8-coordinated tin. Conductivity measurements in nitrobenzene preclude an ionic structure $[Sn(Ox)_3]^\oplus Ox^\ominus$. The chelate is present in the monomeric form in its solution in acridine. Polarographic investigations indicate two reduction steps identical with those of diphenyltin dichloride. The infrared spectrum and thermal stability of the compound and the resistance to methylation of its nitrogen atoms make it appear likely that the coordinate bonds occur between the quinoline nitrogens and the tin. / Chem. Commun. *1965*, 130 / –Gn.

[Rd 366/575 IE]

Selective hydrolysis of aspartate bonds in tryptic peptides was achieved by *C. M. Tsung* and *H. Fraenkel-Konrat*. After 16 h in 0.03 N hydrochloric acid at 105 °C, all aspartate residues plus about 50 % of the aspartate residues from asparagine were split off as free aspartic acid. All other amino acids remained practically unaffected. Kinetic measurements revealed that the hydrolysis of peptide bonds involving asparagine is preceded by elimination of ammonia to give aspartate. The rate of hydrolysis of aspartate-peptide bonds is not affected by the nature of the neighboring amino acid. The products of the reaction are ammonium ion, aspartic acid, and peptides that are completely free of aspartate and asparagine. The method should by useful for sequence analysis. / Biochemistry *4*, 793 (1965) / –Hö. [Rd 368/577 IE]

N-Acyloxyammonium salts *(1)* have been made by *R. Huisgen* and *W. Kolbeck*. Anhydrous quinuclidine-*N*-oxide *(2)* and benzoyl chloride or acetyl chloride react in benzene to give the colorless salts *(3a)* or *(3b)* in yields of 89–91 %. The NMR spectra of *(3)* prove that the bicyclic moiety remains intact. Compound *(3a)* is surprisingly stable in acidic or neutral solution but is readily decomposed by alkali. Aniline



(2) *(3a)*: R = C_6H_5 *(1)* *(4)*

(3b): R = CH_3

is benzoylated by *(3a)* in the cold with release of *(2)*. The corresponding *N*-tosylquinuclidinium chloride can be kept in the crystalline state only below –20 °C, but the hexachloroantimonate is stable even at room temperature. The use of a bridgehead amine oxide such as *(2)* suppresses the base-catalysed reaction leading to the immonium ion *(4)* otherwise observed with *(1)*. / Tetrahedron Letters *1965*, 783 / –Ma. [Rd 289/498 IE]

The repressor of the β-galactosidase synthesis in *Escherichia coli* was studied by *J. R. Sadler* and *A. Novick*, who managed to isolate mutants which synthesize a labile repressor. The repression of the β-galactosidase formation in a bacterial culture could be eliminated merely by brief heating. This derepression proceeded like the reaction after addition of an inducer, *e.g.* isopropyl thiogalactoside. In the presence of inducer, the repressor becomes more thermolabile. In agreement with the concepts of *Monod* [1], it is assumed that attachment of the inducer onto the repressor produces a change in the conformation of the latter which inactivates its point of attachment for the Lac-operon. Accordingly, repressors should be classified among the allosteric proteins. / J. molecular Biol. *12*, 305 (1965) / –Hö. [Rd 369/578 IE]

[1] *J. Monod*, *J. P. Changeux*, and *F. Jakob*, J. molecular Biol. *6*, 306 (1963).

A new method of preparing dihalogenocarbenes from organometallic compounds in good yields under mild conditions is described by *D. Seyferth, J. Yick-Pui Mui, M. E. Gordon*, and *J. M. Burlitch*. When $(CH_3)_3SnCF_3$ and NaI are heated with cyclohexene in dimethoxyethane under nitrogen at 80 °C for 12 h, the product is 7,7-difluorobicyclo[4,1,0]heptane in 73 % yield; with tetramethylethylene instead of cyclohexene, 1,1-difluorotetramethylcyclopropane *(1)* is formed (77 % yield).

$$(CH_3)_3SnCF_3 + NaI + (CH_3)_2C{=}C(CH_3)_2 \rightarrow$$

$$(CH_3)_3SnI + (CH_3)_2\overset{CF_2}{\overset{/\backslash}{C}}C(CH_3)_2 + NaF$$

(1)

An analogous reaction between $C_6H_5HgCCl_3$ and cyclohexene affords 7,7-dichlorobicyclo[4,1,0]heptane (72 %) after 48 h at 30 °C. Here a trichloromethide anion, $CCl_3^{\ominus}$, is formed as an intermediate. $C_6H_5HgCCl_2Br$, NaI, and acrylonitrile react at room temperature in 1,2-dimethoxyethane to

$$H_5C_6HgCX_3 + I^- \rightarrow H_5C_6HgI + CX_3^- \quad (2)$$

$$CX_3^- \rightarrow CX_2 + X^-$$

$$CX_2 + (CH_3)_2C{=}C(CH_3)_2 \rightarrow (CH_3)_2\overset{CX_2}{\overset{/\backslash}{C}}C(CH_3)_2$$

yield 1,1-dichloro-2-cyanocyclopropane (16 %), bromodichloromethane (28.5 %), and 4-bromo-4,4-dichlorobutyronitrile (2 %). / J. Amer. chem. Soc. *87*, 681 (1965) / –Ma.
[Rd 288/497 IE]

The reduction of tertiary phosphine oxides with trichlorosilane to tertiary phosphines is reported by *H. Fritzsche, U. Hasserodt*, and *F. Korte*. The reduction can be effected not only with organosilanes alone – as previously thought – but also with trichlorosilane. The Reactions (a) and (b) are carried out in an autoclave or simply in benzene or toluene; both aromatic and aliphatic tertiary phosphine oxides can be re-

$$R_3PO + 2\,SiHCl_3 \rightarrow R_3P + SiCl_4 + H_2 + 1/n\,(Cl_2SiO)_n \quad (a)$$

$$R_3PO + SiHCl_3 + R'_3N \rightarrow R_3P + 1/n\,(Cl_2SiO)_n + HNR'_3Cl \quad (b)$$

duced. The siloxanes formed are dissolved by boiling with 20–30 % sodium hydroxide, and the tertiary phosphines are then isolated from the organic phase. Thus, for example, $(C_6H_5)_3PO \rightarrow (C_6H_5)_3P$, m.p. 80 °C, in 98 % yield without amine, or in 85 % yield with triethylamine; $(p\text{-}CH_3O\text{-}C_6H_4)_3PO \rightarrow (p\text{-}CH_3O\text{-}C_6H_4)_3P$, m.p. 135 °C, in 65 % yield; $(n\text{-}C_4H_9)_3PO \rightarrow (n\text{-}C_4H_9)_3P$, b.p. 111 °C/14 mm, in 92.5 % yield. / Chem. Ber. *98*, 170 (1965) / –Ma.
[Rd 256/465 IE]

Free arylboron radicals have been obtained by *J. E. Leffler E. Dolan*, and *T. Tanigaki*. Dimesitylboron fluoride reacts in 1,2-dimethoxyethane with a Na/K alloy to give the dimesitylboron radical *(1)* which can be kept for at least 4 months in the degassed solvent, as shown by ESR spectra. Trimesitylboron also reacts with alkali metals in dimethoxyethane or tetrahydrofuran to form blue solutions containing free radicals. On further reaction with alkali metal or Na/Hg in

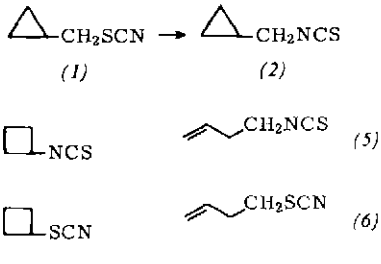
$$R_2BF \xrightarrow{Na\text{-}K} R_2B\cdot \qquad R = \text{2,4,6-trimethylphenyl}$$

(1)

tetrahydrofuran, aryl groups are split off and the ESR spectrum of the resulting product is identical with that of *(1)*. / J. Amer. chem. Soc. *87*, 927 (1965) / –Ma.
[Rd 290/499 IE]

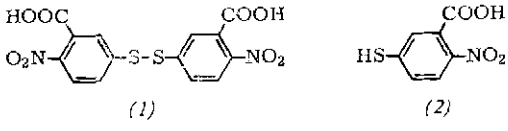
The selective reducing properties of borane carbonyl derivatives have been examined by *R. D. Shoup* and *J. C. Carter*. $[NH_3CH_3]^{\oplus}$ $[H_3BCONHCH_3]^{\ominus}$ can reduce aldehydes, ketones, acyl chlorides, pyridinium salts, and oxides. Suitable solvents are water, tetrahydrofuran, and dimethoxyethane; in the latter the reduction proceeds less intensively but more selectively. The three hydrogens attached to the boron are involved in the reduction. Interesting reactions include the reduction of the pyridinium ring in the 1,4- and 1,2-positions, the stereoselective reduction of 3,3,5-trimethylcyclohexanone to form 3–4 times more *trans*- than *cis*-alcohol, and the 90–95 % selective reduction of an aldehyde in the presence of a ketone. $[NH_2(CH_3)_2]^{\oplus}$ $[H_3BCON(CH_3)_2]^{\ominus}$ is less active than the above reagent but reduces aldehydes very selectively in the presence of ketones. It converts 3,3,5-trimethylcyclohexanone preferentially into the *trans*-alcohol. Nitriles, olefins, and esters are not reduced by this reagent. / Abstracts 149th Meeting Amer. Chem. Soc. *1965*, 49 P / –Ma.
[Rd 328/537 IE]

Thermal isomerization of thiocyanomethylcyclopropane *(1)* was found by *P. E. Newallis* and *L. A. Spurlock* to give rise to compounds *(2)–(6)*. This is the first example of a rear-



rangement of a carbon skeleton coupled with a simultaneous thiocyanate-isothiocyanate isomerization. / Abstracts 149th Meeting Amer. Chem. Soc. *1965*, 29P / –Ma. [Rd 329/538 IE]

A colorimetric micro-assay of glutathione has been developed by *C. W. Owens* and *R. V. Belcher*. Only 30 mg of tissue is required for an estimation. The tissue is homogenized and filtered through a sintered-glass funnel. The filtrate containing the glutathione (GSH) is filled into an absorption cell with phosphate buffer at pH 7.1, bis-(4-nitro-2-carboxyphenyl) disulfide *(1)*, and ethylenediaminetetraacetic acid. When TPNH is added to start the reaction, the disulfide *(1)* is reduced to 5-mercapto-2-nitrobenzoic acid *(2)* by catalytic amounts of GSH. The rate of increase in the optical density of *(2)* at 412 mμ, which is proportional to the concentration of GSH, is recorded. The reduction is probably a cyclic



process: GSH reacts with *(1)* to give a molecule of *(2)* and a mixed disulfide, which reacts with a second molecule of GSH to yield another molecule of *(2)* and GSSG. The GSSG is reduced by TPNH at GSH-reductase with regeneration of the GSH. / Biochemical J. *94*, 705 (1965) / –Hö.
[Rd 319/528 IE]

A radiochemical estimation of terminal lithium in polymers, developed by *D. R. Campbell* and *W. C. Warner*, is based on their reaction with tritium-labelled alcohols. The lithium is exchanged for the tritium of the alcoholic hydroxyl group, and the excess alcohol is washed out with water; the content of labelled end-groups is then determined radiometrically. This process yields results in good agreement with the lithium estimation by carbonation when alcohols containing up to 4 carbon atoms and temperatures of 25–65 °C are used. / Analytic. Chem. *37*, 276 (1965) / –Hl. [Rd 297/506 IE]

Spectroscopy in the far infrared for the analysis of high polymers, resins, monomers, and plasticizers is recommended by *D. Hummel* to supplement the data from spectroscopy in the middle infrared. Spectra in the far infrared (between 700 and 250 cm^{-1}) are particularly sensitive towards alterations in intra- and intermolecular forces and are therefore valuable for examining the conformations and crystallinity of high polymers. Although strongly polar and crystalline materials generally have many relatively strong absorptions in the far infrared, amorphous resins often give spectra with hardly any prominent features. Since light in the far infrared is scattered less by turbid samples than that in the middle infrared, the techniques for measuring far-infrared spectra are ofter much simpler. / Kunststoffe *55*, 102 (1965) / –Hl.

[Rd 296/505 IE]

BOOK REVIEWS

Optical Circular Dichroism. Principles, Measurements, and Applications. By *L. Velluz, M. Legrand*, and *M. Grosjean*, transl. by *J. MacCordick*. Verlag Chemie GmbH., Weinheim/Bergstr. (Germany) and Academic Press, New York-London 1965. XII+247 pp., 149 figs., 10 tables, linen DM 40.– (about $ 10.00).

The measurement of optical circular dichroism, *i.e.* the difference in absorption of left-hand and right-hand circularly polarized light by optically active compounds, is one of the most modern optical methods of investigation. Circular dichroism yields valuable information about the configuration of organic molecules having a chromophore in the vicinity of their center of asymmetry. Some years ago *L. Velluz, M. Legrand*, and *M. Grosjean* developed an apparatus with which dichrograms can be measured as conveniently and rapidly as ordinary absorption spectra, thus making the method accessible to the organic chemist interested in configurational problems. The authors have made a further significant contribution with this first monograph on the subject.

One of the two introductory chapters contains a comparison of circular dichroism and optical rotatory dispersion. The experimentally easier, and therefore previously applied, measurement of the rotation of plane polarized light as a function of wavelength also gives information about the configuration of optically active compounds. Whereas measurable dichroism occurs only in the region of absorption of the responsible chromophore, optical rotation extends well beyond this range, although with diminishing magnitude. This leads to specific differences which makes the two methods complementary. The authors justifiably regard the simpler form of the dichrograms as an advantage in the analysis of the experimental data. In compounds having several chromophores near the asymmetric center, or a chromophore with several absorption bands, a detailed investigation and assignment of the separate effects is often possible only with the aid of circular dichroism. On the other hand, measurement of rotatory dispersion is indispensible for configurational studies on compounds which absorb below 220 mμ and into which no chromophore absorbing at higher wavelengths can be introduced.

Readers primarily interested in the application of the method to structural problems may find the following chapter (58 pp.) somewhat too detailed and theoretical. For circular dichroism it is, however, particularly worthwhile to learn more about the principles and selection of the method of measurement, since considerable difficulties in instrumentation had to be surmouted. It would, however, be desirable if in a later edition a separate chapter could be added here on measuring techniques, cells for kinetic and low-temperature measurements, possibilities to enhance the fine structure, *etc.*

The main part of the book (105 pp.) is devoted to the application of circular dichroism. Optically active compounds containing the ideally suited carbonyl chromophore – mainly steroid ketones – are described first in this section. After a theoretical analysis of the carbonyl chromophore, a clear explanation of the octant rule is given. The application of this rule to determinations of absolute configuration is demonstrated on systematically ordered groups of steroid ketones and extended to compounds in which the keto group is not in a saturated six-membered ring. An advance for the theory and applications of circular dichroism is the introduction by the authors of the normalized dichrograms, in which all ordinate values are divided by the maximum height of the curve. The shape and position of these dichrograms are characteristic for a given combination of chromophore and asymmetric center and independent of the rest of the molecule. – Next alcohols, amines, and carboxylic acids, which do not ahsorb above 220 mμ, and which were investigated after conversion to derivatives absorbing at longer wavelengths, *e.g.* xanthates, nitrosamines, and acylthioureas are discussed. It is then shown with cobalamines, anthracyclinones, peptides, and polynucleotides, that successful configurational investigations of natural products containing a complicated chromophore are possihle with the aid of circular dichroism. The anthracyclinones are also an example of measurements on compounds of low optical activity and very high extinction coefficients. – It is remarkable that most of the numerous measurements puhlished to date have been made on an apparatus described by the authors. The next chapter (10 pp.) describes the effects of concentration, temperature, and solvent on optical circular dichroism in three sections. Some references to application to kinetic measurements, analysis of mixtures, and measurements at low temperatures are also concealed under these headings. The book closes with a brief presentation of the present status of the molecular theory of optical activity and with a valuable appendix listing wavelength and intensity of the dichroism maxima of over 400 compounds.

Configurational analysis using optical circular dichroism is becoming increasingly important through new developments in the elucidation and synthesis of optically active compounds. As the first monograph on the subject, and with the originators of the method as authors, the book hardly needs recommendation. It is very welcome that the publishers have presented it in English and thus made it immediately accessible to a wide range of readers. *B. Franck* [NB 424/269 IE]

Polycyclic Hydrocarbons. Volume I. By *E. Clar*. Academic Press, London-New York, and Springer Verlag, Berlin-Göttingen-Heidelberg 1964. 1st Edit., XXVIII + 488 pp., 80 figures, 8 tables, linen, DM 70. - (about $ 17.50).

Since the appearance of the well known monograph by *E. Clar* on polycyclic aromatic hydrocarbons in 1952, this field has undergone vast material and theoretical developments. Almost 40% of the polycyclic systems known at present have been synthesized within the past 12 years. This new English monograph is therefore much larger than the previous edition and appears in two volumes. The first volume contains general chapters on the chemistry, physics, and biological importance of aromatic hydrocarbons and a systematic discussion of cata-annellated systems.

Although the text covers the synthesis, properties, spectra, and biological activities of all the hydrocarbons described in the literature up to 1963 and thus gains the informational value of a work of reference, *Clar*'s own contributions are placed in the forfront of the theoretical chapters. In the preface, he states that the book is written "... to present the facts in a simple and clear order ... but it does not present a com-

prehensive theory about polycyclic hydrocarbons". By systematic use of simple symbols (Kekulé structures and π-sextets), an attempt is made to achieve a uniform description of the chemical and spectroscopic behavior of aromatic hydrocarbons. These chapters, which contain many new and unconventional proposals, will certainly stimulate discussions.

In addition there is an informative contribution by *Regina Schoental* on the carcinogenic effect of aromatic hydrocarbons.

This book ought to prove an indispensable companion for every chemist, physicist, or physician working directly or indirectly with polycyclic aromatic compounds.

M. Zander [NB 338/196 IE]

Polycyclic Hydrocarbons. By *E. Clar*. Vol. 2. Academic Press, London-New York; Springer Verlag, Berlin-Göttingen-Heidelberg 1964. 1st. edit., LVIII + 487 pp., linen DM 78.40 (about $ 20.00).

The second volume of *E. Clar*'s monograph on polycyclic aromatic hydrocarbons contains descriptions of *peri*-condensed systems, *i.e.* the hydrocarbons derived from perylene, pyrene, fluoranthene, *etc.* A total of about 200 aromatic systems is described. The literature has been completely scanned until the end of 1962 and sometimes up to the end of 1963.

In the chapters on the various hydrocarbons, the well-proved divisions used in *Clar*'s German monograph (1952) on aromatic hydrocarbons has been retained. First the syntheses of the hydrocarbons are described; here many well-printed formulae help to maintain clarity. This is followed by a description of the most important physical properties. Ultraviolet spectra are recorded clearly in illustrations with data on the band maxima and extinction coefficients. On account of its numerous spectra alone, the book should be of great value to the chemist interested in spectroscopy. Furthermore, the most important reactions of the hydrocarbons – substitution, hydrogenation, oxidation, *etc.* – are discussed. Whenever possible, data on their biological activities are given.

This second volume, which now completes the treatise, will also be of great service to anyone working in the field of polycyclic aromatic compounds.

M. Zander [NB 400/258 IE]

The Enzymes. Edited by *P. D. Boyer, H. Hardy*, and *K. Myrbäck*. Vol. 8. Academic Press, New York-London 1963. 2nd completely revised edit., XX + 484 pp., numerous illustrs. and tables, linen $ 16.50.

This volume contains a discussion on the porphyrin enzymes and on the oxidases involved in direct oxygenation. As in the previous volumes, an opening chapter *(Nicholls)* gives an orderly survey of the functions of the cytochromes, whose cofactors are so similar but whose catalytic activities – determined by the protein moiety – are so different. The individual cytochromes are then given due consideration. Although naturally the recently discovered structure of the porphyrin of the respiratory enzyme is not included, the expanse and orderliness of data given are highly impressive, and abundant references are cited covering literature up to 1962. There is only little quantitative information given on the phenol and amine oxidases containing iron or copper. On the other hand, a thorough treatment is given (*Nicholls-Schonbaum, K. G. Paul*) to "the fossil enzymes of unknown function in mammals" – catalase and peroxidase, which played so important a role in the development of the fundamentals of the molecular biochemistry of enzymes, for with them *B. Chance* worked out the methods of kinetic analysis for studying the enzyme-substrate complex and its quantitative dependence on the physico-chemical parameters of the reaction medium. The new field of mixed-function oxidases is discussed with accustomed authority by *O. Hayaishi*, and a clear and poignant description of the interesting topic of phenylalanine hydroxylation is given by its discoverer *S. Kaufman*. The agglomeration of facts in this way awakes reasonable hopes that with their help, the basic principles of enzyme action may soon be recognized, about which, unfortunately, little is said. It is regrettable that here the authors – perhaps in contrast to the earlier edition – have steered clear of hypotheses, which would at least incite discussions. The volume not only completes the description of the oxidizing enzymes, but also closes the entire work and ends with a collective index. The series provides a firm foundation on which molecular biophysical research can continue to build.

L. Jaenicke [NB 382/240 IE]

Analysis of Ancient Metals. By *E. R. Caley*. International Series of Monographs on Analytical Chemistry. Edited by *R. Belcher* and *L. Gordon*. Vol. 19. Pergamon Press, Oxford-London-Edinburgh-New York-Paris-Frankfurt 1964. 1st edit., XI + 176 pp., 64 tables, linen £3.10.0 (about $ 10.–).

After an indication is given of the irregularities caused by weathering processes on various layers of metallic archeological finds, proposals are made for eliminating such interferences, and the most important corrosion products and their analysis are described. This is followed by highly detailed practical procedures for chemical investigations of the metals Au, Ag, Cu, Pb, Sn, Sb, and their historically interesting alloys, and of iron and steel and their weathering products. Mainly classical analytical procedures are applied. More recent assay and separation procedures, and micromethods are not included, although these are probably valuable for rapid series estimations.

The purely chemical section is aptly supplemented by numerous sample analyses and an extensive list of references. The book is well printed and furbished and is of interest to anyone engaged in analyses of ancient metals.

W. Geilmann [NB 365/223 IE]

Recent Progress in Surface Science. Vol. 1. Edited by *J. F. Danielli, K. G. A. Pankhurst*, and *A. C. Riddiford*. Academic Press, New York-London 1964. 1st edit., XII + 414 pp., numerous figs., a few tables, clothbound $ 16.00.

In this book, eleven chapters by several authors give reviews of sections of this very broad field of knowledge, which attracts the interest and research participation of biologists, chemists, physicists, and engineers alike. Subjects dealt with include the viscosity of interfaces, foams, films of free liquids, electrical double layers and electrokinetic phenomena, electrode processes, corrosion of metals, surfactants, the chemistry of semiconductor surfaces, facilitated diffusion through cell membranes, cell contacts, the external surface of cells and intercellular adhesion, and the formation and properties of bimolecular lipid membranes.

Progress reports of this kind are very valuable, for they save the scientist who wants to secure a preliminary survey of the latest results on a certain topic much time that would otherwise be required for studying widely scattered original publications. The encyclopaedic nature of this book makes its purchase recommendable particularly for both large and small libraries.

B. Fell [NB 380/238 IE]

Water and Solute-Water Interactions. By *J. L. Kavanau*. Holden-Day, Inc., San Francisco-London-Amsterdam 1964. 1st edit., 101 pp., 7 figs., linen $ 5.50.

Because of the fundamental significance of its subject, this little book should arouse great general interest. The author briefly treats the following in particular: the structures of water and ice, short- and long-range order in water, proton mobility and proton exchange, and interactions of water with ions and macromolecules. Many advances in these fields have been made so recently that they have not yet found their way into most textbooks. However, many important questions still remain the object of occasionally contradictory speculations and hypotheses. The author's attempt to make his publication as up to date as possible is

illustrated by the fact that he reviews even the latest papers, including some dated 1964. However, the selection of literature reviewed sometimes appears to be a little one-sided, and some relevant matters have been omitted or are only mentioned incidentally, *e.g.* the bonding effect of hydrophobic interactions or the importance of the structure of water to the mechanism of fast reactions.

G. Schwarz [NB 393/251 IE]

The Application of Mathematical Statistics to Chemical Analysis. By *V. V. Nalimov*. Translated from the Russian by *P. Basu*. Pergamon Press, Oxford-London-Edinburgh-New York-Paris-Frankfurt 1963. 1st edit., IX + 294 pp., 54 figs., numerous tables, linen £4.4.0 (about $11.60).

This book is composed as a manual for analytical chemists or physicists. It has obviously been written with a strong background of personal experience and with careful consideration of the pertinent literature. The reader is assumed to possess a fundamental knowledge of higher mathematics and mathematical statistics.

The book is divided into nine chapters. The first three deal with general principles, mathematical statistics in chemical analysis, and random variables. This is followed by chapters on the normal (Gauss) distribution and the distribution functions derived from this and on Poisson and binomial distributions. Chapter 6 deals with the comparative evalution of chemical analyses, and Chapter 7 with variance analysis. The eighth chapter presents a statisical treatment of linear relationships, including a short section on correlation analysis. The closing chapter gives rules and proposals for the planning of statistical experiments. A particularly valuable list of further literature is given: 172 references with short descriptions of the contents of books and papers covering the period up to 1959. This is followed by a most useful appendix with 15 clear tables of the most important statistical functions.

The book contains a wealth of interesting and original thoughts and of step-by-step calculations of numerical examples. The experienced worker in this field will find many suggestions here. The reviewer considers the volume less suitable as an introduction for the beginner, for the main themes cannot he followed well enough. The book adopts a very wide scope, and important conclusions are given unobtrusively in the text; if these had been made more prominent by using italic or bold-faced type, their importance would be more immediately apparent. The symbols used are clear, but the number of concepts introduced could have been reduced. Some definitions are imprecise, and the curves of the Gauss distribution in Figure 11 are poorly reproduced. Some aspects are omitted or given only brief treatment, *e.g.* the question of the distribution of possible true values around a result found by experiment and the definition of the limit of detection.

On the other hand, the book is full of useful ideas and hints. For instance, it is pointed out that decisions reached as a result of statistical criteria are of the nature of agreements. Admirable features of the hook are the applications of Poisson distribution to semiquantitative analysis and of binomial distribution to qualitative analysis. Even the Chebysheff inequality is used in analyses when nothing is known of a distribution function. *Nalimov* himself states in his foreword that he considers his book to be a contribution to the further development of a general statistical theory of chemical analysis. It is certainly a most stimulating and useful contribution.

H. Kaiser [NB 406/264]

Mucopolysaccharides. Chemical Structure, Distribution, and Isolation. By *J. S. Brimacombe* and *J. M. Webber*. B. B. A. Library, Vol. 6. Elsevier Publishing Co., Amsterdam-London-New York 1964. 1st edit., IX + 181 pp., 10 figs. 13 tables, linen DM 31.– (about $8.00).

Although numerous monographs have appeared within recent years on this topic, the present volume is appealing because it brings a careful and comprehensive survey of the more recent literature in clear terms and a systematic order. The authors have attained this their aim firstly by restricting the material covered to the mucopolysaccharides the structures of which have been completely or largely elucidated and secondly by stressing the classical methods of structural analysis in carbohydrate chemistry. There are six chapters given on the individual types of mucopolysaccharides, even blood-group substances being regarded as such (!). Although data are presented on their distribution, preparation, biosynthesis, and enzymatic degradation, the book is not suitable as a work of reference nor for use as a laboratory manual. For example, data on molecular weights and specific optical rotations, which the reader would have preferred in tabular form, are scattered throughout the text, and other physical properties that are of importance especially for the biological function, such as viscosities, electrophoretic mobilities, sedimentation constants, *etc.*, are omitted altogether. In addition, the authors have restricted their discussion in the chapters on quantitative estimation, separation, and purification to a mere reiteration of the methods available without commenting on their usefulness. Despite these shortcomings, the experienced worker in this field will take recourse to this very informative book, especially on account of its reliable bibliography, which encompasses 946 titles.

E. Buddecke [NB 402/260 IE]

Treatise on Analytical Chemistry. Edited by *I. M. Kolthoff*, *P. J. Elving*, and *E. B. Sandell*. Part I: Theory and Practice. Vol. 3 and Vol. 4. Interscience Publishers, a Division of John Wiley & Sons, New York-London-Sydney 1961 and 1963. 1st edit., Vol. 3, Section C (concluded) Separation: Principles and Techniques: XVII + 439 pp., numerous figs. and tables, linen £5.15.0 (about $16.00); – Vol. 4, Section D–1: Magnetic Field Methods of Analysis; Section D–2: Electrical Methods of Analysis: XXV + 953 pp., numerous figs. and tables, linen £9.9.0 (about $26.50).

Fifty-three of the total of 124 sections planned for the first part – Theory and Practice of Analytical Chemistry – of the analytical handbook "Treatise on Analytical Chemistry" have now appeared. The present partial volume I 3 concludes the Section C begun in the partial volume I 2 on separatory methods and their principles and practical techniques; the partial volume I 4 contains section D–1 on magnetic analytical methods and section D–2 on electrical methods of analysis. As for the first two partial volumes, the editors have secured competent specialists to write the individual portions. The fundamentals of the methods are described very carefully and comprehensively, but often the practical aspects receive too little attention. For this reason, the reader will miss a comparitive appraisal of various methods for solving different specific analytical tasks.

In the partial volume I 3, *H. Irving* and *R. J. P. Williams* deal with liquid-liquid extraction, and *J. A. Hermann* and *J. F. Suttle* with methods of separation based on solid-liquid equilibria. Separation and purification by crystallization and precipitation are given much more space than the important new technique of zone melting (only 3 pp.).

The major portion of volume I 3 is devoted to chromatography. The fundamentals of chromatographic methods are discussed by *I. Rosenthal*, *A. R. Weiss*, and *V. R. Usdin*; thereafter individual methods are described: liquid-solid adsorption chromatography by *B. J. Mair*, liquid-solid ion-exchange chromatography by *W. Rieman* and *A. C. Breyer*, paper chromatography by *H. J. Pazdera* and *W. H. McMullen*, and gas chromatography by *C. E. Bennett*, *S. Dal Nogare*, and *L. W. Safranski*. Here too, the 240-odd pages afford far too little space to go beyond the fundamentals and general execution to stress the importance of these methods. Thin-layer chromatography is unfortunately not treated in this partial volume, which appeared in 1961. Electrochromatography could at least have been mentioned in the discussion of the fundamentals of chromatographic processes,

if only for the sake of maintaining the principles of classification.

The measurement of magnetic susceptibility for analytical purposes is reviewed by *L. N. Mulay* to start partial volume I 4. This section gives a good survey of the subject and deals with both fundamentals and experimental methods and applications. The section by *N. F. Chamberlain* on nuclear magnetic and electron paramagnetic resonance conveys the impression that these methods which have been applied so much in analysis within recent years are still in the throes of development; the status reflected in this section is that of 1961, but it is written lucidly and intelligibly. This statement also applies in particular to the following section on mass spectrometry by *F. W. Melpolder* and *R. A. Brown*. The fundamentals, measuring techniques, and applications are described in detail; a further useful addition is a literature review of potential analytical applications of mass spectrometry. The section D–1 on magnetic methods of analysis is then closed by an article on ion scattering by *S. Rubin*. The content of this chapter is good and shows possible analytical applications of this method, which, because of the extensive apparatus required, will at present probably remain restricted to physics laboratories.

The larger portion (over 550 pp.) of partial volume I 4 is allocated to section D–2 on electrical methods of analysis. Following a chapter by *C. N. Reilley* on the fundamentals of electrochemical processes at electrodes and another by *R. W. Murray* on electrochemical techniques, a series of detailed, well-written sections on individual electroanalytical methods is given: chronoamperometry and chronopotentiometry *(P. Delahay)*, potentiometry *(N. H. Furman)*, polarography *(L. Meites)*, coulometric analysis *(D. D. De Ford* and *J. W. Miller)*, stripping analysis *(I. Shain)*, conductometry and oscillometry *(J. W. Loveland)*, and the analytical importance of dielectric constants *(B. W. Thomas* and *R. Pertel)*.

The sections are arranged according to methodical aspects of the subject and frequently – as already pointed out in earlier reviews – overemphasize theory and underestimate practice. Moreover, the presentation often should have followed physico-chemical fundamentals more closely and not the historical developments. Comparisons of the values of different methods in practical analysis are often sadly missed. Despite these shortcomings, the two partial volumes I 3 and I 4 of this series nonetheless represent a valuable addition to the literature on analytical chemistry.

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Synthesis of Transcurium Elements by Nuclear Reactions with Heavy Ions

BY PRIV.-DOZ. DR. C. KELLER

LEHRSTUHL FÜR RADIOCHEMIE, TECHNISCHE HOCHSCHULE KARLSRUHE (GERMANY) AND INSTITUT FÜR RADIOCHEMIE, GESELLSCHAFT FÜR KERNFORSCHUNG M.B.H. KARLSRUHE, KERNFORSCHUNGSZENTRUM

Experimental techniques are described for the preparation of transcurium elements. Nuclear reactions with heavy ions appear to be most promising for the preparation of new transcurium elements and isotopes. Since these nuclear reactions have extremely small cross-sections, only few atoms will be produced. Owing to their short half-lives, the heaviest nuclei can presumably be identified only indirectly through the probabilities of their formation and distintegration.

A. Introduction

Although the transmutation of chemical elements had often been attempted, *Becquerel* was the first to succeed in 1896. The new element was however not produced through human agency, but by the spontaneous decay of heavy nuclei. The first true nuclear synthesis was carried out by *Rutherford* in 1919 by the reaction $^{14}_{7}N(\alpha,p)^{17}_{8}O$.

The first artificial element discovered was technetium, which does not occur in nature (*Perrier* and *Segrè*, 1937). The first transuranium element, neptunium, was prepared three years later (*McMillan* and *Abelson*, 1940). The following years witnessed the discovery of the missing element 61 (promethium), and of the transuranium elements up to number 104, the last one being the first transactinide element.

B. Possible Synthesis of the Heaviest Elements

The starting materials for the synthesis of the heaviest elements are either naturally occurring heavy nuclei (*e.g.* ^{238}U and ^{232}Th), or those produced in nuclear reactions (*e.g.* ^{242}Pu and ^{246}Cm). Transurium isotopes can be made in the following two ways:

1. Heavy-ion bombardment of target nuclei of lower atomic number, in the course of which the intermediate compound nuclei emit charged and uncharged particles, as in the reactions

$^{239}_{94}Pu(^{13}_{6}C,4n)^{248}_{100}Fm$

and

$^{238}_{92}U(^{22}_{10}Ne,p3n)^{256}_{101}Md.$

Such nuclear reactions clearly can only be performed with the aid of particle accelerators and yield only unweighable amounts, or even just a few atoms, of the required elements. Apart from a few exceptions, only neutron-deficient isotopes of the heaviest elements can be prepared by this method.

2. Multiple neutron capture followed by β^--decay of the neutron-rich nuclei. This process can take place in three ways:

a) Neutron capture in very high neutron flux densities (10^{23} to 10^{25} neutrons per cm^2), such as those produced for about 10^{-6} to 10^{-8} sec in nuclear explosions. For example, $^{238}_{92}U$ undergoes multiple neutron capture in such high fluxes to give uranium isotopes containing a high excess of neutrons. Thus uranium isotopes up to ^{255}U have resulted from nuclear explosions [1-3]. The number of successive neutron captures depends mainly on the intensity and duration of the neutron pulse. The short-lived, neutron-rich uranium isotopes undergo multiple β^--decays to form the isobars with the longest half-life, *e.g.*

$$^{250}_{92}U \xrightarrow{6\,\beta^-} {}^{250}_{98}Cf$$

$$^{255}_{92}U \xrightarrow{8\,\beta^-} {}^{255}_{100}Fm$$

[1] *H. Diamand, P. R. Fields, C. S. Stevens, M. H. Studier, S. M. Fried, M. G. Inghram, D. C. Hess, G. L. Pyle, J. F. Mech, W. M. Manning, A. Ghiorso, S. G. Thompson, G. H. Higgins, G. T. Seaborg, C. I. Browne, H. L. Smith,* and *R. W. Spence*, Physic. Rev. *119*, 2000 (1960).

[2] *R. W. Hoff* and *D. W. Dorn*, Universtity of California (Berkeley), Radiation Laboratory, Report UCRL-7314 Rev. I (1963).

[3] *R. W. Hoff* and *D. W. Dorn*, University of California (Berkeley), Radiation Laboratory, Report UCRL-7347 (1963).

b) Neutron capture in high-flux nuclear reactors (10^{14} to 10^{16} neutrons per cm^2 per sec). The synthesis of neutron-rich isotopes is in this case limited by the competing radioactive decay of the latter. Consequently, all nuclides synthesized in this manner are near the maximum of nuclear stability. Owing to the short half-life of isotopes with atomic number Z higher than 102, this method is not suitable for the synthesis of such elements. The synthesis of high mass number nuclei is a slow process: four years were required to produce $^{257}_{100}Fm$ in detectable quantities (one α-decay in about 10 min) by irradiating a mixed sample of $^{242}_{92}Pu$-$^{243}_{93}Am$-$^{244}_{94}Cm$ with a neutron intensity of 3×10^{14} neutrons/cm^2/sec [4]. Nuclei with mass number A above 257 have not yet been found.

c) Neutron capture in fluxes of 10^{19} to 10^{21} neutrons/cm^2/sec, the process being similar to that in b) above, but involving nuclei not so close to the maximum in the stability curve. This type of neutron capture is responsible for nuclear syntheses in stars (r-process) [5,6]. It has not yet been possible to carry out such reactions, since they require the maintenance of high neutron flux densities for at least a few seconds. Pulsed reactors may accomplish this aim in the near future.

Fig. 1 shows a scheme for the preparation of fermium isotopes (Z = 100) by the methods 1), 2a), and 2b) above.

C. Reactions of Heavy Nuclei on Bombardment with Heavy Ions

I. The Production of High-Energy Heavy Ions

The first attempts, by *Alvarez* [7] in 1940, to produce accelerated, multiply charged heavy ions resulted in only a trickle of $^{12}_{6}C$ ions (10 ions/sec) with an energy of 50 MeV. Since then, ion beams of higher energy and intensity, but also of better monochromaticity, have been obtained. The conventional ion sources of light-particle cyclic accelerators yield only doubly or triply charged heavy ions, which lose further electrons on collision with the residual gas. The more highly ionized particles are then accelerated more strongly, resulting in a wide energy spread of the particle beam. This can now be avoided in two ways:

1. by the use of a linear accelerator, such as the Heavy-Ion Linear Accelerator (HILAC) at Berkeley, California, in which heavy ions reach an energy of 10.3 MeV per nucleon;

2. by using special ion sources giving a uniformly ionized beam, which is not ionized further in the cyclic accelerator. For example, the maximum energy of the ion beam in the 310 cm cyclotron at Dubna, USSR, is 8.5 MeV per nucleon with a half-width of about 3 MeV for the 100 MeV $^{12}_{6}C$ beam [8,9].

II. Reactions of Heavy Target Nuclei with Heavy Ions

Interactions observed on bombarding heavy (Z > 80) nuclei with heavy ions (Z > 2) can be classified into distance, direct, and fusion reactions [8].

Distance reactions, incorporating all scattering processes, are of no significance in the preparation of heavy elements.

Direct reactions include transfer reactions, in which the projectile carries off some nucleons from the target (pick-up reactions), or donates some to it (stripping reactions) [9, 9a]; *e.g.*

$$^{181}Ta + {}^{14}N \rightarrow {}^{17}N$$
$$^{181}Ta + {}^{20}Ne \rightarrow {}^{17}N$$

Direct reactions involve also those in which the projectile knocks out several nucleons from the target, without absorbing them completely [10, 11]. The daughter products of the residual nuclei formed in such reactions undergo α-decay with energies of 8 MeV or more. Similar decay energies can be expected from the heaviest, α-active nuclei formed in fusion reactions followed by neutron emission from the compound nuclei. Therefore the assignment of mass number on the basis of the energy and the scheme of α-decay, frequently used with the short-lived α-active isotopes of the artificial elements, is rendered very difficult [11a, 11b].

Fusion reactions result in compound nuclei which subsequently decay either by fission or by emitting nucleons. The compound nucleus is characterized by a quasistationary nuclear state, whose lifetime of about 10^{-14} sec is long in comparison with the time needed for a projectile to traverse the length of the nucleus [12].

The term "compound nucleus" will be used in the following to denote the intermediate product of a nuclear reaction, irrespective of whether it is known that the compound nucleus has a finite lifetime and that its excitation energy is distributed equally over all the nucleons [13]. Recent work [14–17] shows that alone the assumption of a compound nucleus is often an oversimplification of the mechanisms of the reactions described in Section III.

[4] *E. K. Hulet, R. W. Hoff, J. E. Evans,* and *R. W. Lougheed,* Physic. Rev. Letters *13,* 343 (1964).

[5] *E. M. Burbridge, G. R. Burbridge, W. A. Fowler,* and *F. Hoyle,* Rev. mod. Physics *29,* 547 (1957).

[6] *G. R. Burbridge, F. Hoyle, E. M. Burbridge, R. F. Christy,* and *W. A. Fowler,* Physic. Rev. *103,* 1145 (1956).

[7] *L. W. Alvarez,* Physic. Rev. *58,* 192 (1940).

[8] *G. N. Flerov,* Proceedings 2nd International Conference on the Peaceful Uses of Atomic Energy, Geneva 1958; *14,* 151 (1958).

[9] *V. V. Volkov, L. Pomorski, J. Tys,* and *G. N. Flerov,* Sov. Phys. JETP [English Transl.] *15,* 442 (1962).

[9a] *G. N. Flerov* and *V. A. Karnaukhov,* Joint Institute of Nuclear Research (Dubna, U.d.S.S.R.), Preprint D-1798 (1964).

[10] *H. Kumpf* and *E. D. Donets,* Sov. Phys. JETP [English Transl. *17,* 539 (1963).

[11] *I. Brandstetr, M. Krzivanek, J. Maly,* and *Su Chun-Guy,* Radiokhimiya *5,* 699 (1963).

[11a] *I. Kaplan,* Physic. Rev. *81,* 962 (1951).

[11b] *R. A. Glass, S. G. Thompson,* and *G. T. Seaborg,* J. inorg. nuclear Chem. *1,* 3 (1955).

[12] *N. Bohr,* Nature (London) *137,* 344 (1936).

[13] *A. Zucker,* Annu. Rev. nuclear Sci. *10,* 27 (1960).

[14] *A. B. Smith, P. R. Fields,* and *A. Friedman,* Physic. Rev. *104,* 699 (1956).

[15] *T. Sikkeland, E. L. Haines,* and *V. Viola,* Physic. Rev. *125,* 1350 (1962).

[16] *H. C. Britt* and *A. R. Quinton,* Physic. Rev. *124,* 877 (1961).

[17] *R. Kaufmann* and *R. Wolfgang,* Physic. Rev. *121,* 192 (1961).

III. Types of Disintegration of Compound Nuclei

1. Fission and Neutron Evaporation from the Compound Nucleus

When a heavy target nucleus is bombarded with heavy ions of energy somewhat above the coulomb barrier (*i.e.* the coulombic repulsion energy), the heavy ions will be captured with an effective cross-section corresponding approximately to the geometric cross-section of the nucleus. A compound nucleus is formed having an excitation energy E_A of about half the kinetic energy of the captured projectile. The nucleus then dissipates the excitation energy either by fission, or by emitting nucleons. Fission predominates in heavy nuclei (which have a low threshold energy of fission), so that the cross-sections for the nuclear syntheses are very small. The experimental value of the effective cross-section σ_c for compound-nucleus formation agrees within 15%

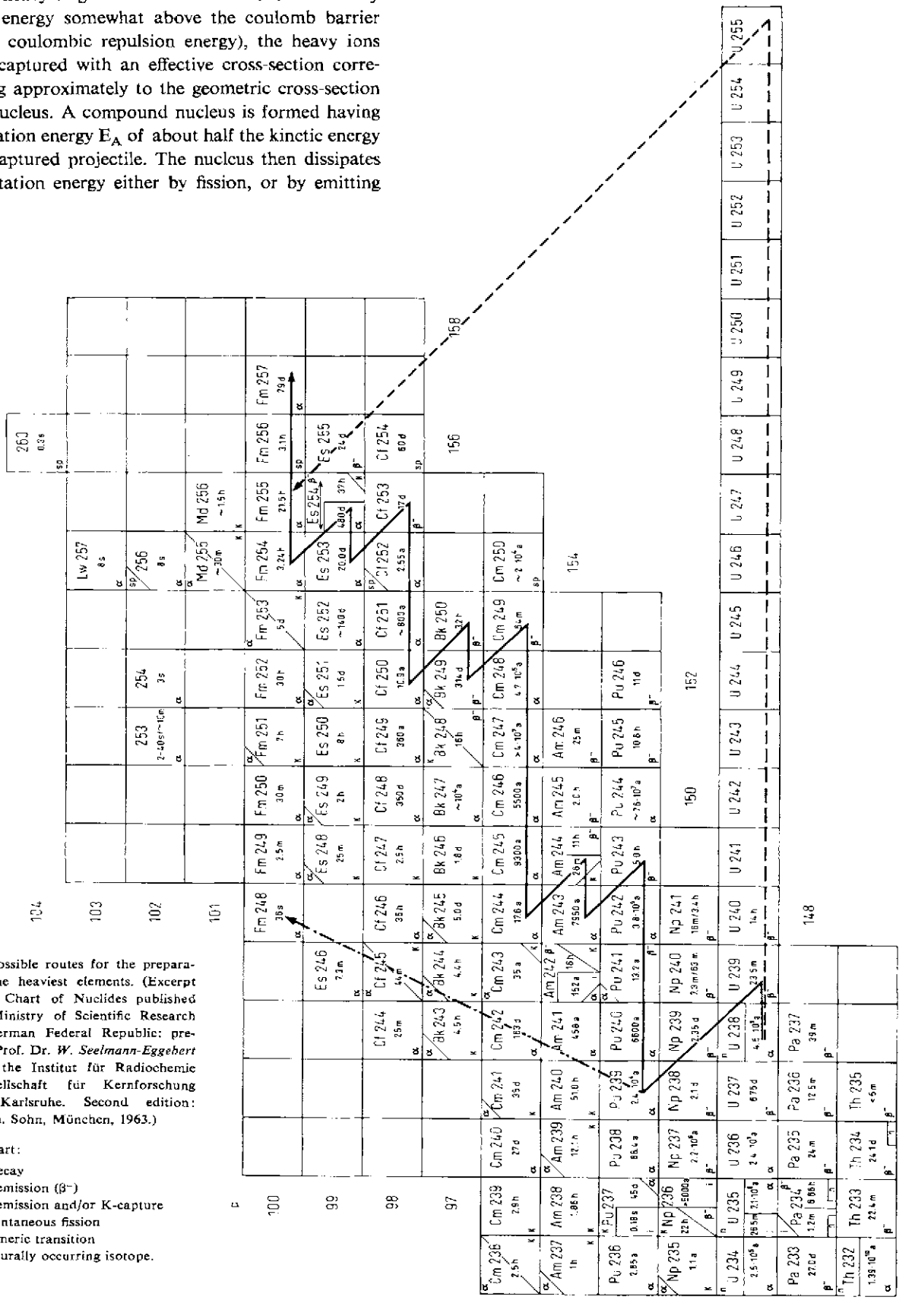

Fig. 1. Possible routes for the preparation of the heaviest elements. (Excerpt from the Chart of Nuclides published by the Ministry of Scientific Research of the German Federal Republic: prepared by Prof. Dr. *W. Seelmann-Eggebert* et al. in the Institut für Radiochemie der Gesellschaft für Kernforschung m.b.H., Karlsruhe. Second edition: Gorbach u. Sohn, München, 1963.)

Key to chart:

α	α-decay
β⁻	β⁻-emission (β⁻)
β⁺	β⁺-emission and/or K-capture
Sp	Spontaneous fission
I	Isomeric transition
n	Naturally occurring isotope.

with that calculated by Equation (1), proposed by *Blatt* and *Weisskopf* [19] and modified by *Druin* [18]:

$$\sigma_c = \pi \cdot r_0^2 (A_T^{1/3} + A_P^{1/3})^2 (1 - E_C/E) \quad (1)$$

A_T and A_P are respectively the mass numbers of the target and projectile nuclei, E is the energy of the projectile, and E_C the coulomb barrier for the nuclear reaction under consideration. E_C is calculated from:

$$E_C = \frac{Z_T Z_P e^2}{r_0 (A_T^{1/3} + A_P^{1/3})} \cdot \frac{A_T + A_P}{A_T} \quad (2)$$

Z_T and Z_P denote respectively the nuclear charges of the target and projectile. However, satisfactory agreement of the calculated and measured cross-sections is obtained only for $E > 1.2\ E_C$. The value 1.5×10^{-13} cm is generally used for the radius r_0 of a nucleon.

The relationship between σ_c and the fission cross-section σ_f is

$$\sigma_f = W_f \sigma_c \quad (3)$$

where W_f is the fission probability of the compound nucleus, which rapidly increases both with the nuclear charge of the latter (approximately in proportion to Z^2/A) and with its excitation energy [18, 20, 21]. At mass numbers $A > 220$ and excitation energies as low as about 30 MeV, the value of W_f is practically unity, so that the compound nucleus disintegrates almost exclusively by fission and the cross-sections for the emission of light particles are extremely small. This is shown by Fig. 2 for fermium isotopes [22] formed by bombarding $^{238}_{92}U$ with $^{16}_{8}O$ ions to give the $^{254}_{100}Fm$ compound nucleus, followed by neutron emission from the latter.

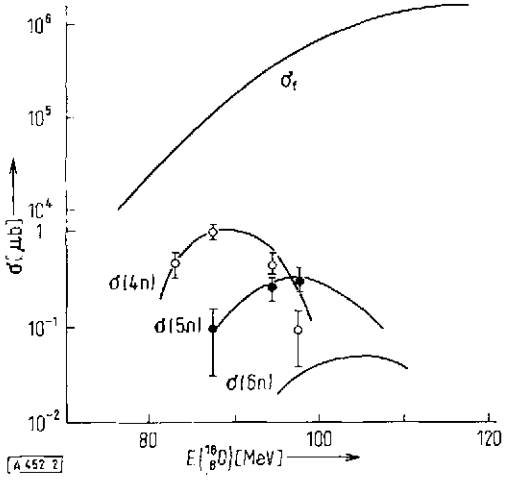

Fig. 2. Cross-sections for ($^{16}_{8}$O,xn) reactions and for fission in the bombardment of $^{238}_{92}U$ with $^{16}_{8}O$ ions, as a function of the projectile energy. (The solid lines denote calculated cross-sections).

[18] *V. A. Druin, S. M. Polikanov,* and *G. N. Flerov,* Sov. Phys. JETP [English Transl.] *5,* 1059 (1957).

[19] *J. M. Blatt* and *V. F. Weisskopf*: Theoretical Nuclear Physics. Wiley, New York 1952, Ch. VIII.

[20] *J. R. Huizenga,* Conference on Reactions between Complex Nuclei, Gatlinburg, Tenn. (U.S.A.), 1958; Report ORNL-2606 (1958).

[21] *N. I. Tarantin,* Sov. Phys. JETP [English Transl.] *10,* 250 (1960).

[22] *V. P. Perelygin, E. D. Donets,* and *G. N. Flerov,* Sov. Phys. JETP [English Transl.] *10,* 1106 (1960).

Jackson [23] has shown that the experimental cross-sections for (p,xn) reactions of lead and bismuth are in good agreement with the calculated values obtained from a simplified evaporation model assuming constant nuclear temperature. The latter is calculated from the excitation energy E_A of the nucleus with the aid of Equation (4):

$$T = (aE_A)^{1/2} \quad (4)$$

in which the value of 0.1 is generally assigned to the constant a [18]. As shown by a comparison of the calculated and observed cross-sections for the ($^{16}_{8}$O,xn) reactions in Fig. 2, *Jackson*'s nuclear model is also applicable in the case of heavy ion reactions. In the calculation of σ(X,xn), the nuclear temperature T was taken to be 1.6 MeV. It also follows from Fig. 2 that the highest yields of heavy nuclei are obtained when the energy of the projectile exceeds the Coulomb barrier only by a small margin, *i.e.* by 10–20 MeV, according to the type of reaction.

2. Emission of Charged, Light Particles from the Compound Nucleus

Not only W_f but also the probability of the emission of light charged particles from the compound nucleus increases with increasing energy of the projectile, and therefore the fission cross-section becomes comparable to that of the neutron emission. This further complicates the interpretation of experimental results, as shown in the following example.

The bombardment of $^{238}_{92}U$ with $^{22}_{10}Ne$ ions ($E > 100$ MeV) leads to $^{256}_{101}Md$ [24–26], identified by genetic correlation with its daughter nucleus $^{256}_{100}Fm$, which undergoes spontaneous fission [*]. $^{256}_{101}Md$ may be formed in either of two ways:

a) directly in the nuclear reaction:

$$^{238}_{92}U(^{22}_{10}Ne,p3n)^{256}_{101}Md \xrightarrow[1.5\ h]{e} {}^{256}_{100}Fm,$$

b) indirectly as a daughter product of the decay of $^{256}102$ by electron capture:

$$^{238}_{92}U(^{22}_{10}Ne,4n)^{256}102 \xrightarrow[8\ sec]{e} {}^{256}_{101}Md$$

Which of these processes takes place has not yet been determined. However, direct formation is more probable, since the maximum of the yield curve for $^{256}_{101}Md$ corresponds to a projectile energy which is higher by about 15 MeV (relative to the coulomb barrier) than that corresponding to maximum yield in known reactions of the type (b). The maximum yield of $^{256}_{101}Md$ lies at 128 MeV, whereas that of the reaction $^{242}_{94}Pu(^{20}_{10}Ne,4n)^{260}104$ is at 113 MeV. This shift in the maximum effective cross-section is also in good agreement with the probability of the emission of a proton from heavy compound nuclei, for which the potential well is 14 MeV. Further, no decay through electron capture has so

[23] *J. D. Jackson,* Canad. J. Physics *34,* 767 (1956).

[24] *V. A. Druin,* Joint Institute of Nuclear Research (Dubna, USSR), Preprint R-874 (1962) and KFK-tr-151 (1964).

[25] *V. A. Druin,* Nukleonika (Warszawa) *7,* 473 (1962).

[26] *J. Maly* and *J. Brandstetr,* Chem. Listy *58,* 751 (1964).

[*] Spontaneous fission is the radioactive autodisintegration of heavy nuclei into two fragments of about equal masses, without external influence, and therefore obeys the statistical laws of radioactivity.

far been detected in the case of $^{256}102$ [27, 28]. It is very difficult to decide which of the routes leads to $^{256}_{101}$Md – which has been isolated in the pure state [26, 29, 29a] – on account of the short half-life of the possible intermediate, product $^{256}102$ ($\tau^1/_2$ = 8 sec) and its small cross-section of formation ($\sigma_{max} \approx 2\times10^{-9}$ barn). An effective cross-section of 2×10^{-9} barn means that only 25 nuclei of $^{256}_{101}$Md are obtained on a three-hour irradiation of a thin uranium foil [*] with a $^{22}_{10}$Ne ion beam of 3 μA, which corresponds to about 2×10^{12} $^{22}_{10}Ne^{8+}$ ions per second. The observed $^{256}_{100}$Fm cannot be formed by ($^{22}_{10}$Ne,α) or ($^{22}_{10}$Ne,2p2n), since the effective cross-sections for these reactions are certainly less than 5×10^{-11} barn.

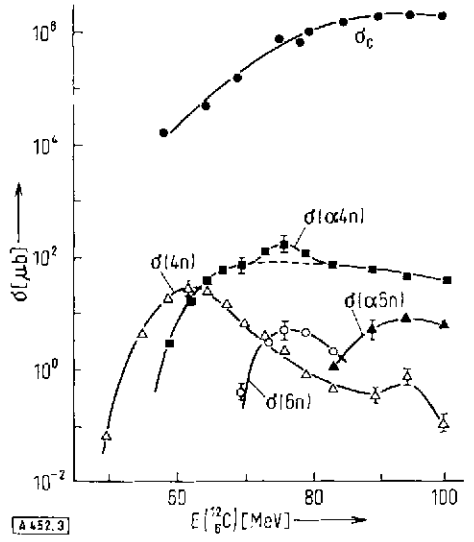

Fig. 3. Cross-sections for the nuclear reactions ($^{12}_{6}$C,xn) and ($^{12}_{6}$C,αxn) of a $^{238}_{93}$U target, as a function of the projectile energy.

Fig. 3 shows the energy-dependence of the cross-section for the reactions ($^{12}_{6}$C,xn) and ($^{12}_{6}$C,αxn) of bombarded $^{238}_{92}$U [30]. Both the form and the position of the maximum of the excitation function for neutron emission are those expected from a reaction proceeding *via* a compound nucleus. On the other hand, the curve for ($^{12}_{6}$C,α4n) is composed of at least two components. The sharp peak at 76 MeV indicates a reaction *via* a compound nucleus; the wide plateau is due to other reactions. The most likely, though unproven, suggestion is that the $^{12}_{6}$C ion is disintegrated by the nuclear forces of the target nucleus to $^{4}_{2}$He + $^{8}_{4}$Be.

Certain internuclear orientations might favor the capture of $^{8}_{4}$Be and impede α-capture, causing the reaction $^{238}_{92}$U(^{8}Be,4n)$^{242}_{96}$Cm. The possibility of the new projectile $^{8}_{4}$Be taking over varying fractions of the total energy of the parent $^{12}_{6}$C might account for the wide maximum of the cross-section for the $^{12}_{6}$(C,α4n) reaction. The fission of $^{12}_{6}$C mentioned here has already been detected on nuclear plates [31].

IV. The Best Combination of Target and Projectile for the Synthesis of Heavy Nuclei

Table 1 lists the transcurium isotopes which have been obtained by heavy-ion bombardment. Evidently most of the nuclides can be obtained by different reactions. For the synthesis of even heavier nuclei, it is important to know which target-projectile combination has the greatest cross-section for the formation of a certain end-product.

Table 1. Transcurium isotopes prepared so far by heavy-ion bombardment (σ_{max} = maximum cross-section).

Isotope	Nuclear reaction	σ_{max} [μbarn]	E [MeV]	Ref.
$^{243}_{97}$Bk	$^{238}_{92}$U($^{14}_{7}$N, α5n)$^{243}_{97}$Bk			[32]
$^{244}_{98}$Cf	$^{237}_{93}$Np($^{11}_{5}$B,4n)$^{244}_{98}$Cf	3	50–55	[32a]
	$^{238}_{92}$U($^{12}_{6}$C,6n)$^{244}_{98}$Cf	7	75	[30, 33]
	$^{238}_{92}$U($^{14}_{7}$N,p7n)$^{244}_{98}$Cf			[32]
$^{245}_{98}$Cf	$^{238}_{92}$U($^{12}_{6}$C,5n)$^{245}_{98}$Cf	90	78	[34–36]
	$^{238}_{92}$U($^{13}_{6}$C,6n)$^{245}_{98}$Cf			[35, 36]
	$^{241}_{95}$Am($^{16}_{8}$O,$^{10}_{5}$B2n)$^{245}_{98}$Cf	30	80	[37]
	$^{244}_{96}$Cm($^{12}_{6}$C,$^{8}_{4}$Be3n)$^{245}_{98}$Cf			[37]
	$^{244}_{96}$Cm($^{13}_{6}$C,$^{8}_{4}$Be4b)$^{245}_{93}$Cf	100	110	[37]
	$^{244}_{96}$Cm($^{16}_{8}$O,$^{12}_{6}$C3n)$^{245}_{98}$Cf	350	83	[37]
$^{246}_{98}$Cf	$^{232}_{90}$Th($^{18}_{8}$O,4n)$^{236}_{98}$Cf	7		[38]
	$^{238}_{92}$U($^{12}_{6}$C,4n)$^{246}_{98}$Cf	60	66	[35]
		30	64	[30, 33, 34, 36]
	$^{238}_{92}$U($^{13}_{6}$C,5n)$^{246}_{98}$Cf	130	78	[35, 36]
	$^{238}_{92}$U($^{14}_{7}$N,p5n)$^{246}_{98}$Cf			[32]
	$^{238}_{92}$U($^{16}_{8}$O,α4n)$^{246}_{98}$Cf	8		[38]
	$^{238}_{92}$U($^{20}_{10}$Ne,2α4n)$^{246}_{98}$Cf			[28]
	$^{241}_{95}$Am($^{16}_{8}$O,$^{10}_{5}$Bn)$^{246}_{98}$Cf	3	80	[37]
	$^{244}_{96}$Cm($^{12}_{6}$C,$^{7}_{4}$Be2n)$^{246}_{98}$Cf			[37]
	$^{244}_{96}$Cm($^{13}_{6}$C,$^{8}_{4}$Be3n)$^{246}_{98}$Cf	300	110	[37]
	$^{244}_{96}$Cm($^{16}_{8}$O,$^{12}_{6}$C2n)$^{246}_{98}$Cf	900	88	[37]
$^{247}_{98}$Cf	$^{238}_{92}$U($^{14}_{7}$N,p4n)$^{247}_{98}$Cf			[32]
$^{248}_{98}$Cf	$^{238}_{92}$U($^{14}_{7}$N,p3n)$^{248}_{98}$Cf			[32]
$^{245}_{99}$Es	$^{237}_{93}$Np($^{12}_{6}$C,4n)$^{245}_{99}$Es			[39]
	$^{240}_{94}$Pu(B,xn)$^{245}_{99}$Es			[39]
$^{246}_{99}$Es	$^{238}_{92}$U($^{14}_{7}$N,6n)$^{246}_{99}$Es			[32]
$^{247}_{99}$Es	$^{238}_{92}$U($^{14}_{7}$N,5n)$^{347}_{99}$Es			[32]
$^{248}_{100}$Fm	$^{240}_{94}$Pu($^{11}_{6}$C,4n)$^{248}_{100}$Fm	0.5	70	[32a, 40]
	$^{241}_{95}$Am($^{11}_{5}$B,4n)$^{248}_{100}$Fm	0.9	50–55	[32a]
$^{249}_{100}$Fm	$^{238}_{92}$U($^{16}_{8}$O,5n)$^{249}_{100}$Fm	0.4	98	[22]
$^{250}_{100}$Fm	$^{233}_{90}$Th($^{22}_{10}$Ne,4n)$^{250}_{100}$Fm	0.3		[38]
		0.25	106	[41]
	$^{238}_{92}$U($^{16}_{8}$O,4n)$^{350}_{100}$Fm	1	88	[22, 38, 42, 43]
	$^{238}_{93}$U($^{20}_{10}$Ne,α4n)$^{250}_{100}$Fm			[28]
	$^{241}_{94}$Pu($^{13}_{6}$C,4n)$^{250}_{100}$Fm	6	68	[42]
	$^{242}_{94}$Pu($^{12}_{6}$C,4n)$^{250}_{100}$Fm	10	65	[30]
	$^{243}_{95}$Am($^{11}_{5}$B,4n)$^{250}_{100}$Fm	10	50–55	[32a]
	$^{244}_{96}$Cm($^{16}_{8}$O,$^{8}_{4}$Be2n)$^{250}_{100}$Fm	1		[37]
	$^{246}_{96}$Cm($^{12}_{6}$C,α2n)$^{250}_{100}$Fm			[39]
$^{252}_{100}$Fm	$^{238}_{92}$U($^{22}_{10}$Ne,α4n)$^{252}_{100}$Fm	0.2	123	[28, 38]
	$^{250}_{98}$Cf($^{9}_{4}$Be,α3n)$^{252}_{100}$Fm			[39]
$^{256}_{101}$Md	$^{242}_{94}$Pu($^{18}_{8}$O,p3n)$^{256}_{101}$Md			[44]
	$^{238}_{92}$U($^{22}_{10}$Ne,p3n)$^{256}_{101}$Md	0.002	125–130	[24, 25, 45]
253102	$^{241}_{94}$Pu($^{16}_{8}$O,4n)^{253}102	0.005	100	[46–48]
254102	$^{241}_{96}$Cm($^{13}_{6}$C,5n)^{254}102			[49]
	$^{246}_{96}$Cm($^{12}_{6}$C,4n)^{254}102	0.6	70 ± 5	[32a, 40]
255102	$^{252}_{98}$Cf($^{10}_{5}$B,p6n)^{255}102			[39]
256102	$^{238}_{92}$U($^{22}_{10}$Ne,4n)^{256}102	0.045	112	[27, 28]
$^{257}_{103}$Lw	$^{249-252}_{98}$Cf($^{10+11}_{5}$B,xn)$^{257}_{103}$Lw			[50]
260104	$^{242}_{94}$Pu($^{22}_{10}$Ne,4n)^{260}104	1.5×10^{-4}	113	[44, 45]

[27] *E. D. Donets, V. A. Shechegolev,* and *V. A. Ermakov,* Joint Institute of Nuclear Research (Dubna, USSR), Preprint R-1383 (1963).

[28] *E. Donets, V. A. Sochegolev,* and *V. A. Ermakov,* Atomn. Energ. *16*, 195 (1964).

[29] *H. Beranova, J. Brandstetr, V. Druin, V. Jermakov, M. Kryranek, J. Maly, S. Polikanov,* and *Su Chun-Guy,* Nucleonika (Warszawa) *7*, 465 (1962).

[29a] *J. Brandstetr, W. Tung-Seng, K. A. Gavrilov, E. Gwusd, J. Maly,* and *M. Taube,* Radiokhimiya *6*, 26 (1964).

[*] *i.e.* the thickness of the foil is comparable to the recoil distance of the nuclei formed, since the new atoms would remain stuck in a thicker foil.

[30] *T. Sikkeland, S. J. Thompson,* and *A. Ghiorso,* Physic. Rev. *112*, 543 (1958).

[31] *J. F. Miller,* University of California (Berkeley), Radiation Laboratory, Report UCRL-1902 (1952).

For example, $^{250}_{100}$Fm is formed by the emission of four neutrons by the compound nucleus $^{254}_{100}$Fm, which is obtainable by any of the reactions $^{232}_{92}$Th + $^{22}_{10}$Ne, $^{238}_{92}$U + $^{16}_{8}$O, and $^{241}_{94}$Pu + $^{13}_{6}$C. Fig. 4 represents the cross-sections for the syntheses of $^{250}_{100}$Fm by these reactions. The highest yield is seen to be ensured by combining a target nucleus of high atomic number with a projectile of low atomic number. This is understandable, since the higher the nuclear charge of the projectile, the greater the kinetic energy required to overcome the Coulomb barrier, resulting in a higher excitation of the compound nucleus. This in turn increases the probability for the fission of the compound nucleus, since – according to *Vandenbosch* and *Seaborg* [51] – an 0.13 MeV increase in the excitation energy of a heavy nucleus is accompanied with a tenfold increase in the fission probability.

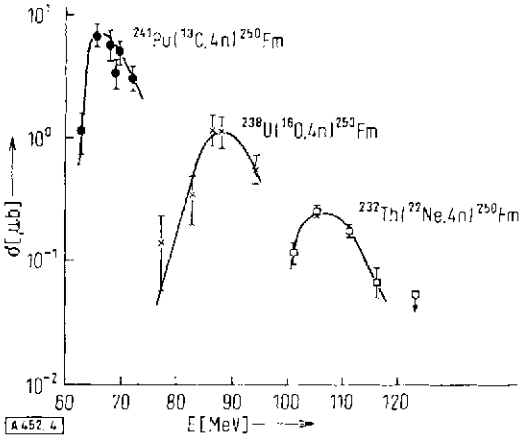

Fig. 4. Cross-sections for the synthesis of $^{250}_{100}$Fm by the reaction (X,4n) as a function of the projectile energy.

In order to show the effect of the target nuclide and the type of the projectile on the yields of the heavy nuclei, the maximum cross-sections of the nuclear reactions are shown in Table 2. Only one variable (either the target or the projectile) is changed at a time in these reactions. These data show that an increase in the nuclear charge of either the target or the projectile reduces the maximum cross-section, this decrease being particularly marked when the nuclear charge of the projectile is increased. A comparison of those nuclear reactions in which only neutrons are emitted reveals that the highest value of the maximum cross-section is usually associated with the (X,4n) reaction (cf. Fig. 2).

Table 2. Maximum cross-sections for the synthesis of heavy nuclei with various target-projectile combinations.

Target nucleus	Projectile	Reaction	Product	σ_{max} [μbarn]	E [MeV]
$^{238}_{92}$U	$^{12}_{6}$C	($^{12}_{6}$C,4n)	$^{246}_{98}$Cf [a]	30; 60 [d]	66
$^{238}_{92}$U	$^{16}_{8}$O	($^{16}_{8}$O,4n)	$^{250}_{100}$Fm[b]	1	88
$^{238}_{92}$U	$^{22}_{10}$Ne	($^{22}_{10}$Ne,4n)	^{256}102[c]	0.045	112
$^{238}_{92}$U	$^{13}_{6}$C	($^{13}_{6}$C,5n)	$^{246}_{98}$Cf	130	78
$^{238}_{92}$U	$^{12}_{6}$C	($^{12}_{6}$C,α4n)	$^{242}_{96}$Cm	100	76
$^{238}_{92}$U	$^{16}_{8}$O	($^{16}_{8}$O,α4n)	$^{246}_{98}$Cf	10	105
$^{238}_{92}$U	$^{22}_{10}$Ne	($^{22}_{10}$Ne,α4n)	$^{252}_{100}$Fm	0.2	150
$^{232}_{90}$Th	$^{12}_{6}$C	($^{12}_{6}$C,4n)	$^{240}_{96}$Cm	80	68
$^{242}_{94}$Pu	$^{12}_{6}$C	($^{12}_{6}$C,4n)	$^{250}_{100}$Fm	9	65
$^{246}_{96}$Cm	$^{12}_{6}$C	($^{12}_{6}$C,4n)	^{254}102	2	70

[a] $\sigma_f \approx 40 \times 10^3$ μb; $\sigma_f/\sigma(X,4n) \approx 10^3$.
[b] $\sigma_f \approx 10^5$ μb; $\sigma_f/\sigma(X,4n) \approx 10^5$.
[c] $\sigma_f \approx 10^5$ μb; $\sigma_f/\sigma(X,4n) \approx 2 \times 10^6$.
[d] Values from various authors.

V. Spontaneous Fission from an Isomeric State

The first nuclar disintegration by spontaneous fission (s.f.) from an isomeric state was demonstrated at Dubna in the USSR [52–54]. The nuclide involved was $^{242m}_{92}$Am

[32] *A. Ghiorso, G. B. Rossi, B. G. Harvey*, and *S. G. Thompson*, Physic. Rev. *93*, 257 (1954).

[32a] *A. Ghiorso* and *T. Sikkeland*, quoted in *E. K. Hyde, I. Perlman*, and *G. T. Seaborg*: The Nuclear Properties of the Heavy Elements I. Prentice Hall, Englewood Cliffs, N. J., 1964.

[33] *A. Ghiorso, S. G. Thompson, K. Street*, and *G. T. Seaborg*, Physic. Rev. *81*, 154 (1951).

[34] *J. B. Gerlit, L. J. Guseva, B. F. Miasoedov, N. J. Tarantin, K. V. Filippova*, and *G. N. Flerov*, Sov. Phys. JETP [English Transl.] *6*, 263 (1958).

[35] *V. V. Volkov, L. J. Guseva, A. S. Pasyuk, N. J. Tarantin*, and *K. V. Filippova, ibid. 9*, 536 (1959).

[36] *J. H. Fremlin, K. M. Glover*, and *J. Milsted*, J. inorg. nuclear Chem. *2*, 263 (1956).

[37] *A. Ghiorso* and *T. Sikkeland*, Proceedings 2nd International Conference on the Peaceful Uses of Atomic Energy, Geneva 1958; P/2440.

[38] *I. Brandstetr, V. V. Volkov, V. A. Ermakov, T. S. Zvarova, M. Krzibanek, J. Maly*, and *Su Chun-Guy*, Radiokhimiya *5*, 706 (1964).

[39] *G. T. Seaborg*: Man Made Transuranium Elements. Prentice-Hall Inc., Englewood Cliffs, N. Y., 1963, p. 110.

[40] *A. Ghiorso, T. Sikkeland, J. R. Walton*, and *G. T. Seaborg*, Physic. Rev. Letters *1*, 18 (1958).

[41] *E. D. Donets, V. A. Karnaukhov, G. Kumpf, B. A. Gvozdev*, and *Y. T. Chuburkov*, Sov. Phys. JETP [English Transl.] *16*, 7 (1963).

[42] *V. V. Volkov, L. I. Guseva, B. F. Myasoedov, N. J. Tarantin*, and *K. V. Filippova, ibid. 10*, 859 (1960).

[43] *H. Atterling, W. Forsling, L. W. Holm, L. Melander*, and *B. Aström*, Physic. Rev. *95*, 585 (1954).

[44] *G. N. Flerov, Y. T. Oganesyan, Y. V. Lobanov, V. I. Kusnezov, V. A. Druin, V. P. Perelygin, K. A. Gavrilov, S. P. Tretjakova*, and *V. M. Plotko*, Physics Letters *13*, 73 (1964).

[45] *G. N. Flerov, Y. T. Oganesyan, Y. V. Lobanov, V. I. Kusnezov, V. A. Druin, V. P. Perelygin, K. A. Gavrilov, S. P. Tretjakova*, and *V. M. Plotko*, Joint Institute of Nuclear Research (Dubna, U.d.S.S.R.), Preprint D-1818 (1964).

[46] *G. N. Flerov, S. M. Polikanov, A. S. Karamyan, A. S. Payuk, D. M. Parfanovich, N. J. Tarantin, V. A. Karnaukhov, V. A. Druin, V. V. Volkov, A. M. Semchinova, Y. T. Oganesyan, V. I. Khalizev, G. I. Khlebnikov, B. F. Myasoedov*, and *K. A. Gavrilov*, Sov. Phys. JETP [English. Transl.] *11*, 61 (1960).

[47] *G. N. Flerov, A. S. Karamyan, A. S. Pasyuk, D. M. Karfanovich, S. M. Polikanov, N. I. Tarantin, V. A. Karnaukhov, V. A. Druin, V. V. Volkov, A. M. Semchinova, Y. T. Oganesyun, V. J. Khalizer*, and *G. I. Khlebnikov*, Sov. Phys. Dokl. [English. Transl.] *3*, 546 (1958).

[48] *G. N. Flerov*, Proceedings 2nd International Conference on the Peaceful Uses of Atomic Energy, Geneva 1958; P/2299/Add. 1.

[49] *A. Ghiorso*, Proceedings of the Conference on Reactions between Complex Nuclei, Gatlinburg, Tenn. (U.S.A.), 1958; Report ORNL-2606 (1958).

[50] *A. Ghiorso, T. Sikkeland, A. E. Larsh*, and *R. M. Latimer*, Physic. Rev. Letters *6*, 473 (1961).

[51] *R. Vandenbosch* and *G. T. Seaborg*, Physic. Rev. *110*, 507 (1958).

[52] *S. M. Polikanov, V. A. Druin, V. A. Karnaukhov, V. L. Mikheev, A. A. Pleve, N. N. Skobelev, V. G. Subbotin, G. M. Ter-Akopyan*, and *V. A. Formichev*, Sov. Phys. JETP [English Transl.] *15*, 1016 (1962).

[53] *S. M. Polikanov, Wang T'Ung-Sen, Chr. Keck, V. L. Mikheev, Y. T. Oganesyan, A. A. Pleve*, and *B. V. Fefilov, ibid. 17*, 544 (1963).

[54] *G. N. Flerov, S. M. Polikanov, K. A. Gavrilov, V. L. Mikheev, V. P. Perelygin*, and *A. A. Pleve, ibid. 18*, 964 (1964).

with a half-life of $\tau_{s.f.} = 15 \pm 2$ msec, formed by the bombardment $^{241}_{95}$Am and $^{239-242}_{94}$Pu with α-particles, of $^{243}_{95}$Am with α-particles and deuterons, of $^{240-242}_{94}$Pu with deuterons, of $^{238}_{92}$U with $^{22}_{10}$Ne, $^{16}_{8}$O, $^{11}_{5}$B, and $^{10}_{6}$B, of $^{235}_{92}$U with $^{16}_{8}$O, and of $^{232}_{90}$Th and $^{242}_{94}$Pu with $^{22}_{10}$Ne. The spontaneous fission half-life of $^{242m}_{95}$Am is thus seen to be smaller by at least a factor of 10^{20} than that of $^{242}_{95}$Am, indicating an excitation energy of about 3 MeV.

The nuclear reactions of uranium and thorium with heavy ions, leading to $^{242m}_{85}$Am, are stripping reactions and do not proceed *via* a compound nucleus (cf. Section II). The cross-sections of these reactions depend on the type of projectile [$\sigma(^{238}_{92}U + ^{22}_{10}Ne) \approx \sigma(^{238}_{92}U + ^{16}_{8}O)$] to a smaller extent, and on the type of target [$\sigma(^{238}_{92}U + ^{16}_{8}O)/\sigma(^{235}_{92}U + ^{16}_{8}O) \approx 10$] to a greater extent, than is expected for reactions involving a compound nucleus. For projectile energies of 100 to 125 MeV, the maximum cross-sections are only 2×10^{-2} to 4×10^{-2} μbarn, which corresponds to a rate of formation of 10 to 20 $^{242m}_{92}$Am nuclei per μA per h. The bombardment of $^{243}_{95}$Am with fast neutrons also leads to $^{242m}_{95}$Am (σ_{max} = 0.15 mbarn) [55]:

$^{243}_{95}Am(n, 2n)^{242}_{95}Am$

The bombardment of $^{238}_{92}$U with $^{20}_{10}$Ne and $^{16}_{8}$O, and of $^{239}_{94}$Pu with $^{11}_{5}$B has led to two unidentified nuclei decaying by spontaneous fission from isomeric states, with half-lives of 0.9 msec and 3.5 sec respectively [55–57]. All three metastable nuclei were detected by recording their fission with nuclear plates [58] or lithium phosphate glass detectors.

VI. The Discovery of Elements 102 to 104

Elements of atomic number 102, 103, and 104 were first obtained by nuclear reactions with heavy ions. They have so far been identified only by physical methods, and their chemical isolation or enrichment will be possible only when new separation techniques, *e.g.* very fast ion exchange chromatography, are developed.

1. The Discovery of Element 102

The preparation of isotopes of element 102 was first reported in 1957 by a research group working in Stockholm [59], who bombarded a curium sample with $^{13}_{6}$C ions and isolated an α-active nuclide characterized by E_α = 8.5 MeV and τ = 10 min by the recoil method. It was assumed that an isotope with nuclear charge 102 and mass number 251, or 253, or 255 had been formed [60]. The lack of spontaneous fission indicated that no even-even nucleus, *i.e.* one containing an even number of protons and of neutrons, was formed (see Section D). The identification was apparently confirmed by the fact that the α-activity during ion-exchange investigations occurred where it was expected for element 102. The 8.5 MeV α-activity, however, was observed in only 12 out of a total of 50 bombardments, and with only three out of six targets, and even then only on the first bombardment of each target. These results were not confirmed [*] when the above experiments were repeated in the United States [61, 62] and in the Soviet Union [46–48], despite the use of similar experimental conditions and an about ten times stronger ion beam with considerably smaller energy-spread. Further, an α-energy of only 8.0 MeV would be expected for an isotope of element 102 with a half-life of 10 min from the α-decay scheme [11a, 11b].

On bombarding a target containing 4.5 atom-% $^{246}_{96}$Cm with $^{12}_{6}$C ions, *Ghiorso* et al. [40, 49] succeeded in preparing the isotope ^{254}102 by the reaction

$$^{246}_{96}Cm(^{12}_{6}C, 4n)^{254}102 \xrightarrow[3\ sec]{\alpha} {}^{250}_{100}Fm.$$

The daughter element $^{250}_{100}$Fm, used to identify ^{254}102, was isolated by the α-recoil method described below. $^{250}_{100}$Fm is easily detected by its relatively long half-life (30 min) and emission of 7.40 MeV α-radiation.

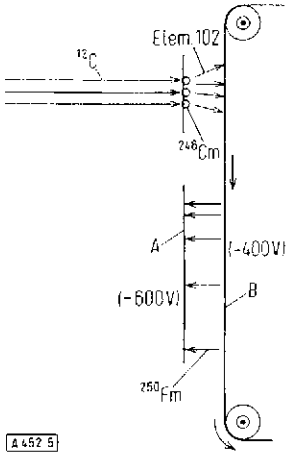

Fig. 5. Explanation of the recoil method (cf. text).

The target used in the above work [61] was a thin nickel foil, on the back of which the curium had been deposited. On irradiation with ^{12}C ions, the atoms of 102 formed are knocked out of the target. Since these are initially highly ionized, they are attracted to the moving metal belt B (Fig. 5) behind the target. About half the recoiling, highly ionized ^{250}Fm atoms formed on α-decay are captured by the more negative collector foil A. In this double recoil separation, relatively pure ^{250}Fm is obtained. The half-life of ^{254}102 can be calculated from the belt speed and the resulting ^{250}Fm activity of the collector.

Flerov et al. [46–48] hombarded $^{241}_{94}$Pu with $^{16}_{8}$O ions, whereupon the reaction

$$^{241}_{94}Pu(^{16}_{8}O, 4n)^{253}102,$$

took place, resulting in the α-active isotope ^{253}102 characterized by an α-energy of 8.9 MeV and a half-life of between 2 and 40 sec. The isotope ^{253}102 was separated from the target by the recoil of the nucleus on

[55] *A. F. Linev, B. N. Markov, A. A. Pleve,* and *S. M. Polikanov,* Joint Institute of Nuclear Research (Dubna, U.d.S.S.R.), Preprint D-1693 (1964).

[56] *V. A. Druin, N. K. Skobelev, B. V. Fefilov, V. I. Kusnezov, Y. V. Lobanov,* and *Y. T. Oganesyan,* Joint Institute of Nuclear Research (Dubna, U.d.S.S.R.), Preprint R-1651 (1964).

[57] *J. V. Lobanov, V. I. Kusnetzov, Y. T. Oganesyan, V. P. Perelygin, S. M. Polikanov,* and *G. N. Flerov,* Joint Institute of Nuclear Research (Dubna, U.d.S.S.R.), Preprint R-1801 (1964).

[58] *V. P. Perelygin, S. M. Almazova, B. A. Gvozdev,* and *Y. T. Chuburkov,* Sov. Phys. JETP [English Transl.] *15*, 1022 (1962).

[59] *L. W. Holm* and *B. Aström,* Physic. Rev. *107*, 1460 (1957).

[60] *P. R. Fields, A. M. Friedman, J. Milsted, H. Atterling, W. Forsling, L. W. Holm,* and *B. Aström,* Ark. Fysik. *15*, 225 (1959).

[*] This is why the suggested name "nobelium" has not yet been ratified by the Commission of Atomic Weights of IUPAC.

[61] *A. Ghiorso, T. Sikkeland, J. R. Walton,* and *G. T. Seaborg,* Physic. Rev. Letters *1*, 17 (1958).

[62] *A. Ghiorso,* University of California (Berkeley), Radiation Laboratory, Report UCRL-8714 (1959).

formation, and identified on the basis of the α-decay scheme by determining the energy of the emitted α-particles on nuclear plates. These results have been confirmed (E_α = 8.8 ± 0.1 MeV, half-life between 10 and 20 sec) [63].

2. The Discovery of Element 103 (Lawrencium)

In spring 1961, *Ghiorso* et al. [50] bombarded 3 μg of californium with accelerated $^{10,11}B$ ions, and observed a resulting α-activity of E_α = 8.6 MeV and $\tau \approx 8 \pm 2$ sec. This activity was attributed to an isotope of element 103 having mass number 257. The possibility of the observed α-activity being due to a 101 or 102 isotope was eliminated by repeating the experiment with a different projectile ($^{12}_{6}C$) and a different target ($^{243}_{95}Am$ instead of $^{249-252}_{98}Cf$).

3. The Discovery of Element 104

In the middle of 1964, *Flerov*'s group carried out the reaction $^{242}_{94}Pu$ ($^{22}_{10}Ne$, 4n) (the target contained 97 atom-% of $^{242}_{94}Pu$), and obtained the isotope $^{260}104$, which undergoes spontaneous fission with a half-life of 0.3 ± 0.1 sec [44,45]. Fig. 6 shows the cross-sections of the spontaneously fissile nuclei formed by bombarding $^{242}_{94}Pu$ with high-energy $^{22}_{10}Ne$ ions. The $^{260}104$ was isolated by the recoil method and detected by glass counters.

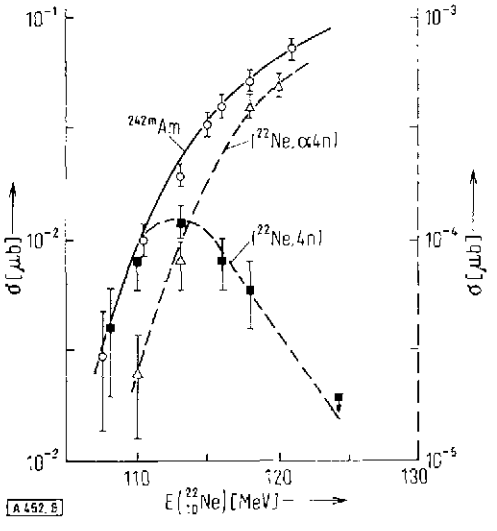

Fig. 6. Cross-sections for the synthesis of spontaneously fissile nuclei by bombarding $^{242}_{94}Pu$ with $^{22}_{10}Ne$ ions.

Element 104 is the first transactinide, and may be regarded as the homologue of hafnium (eka-Hf). This fact should greatly facilitate its chemical separation from the transactinides.

VII. Possible Means of Preparing Neutron-Rich Transcurium Nuclei and Elements with Z > 104

1. Nuclear Reactions with Heavy Ions

Heavy-ion bombardment appears to be the most promising way of preparing further elements. Transuranium elements up to and including einsteinium, which can all be prepared in weighable amounts, may be used as target nuclei. The preparation of the targets might however be rendered very difficult by their high specific activity (*e.g.* 1.06 curie/mg for $^{254}_{99}Es$) and by the high purity required (less than 0.1 ppm of other heavy elements).

The following reactions are suitable for the preparation of element 105 (eka-tantalum): $^{241,243}Am + {}^{22}_{10}Ne$; $^{249}Bk + {}^{16}_{8}O$; $^{249-252}_{98}Cf + {}^{14}_{7}N$; and $^{244}_{99}Es + {}^{12}_{6}C$.

The last reaction will have the highest cross-section. Since however transcurium elements will not be available in sufficient amounts in the next few years, element 105 will probably be first prepared by the reaction $^{241-243}_{95}Am + {}^{22}_{10}Ne$. On the other hand, identification of the sporadically formed 105 nuclei will be very difficult owing to the extremely small cross-section (about 10^{-2} μbarn) of the Am(Ne,xn) reaction. Nevertheless, recent advances in detection techniques make it appear feasible to detect nuclear reaction products characterized by 3 spontaneous fissions per hour, or by an emission of 50 α-particles per hour [18].

If element 105 is assumed to be formed by the reaction

$$^{243}_{95}Am(^{22}_{10}Ne,4n)^{261}105,$$

the product will have a high neutron deficiency, and therefore probably a much shorter half-life than the isotope with mass number 265, which would supposedly be the most stable. It will not however be possible to prepare the latter by any of the reactions discussed, since heavy-ion bombardment can lead only to neutron-deficient isotopes, and accordingly not to the most stable ones. Neutron-rich projectiles such as $^{22}_{10}Ne$, $^{18}_{8}O$, and $^{13}_{6}C$ are often used instead of $^{20}_{10}Ne$, $^{16}_{8}O$, and $^{12}_{6}C$ in order to reduce somewhat the neutron deficiency of the end-products of these reactions. In this case reactions of the types (X,4n), (X,5n), and (X,6n) often have comparable cross-sections. Neutron-rich target isotopes are usually used for the same reason, *e.g.* $^{242}_{94}Pu$ instead of $^{239}_{94}Pu$.

It seems likely that isotopes of elements up to Z = 109 (eka-iridium) will be prepared by similar reactions in the not too distant future. The possible (X,xn) reactions for the synthesis of these elements are as follows (in order of decreasing cross-section):

$$Z = 106 : (^{254}_{99}Es + {}^{14}_{7}N) > (^{252}_{98}Cf + {}^{16}_{8}O) > (^{244-248}_{96}Cm + {}^{22}_{10}Ne)$$

$$Z = 107 : (^{254}_{99}Es + {}^{16}_{8}O) > (^{249}_{97}Bk + {}^{22}_{10}Ne)$$

$$Z = 108 : (^{252}_{98}Cf + {}^{22}_{10}Ne)$$

$$Z = 109 : (^{254}_{99}Es + {}^{22}_{10}Ne)$$

When it becomes possible to accumulate $^{257}_{100}Fm$ in microgram quantities at least – which is not yet the case – the synthesis of element 110 by the reaction $^{257}_{100}Fm + {}^{22}_{10}Ne$ could also be contemplated.

Still unknown neutron-rich fermium and californium isotopes might be prepared by a type of stripping reaction (cf. Section C.II):

$$^{256}_{100}Fm(^{18}_{8}O, {}^{16}_{8}O)^{258}_{100}Fm$$

$$^{254}_{98}Cf(^{22}_{10}Ne, {}^{20}_{10}Ne)^{256}_{98}Cf.$$

63] *A. Ghiorso*, quoted in [40].

In principle it should also be possible to synthesize these nuclei by a ($^3_1$H,p) reaction.

These two isotopes ($^{258}_{100}$Fm and $^{256}_{98}$Cf) cannot be synthesized by multiple neutron capture in nuclear reactors, since the neutron fluxes are too low for this purpose. This is unfortunate, since knowledge of the spontaneous fission half-lives of these nuclei could make an important contribution to our knowledge of the systematics of spontaneous fission. Furthermore, the corresponding values calculated by various authors show large discrepancies [63a].

The prospects of carrying out such processes are promising, since the cross-sections increase with the nuclear charge of the target in the family of reactions:

$$A + {}^{20}_{10}Ne \rightarrow B + {}^{17}_{7}N,$$

in which three protons are captured [9] [*e.g.* in the case of an effective projectile energy of 100 MeV, $\sigma(^{27}_{13}Al)$ = 0.1 mbarn, but $\sigma(^{181}_{73}Ta)$ = 1 mbarn].

2. Nuclear Reactions with Superheavy Ions

In addition to nuclear syntheses using C,N,O, and Ne as projectiles ($^{19}_{9}$F has not been tried), those using even heavier, *i.e.* superheavy ions (*e.g.* $^{24}_{12}$Mg and $^{48}_{20}$Ca) should also be discussed. These ions need very high energies to overcome the potential barrier, so that the resulting compound nuclei will be highly excited. For this reason, the latter will decay almost exclusively by fission (*i.e.* $\sigma_f/\sigma_{(xn)} > 10^{10}$). There is a well-founded hope, however, that cross-sections of at least 10^{-4} μbarn will be found for reactions in which the target captures only part of the projectile, so that detectable numbers of the required nuclei will be formed (detection limit = 10^{-5} μbarn). By capturing only part of the projectile, the compound nucleus will be less excited than after the absorption of the whole ion. Possible reactions of this type are as follows:

$$^{252}_{98}Cf + {}^{36}_{16}S \rightarrow {}^{264-262}104 + (4-6)n + {}^{20}_{10}Ne$$

$$^{752}_{98}Cf + {}^{48}_{20}Ca \rightarrow {}^{276-274}108 + (4-6)n + {}^{20}_{10}Ne.$$

These two reactions are formally equivalent to bombarding $^{252}_{98}$Cf with neutron-rich $^{16}_{6}$C and $^{28}_{10}$Ne ions, respectively. The advantage of such nuclear reactions lies in the possibility of obtaining what are probably the longest-lived isotopes of the elements under consideration. The hope that these reactions have a cross-section of at least 10^{-4} μbarn is based on the assumption that reactions not proceeding *via* compound nuclei, such as

$^{244}_{96}$Cm ($^{13}_{6}$C, $^{8}_{4}$Be3n)$^{246}_{98}$Cf and

$^{244}_{96}$Cm($^{16}_{8}$O, $^{12}_{7}$C3n)$^{245}_{98}$Cf,

have cross-sections which are not smaller (at least not much smaller) than those of the comparable ($^{13}_{6}$C,xn) and (^{16}O,xn) reactions, which do proceed *via* compound nuclei [37].

In addition to the above reactions consisting of partial fusion and subsequent neutron emission, other reactions might also be possible, in which a certain type of interaction with the surface of the nuclei would enable the capture of a larger part of the projectile, without the nuclei becoming highly excited. Such a reaction would be, for example:

$$^{239}_{92}U + {}^{40}_{18}Ar \rightarrow {}^{256}_{100}Fm(^{258}_{100}Fm, {}^{260}_{100}Fm) + {}^{22}_{10}Ne(^{20}_{10}Ne, {}^{18}_{10}Ne).$$

There are several indications that such nuclear reactions are possible, and that they would proceed with measurable cross-sections [64].

3. Capture of Heavy Projectiles without Subsequent Emission of Nucleons

A further possibility of preparing isotopes of the heaviest elements is based on the compound nucleus releasing all its excitation energy by γ-emission (radiative capture) [64], *e.g.*:

$$^{238}_{92}U(^{18}_{8}O,\gamma)^{256}_{100}Fm$$

Cross-sections of about 1 μbarn have been observed [65,66] for the radiative capture of heavy projectiles by light target nuclei (*e.g.* on bombarding $^{27}_{13}$Al or $^{31}_{15}$P with $^{16}_{8}$O ions). Assuming that the radiative capture cross-sections of heavy target nuclei are only five orders of magnitude smaller than the above value, a heavy-ion current of 100 μA should lead to about ten captures per hour. Should spontaneously fissile nuclides be formed, they could be detected even at such a low rate of formation.

4. Secondary Reactions of the Emitted Particles

The possibility of using particles emitted in nuclear reactions as projectiles for further reactions has also been considered [64]. When, for example, $^{232}_{90}$Th nuclei are bombarded with $^{22}_{10}$Ne ions, isotopes of Ra, Ac, and Th with mass numbers ranging from 224 to 227 are known to be formed in a reaction resembling the pick-up process (cf. Section C.II), some of the nucleons released by the target nucleus becoming attached to the projectile. Thus the irradiation of thorium with neon ions results in a secondary beam of Ne, Na, and Mg ions. When the effective cross-section of the pick-up reaction is 1 mbarn, the use of a Ne ion current of 100 μA and a $^{232}_{92}$Th target (10 mg/cm²) leads to about 10^6 secondary ions/sec. Provided their cross-sections are at least 0.1 mbarn, the reactions of these secondary particles are detectable (a few disintegrations per hour). In these reactions, thorium both converts the ion beam and acts as a target for the secondary reaction.

$$^{322}_{90}Th(^{22}_{10}Ne, {}^{28}_{10}Ne)^{226}_{92}Th \quad \text{(primary reaction)}$$

and

$$^{232}_{90}Th(^{28}_{10}Ne, 4n)^{256}_{100}Fm \quad \text{(secondary reaction).}$$

The method under consideration appears promising for the synthesis of neutron-rich isotopes of the heaviest elements, since a cross-section of 0.2 to 0.3 μbarn has been observed

[63a] *N. Feather*, Proc. Roy. Soc. Edinburgh. Sect. A *66*, 20 (1961/62).

[64] *G. N. Flerov, E. D. Donets*, and *V. D. Aruin*, Atomn. Energ. *14*, 18 (1963).

in the formation of astatine (Z = 85) isotopes by the bombardment of lead (Z = 82) with protons, deuterons, and α-particles [67]. This again is a two-stage process: in the first stage the light projectiles generate in a direct process a secondary beam of lithium ions; in the second stage these react with the lead target to form astatine isotopes *via* a compound nucleus.

D. The Stability of Heavy Nuclei

Spontaneous fission and α-decay are the predominant types of disintegration of the heaviest nuclei. As can be seen from Fig. 7, the half-life of the α-activity is about

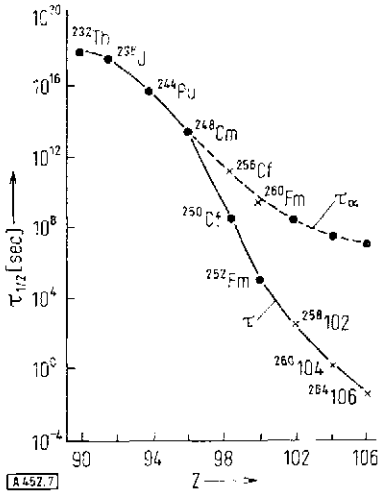

Fig. 7. Half-lives of the longest-lived even-even nuclei of the heaviest elements (×: calculated on the basis of the spontaneous fission scheme or the α-decay scheme; •: determined experimentally). Solid line denotes the overall half-life $\tau_{1/2}$, broken line stands for the α-decay half-life τ_α.

one year for the longest-lived isotopes of elements up to about Z = 106, whereas the half-life of the nuclear disintegration [*] is appreciably shorter. It follows from the liquid drop model of the nucleus that the half-life $\tau_{s.f.}$ of the spontaneous fission of the heaviest nuclei decreases in proportion to increasing Z^2/A [68–70]. However, Fig. 8 shows that this proportionality is merely a rough approximation. The following three deviations occur in the above curve:

1. The half-lives of spontaneous fission do not decrease linearly with increasing Z^2/A even for the longest-lived even-even isotopes of the heaviest elements. Clear deviations occur above $Z^2/A = 37$. The observed $\tau_{s.f.}$ values invariably exceed the calculated ones.

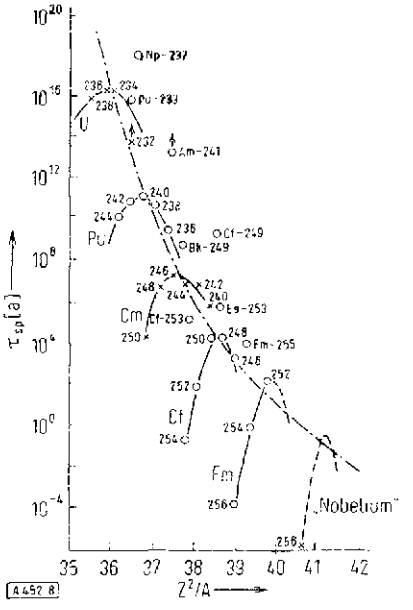

Fig. 8. Spontaneous fission half-lives $\tau_{s.f.}$ of the isotopes of the heavy elements, as a function of Z^2/A (—·—·: calculated curve).

2. As first found by *Huizenga* [71], $\tau_{s.f.}$ values of the isotopes of the same element lie on a parabola.

3. For comparable values of Z^2/A, the values of $\tau_{s.f.}$ are higher by a factor of 10^3 to 10^6 for odd nuclei than for even-even nuclei.

The liquid drop model cannot account for these deviations, and attempts to improve the calculation of $\tau_{s.f.}$ by the introduction of correction terms [72–75] have so far been unsuccessful in the case of most nuclei. In order to predict the spontaneous fission half-lives of unknown nuclei, one still has to resort to extrapolation from experimental values.

Table 3 lists extrapolated decay data of some nuclei with $102 \leqslant Z \leqslant 104$ [76]. It appears, in general, that in the case of the isotopes of elements with Z > 10 the lifetime of the nucleus is determined by α-decay when it is deficient in neutrons, and by spontaneous fission when it has a neutron excess. The half-lives are generally very short, and probably lie somewhere between milli- and microseconds for elements with Z = 106 to 110. However, half-lives of 10^{-2} to 10^{-3} sec can already be determined by recoil methods and nuclear plates. It seems possible to improve detection methods to such an extent as to be able to identify nuclides having half-lives shorter by a further two or three orders of magnitude.

There is a slight hope, derived from the following analogies, that the most stable isotopes of elements with Z = 110 to 112 (from eka-gold to eka-thallium) might have somewhat longer half-lives than expected on the basis of the above discussion (see Fig. 9). Lead and bismuth, which have stable isotopes, are followed by

[*] The partial half-lives τ_x (x = α, β^-, β^+, s.f., ...) of radionuclides with branching decay schemes are inversely proportional to the probabilities W_x of the decay type x. They are related to the (measurable) overall half-life τ by $1/\tau = \Sigma\, 1/\tau_x$. For example, in the decay of Cf (τ = 2.55 years), τ_α = 2.66 years and $\tau_{s.f.}$ = 66 years, so that W_α = 95.9%, $W_{s.f.}$ = 4.1%.

[65] *R. Coleman, D. Herbert,* and *J. Perkin,* Proc. physic. Soc. (London) *77,* 526 (1959).

[66] *D. Fischer* and *A. Zucker,* Physic. Rev. *113,* 542 (1959).

[67] *Wang Yung-Yü, V. Kusnetzov, M. J. Kusnetsova, V. N. Mekhedov,* and *V. Khalkin,* Sov. Phys. JETP [English Transl.] *12,* 370 (1961).

[68] *N. Bohr* and *J. Wheeler,* Physic. Rev. *56,* 426 (1939).

[69] *G. T. Seaborg,* Physic. Rev. *85,* 157 (1952).

[70] *W. Whitehouse* and *W. Galbraith,* Nature (London) *169,* 494 (1952).

[71] *J. R. Huizenga,* Physic. Rev. *94,* 158 (1954).

[72] *S. Johansson,* Nuclear Physics *12,* 449 (1959).

[73] *W. Swiatecki,* Physic. Rev. *100,* 937 (1955).

[74] *D. W. Dorn,* Physic. Rev. *121,* 1740 (1961).

[75] *D. W. Dorn,* Physic. Rev. *126,* 639 (1962).

[76] *M. Foreman* and *G. T. Seaborg,* J. inorg. nuclear Chem. *7,* 305 (1958).

Table 3. Data concerning the decay of some isotopes of elements 102 to 104. τ_α, $\tau_{s.f.}$, and τ_e denote the half-lives for α-decay, spontaneous fission, and electron capture, respectively; $\tau_{1/2}$ is the overall half-life, and E_α is the energy of the emitted α-radiation. The partial half-life that determines the life-time of the nucleus is underlined.

	Estimated					Found
Nucleus	τ_α [sec]	E_α [MeV]	$\tau_{s.f.}$	τ_e	$\tau_{1/2}$ [sec]	τ[sec] (E[MeV])
$^{252}102$	1	8.76	10 d	20 min	1	
$^{253}102$	5	8.56	20 d	10 min	5	τ_α = 2–40 (E_α = 8.3)
$^{254}102$	20	8.36	50 d	2 h	20	τ_α = 3 (E_α = 8.3)
$^{255}102$	20	8.36	2 d	50 min	20	
$^{256}102$	20	8.36	5 h	2 d	20	τ_α = 8; $\tau_{s.f.}$ = 1500
$^{257}102$	60	8.20	1 min	5 h	30	
$^{258}102$	300	8.04	20 sec	stable	20	
^{255}Lw	1	8.90	2 d	10 min	1	
^{256}Lw	2	8.86	5 h	5 min	2	
^{257}Lw	2	8.82	1 min	20 min	2	τ_α = 8 (E_α = 8.6)
^{258}Lw	5	8.66	20 sec	20 sec	4	
^{259}Lw	20	8.50	2 sec	2 h	18	
^{260}Lw	60	8.34	0.1 sec	20 min	0.09	
$^{256}104$	00.5	9.48	5 h	20 min	3	
$^{257}104$	0.1	9.40	1 min	10 min	6	
$^{258}104$	0.2	9.32	20 sec	50 min	0.2	
$^{259}104$	0.2	9.17	2 sec	20 min	0.4	
$^{260}104$	1	9.00	0.1 sec	5 h	0.09	$\tau_{s.f.}$ = 0.3
$^{261}104$	5	8.84	0.005 sec	1 h	0.005	

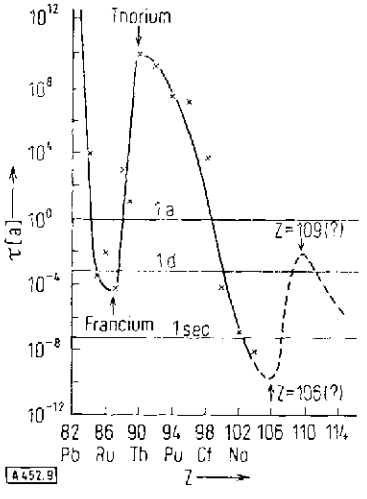

Fig. 9. Stability of the longest-lived transbismuth isotopes, irrespective of the type of decay.

astatine, radon, and francium, with only very short-lived isotopes. The transition period comprising radium and actinium is followed by elements (from thorium to californium) each of which has at least one isotope with a half-life of about a thousand years. The transcalifornium elements again show the same sudden decrease in stability exhibited by the transbismuth elements. Assuming that such an instability-stability sequence occurs again, longer half-lives can once more be expected for elements with Z around 109 to 112, particularly on reaching the next magic neutron number (184). Spontaneous fission has not, however, been taken into account.

The possibility of synthesizing new elements will be exhausted when the rate of decay of the nuclei becomes greater than their rate of formation. It has been suggested [77] that the first "element" characterized by this state of affairs should carry the name "cosmium".

[77] *M. Haissinsky* in *P. Pascal*: Nouveau traité de chimie minérale. Masson et Cie., Paris 1962. Vol. XV,3, p. 1004.

E. The Existence of Superheavy Nuclei

Werner and *Wheeler* [78,79] predicted the possible existence of atomic nuclei up to Z = 147 and A = 500, believed to have half-lives of at least 10^{-4} sec. These authors based their prediction on pre-1957 data concerning the stability of the heaviest elements, and on the binding energies of the individual nucleons of these elements, as derived from *Green*'s semiempirical mass equation. All the assumptions relating to the stability of the superheavy nuclei in the above considerations were derived from extrapolation over a very wide region of the properties of known nuclei. Such extrapolations involve a high degree of uncertainty, but it emerges from these calculations that the capture of peripheral electrons will not determine the stability of the heavy nuclei even with Z > 137. It can be assumed that nuclei with Z > 137 can exist only in stars with neutron fluxes exceeding 10^{30} neutrons per cm² per sec.

F. Neutron Nuclei

Some authors [80–83] do not exclude the possibility of the existence of neutron nuclei, *i.e.* nuclei composed almost exclusively of neutrons, and possessing a lower density than ordinary atomic nuclei. Owing to surface tension, these "neutron drops" can only occur above a certain minimum size. If this assumption is correct, then it is probable that a large range of superheavy neutron nuclei exists, in a region which is either contiguous to that of the known nuclei (Fig. 10b), or not (Fig. 10a).

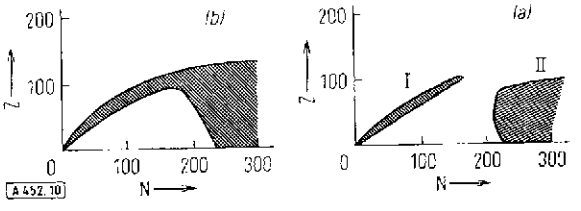

Fig. 10. Possible positions of neutron nuclei in the nuclide field. I: ordinary nuclei; II: neutron nuclei.

G. Outlook

With further improvement in experimental and detection techniques, the next few years may witness the discovery of isotopes of elements up to atomic number 109 (eka-iridium). Since the cross-sections for the reac-

[78] *F. G. Werner* and *J. A. Wheeler*, Physic. Rev. *109*, 126 (1958).

[79] *J. A. Wheeler* in: Niels Bohr and the Development of Physics. Pergamon Press, London *1955*, Ch. 9.

[80] *A. I. Baz, V. I. Goldanskii*, and *Y. B. Zeldovich*, Sov. Phys. Uspekhi [English Transl.] *3*, 729 (1961).

[81] *Y. B. Zeldovich*, Sov. Phys. JETP [English Transl.] *11*, 812 (1960).

[82] *E. E. Salpeter*, Bull. Amer. physic. Soc. *4*, 256 (1959).

[83] *K. A. Brueckner, J. L. Gammel*, and *J. T. Kubis*, Physic. Rev. *118*, 1095 (1960).

tions in which these nuclei may be formed are very small, yields amounting to only a few atoms can be expected, and the new elements will probably be identified only by physical methods. According to *Ghiorso* [62], it might be possible to determine the mass numbers either by the mass-spectrometric separation of the primary recoil atoms, or by measuring their time of flight. To determine the mass numbers of the heaviest nuclei, we must at present generally resort to the use of analogies. Owing to the short half-lives, the chemical isolation of the heaviest elements will be extremely difficult or even impossible.

Data concerning the syntheses and the stability of the heaviest nuclei are mostly based on extrapolations, and therefore the conclusions derived from them must be regarded as at least partly hypothetical. This, however, leaves a reasonable hope of extending the number of elements known today.

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The Alkylating Properties of Alkyl Thiophosphates

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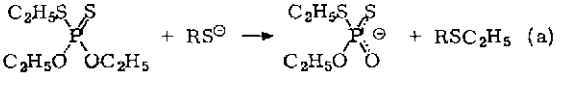
Thiophosphate and phosphate esters have been synthesized in great variety since about 1945, and are being produced in increasing quantities, mainly for plant protection. An important property of alkyl phosphates and thiophosphates is their alkylating power, which is comparable with that of dialkyl sulfates and alkyl p-toluenesulfonates. The chemistry of thiophosphates is largely determined by their alkylating properties, since the sulfur, both in the alkyl thiophosphate and in the thiophosphate anion formed on dealkylation, can act as a point of attack for self-alkylation.

I. Introduction

The importance attained over the past two decades by organic thiophosphates in pest control [1] has also promoted sustained interest in the chemistry of this class of compounds. After the discovery of thiophosphates by *Cloez* [2] and *Carius* [3] about the middle of the last century and the fundamental studies carried out around 1910 by *Pistschimuka* [4], very little work was done on the chemical behavior of these compounds. An important property of tertiary thiophosphates with at least one alkoxy group attached to the phosphorus atom is their alkylating power. This had already been recognized by *Carius*, who made use of it in the synthesis of unsymmetrical sulfides in accordance with Eq. (a) [3]. *Kekulé*, who was a friend of *Carius*, and who had himself almost discovered the dithiophosphates [5], included this reaction in his well-known textbook [6]. The knowledge of the alkylating properties of thiophosphates, however, then fell into oblivion for a century.



$R = CH_3, C_5H_{11}$

In 1954, it was found in *Todd*'s laboratory that the method of "anionic dealkylation" developed on trialkyl phosphates could also be used with thiophosphates [7]. Shortly afterwards, *Hilgetag* and co-workers recognized the decisive participation of alkylation reactions in the thermal rearrangements of thionophosphates [8,9], and demonstrated the alkylating properties of thionophosphates and thiolophosphates [10–14]. *Melnikov* began similar investigations [15]. Several groups began studying the isomerism of various thionophosphates in the

[1] Cf. the reviews: *R. D. O'Brien*: Toxic Phosphorus Esters, Academic Press, New York-London 1960; *D. F. Heath*: Organophosphorus Poisons, Anticholinesterases and Related Compounds. Pergamon Press, London-New York 1961; *G. Schrader*: Die Entwicklung neuer insektizider Phosphorsäureester. 3rd. edit., Verlag Chemie, Weinheim/Bergstr., 1963.

[2] *Cloez*, C. R. hebd. Séances Acad. Sci. *24*, 388 (1847).

[3] *L. Carius*, Ann. Chem. Pharm. *112*, 190 (1859).

[4] *P. Pistschimuka*, Ber. dtsch. chem. Ges. *41*, 3854 (1908); J. prakt. Chem. [2] *84*, 746 (1911); Zh. russ. fiz.-khim. Obshch. *44*, 1406 (1912).

[5] *A. Kekulé*, Ann. Chem. Pharm. *90*, 309 (1854).

[6] *A. Kekulé*: Lehrbuch der Organischen Chemie. F. Enke, Erlangen 1861, Vol. 1, p. 423.

[7] *J. Lecocq* and *A. R. Todd*, J. chem. Soc. (London) *1954*, 2381.

[8] *G. Hilgetag*, *G. Schramm*, and *H. Teichmann*, Angew. Chem. *69*, 205 (1957); J. prakt. Chem. [4] *8*, 73 (1959).

[9] *G. Hilgetag* and *G. Schramm*, Mitteilungsbl. chem. Ges. DDR, Sonderh. Katalyse, *1959*, 205.

[10] *G. Hilgetag* and *H. Teichmann*, J. prakt. Chem. [4] *8*, 90 (1959).

[11] *G. Hilgetag* and *H. Teichmann*, J. prakt. Chem. [4] *8*, 97 (1959).

[12] *G. Hilgetag* and *H. Teichmann*, J. prakt. Chem. [4] *8*, 104 (1959).

[13] *G. Hilgetag*, *G. Lehmann*, *A. Martini*, *G. Schramm*, and *H. Teichmann*, J. prakt. Chem. [4] *8*, 207 (1959).

[14] Cf. the summary: *H. Teichmann* and *G. Lehmann*, S.-B. dtsch. Akad. Wiss. Berlin, Kl. Chem., Geol. Biol. *1962*, No. 5.

[15] *N. N. Melnikow* et al., Zh. obshch. Khim. *30*, 197 (1960).

middle 1950's [8,9,16–22]. We now understand the tendency of thionophosphates to isomerize as a consequence of their alkylating power, and we know that the ability to lose an alkyl group determines the chemical behavior of the thiophosphates to a much greater extent than that of the corresponding phosphates.

II. Alkyl Phosphates and Thiophosphates as Alkylating Agents

1. General

Sulfur-free trialkyl phosphates have already found many uses as alkylating agents, *e.g.* for the etherification of hydroxyl groups attached to aromatic and heterocyclic rings [23,24], as well as in alcohols [25,26], for the *N*-alkylation of primary aromatic amines [27–32], and for the preparation of isothiuronium salts [33,34], alkyl halides [35], and esters of acetic [36,37] and isocyanic acid [38]. Dialkyl chlorophosphates have also been used to alkylate amines [39,40] and to prepare isothiuronium salts for the synthesis of mercaptans [34].

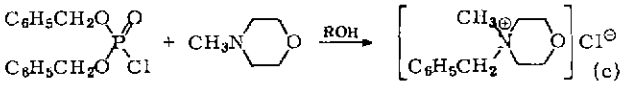
The alkylating properties of thiophosphates are also of general interest, as is shown in Table 1 for the selective monoalkylation of primary amines [cf. Eq. (b)] [41].

Table 1. Alkylation of primary amines with $(RO)_2PO(SC_2H_5)$ according to Eq. (b).

R	R′	Solvent	Time [h]	Temp. [°C]	RR′NH Yield [%]
C_2H_5	C_2H_5	$C_2H_5NH_2$	24	115	42
C_2H_5	c-C_6H_{11}	–	1.5	140	79.7
C_2H_5	C_6H_5	–	5	150	84.3
C_4H_9	C_2H_5	$C_2H_5NH_2$	24	100	45
C_4H_9	c-C_6H_{11}	–	1	150	80.8
C_4H_9	C_6H_5	–	3.5	160	51

$$(RO)_2PO(SC_2H_5) + 2\ R'NH_2 \rightarrow RR'NH + [R'NH_3]^{\oplus}[(RO)(C_2H_5S)PO_2]^{\ominus} \quad (b)$$

The dealkylation of phosphates and thiophosphates, however, is of the greatest importance in phosphate chemistry itself, for the preparation of monobasic dialkyl phosphates and thiophosphates by dealkylation of the triester. Starting from the observation that, during the phosphorylation of alcohols with dialkyl chlorophosphates, tertiary amines, which should bind the hydrochloric acid formed, are quaternized in a competing reaction [Eq. (c)] [42–44], *Todd*'s research group

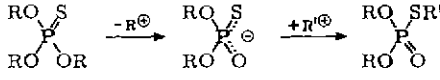


(c)

$$+\ {}^1/_n\,[C_6H_5CH_2OPO_2]_n$$

developed the technique of "monodealkylation", originally using trialkyl phosphates and tetraalkyl pyrophosphates, as an aid in nucleotide chemistry [44–52].

This monodealkylation has since found general use, particularly since mixed triesters can be synthesized by the introduction of a new alkyl group. A particularly important reaction is the stepwise dealkylation and alkylation of thiophosphates, since the alkylation of an ambident thiophosphate anion such as *(1)* takes



(1a) *(1)* *(2)*

[16] *W. Feldheim*, Diploma Thesis, Universität Jena 1954.

[17] *T. R. Fukuto* and *R. L. Metcalf*, J. Amer. chem. Soc. *76*, 5103 (1954).

[18] *A. Henglein* and *G. Schrader*, Z. Naturforsch. *10b*, 12 (1955).

[19] *V. Tichy*, Chem. Zvesti *9*, 3 (1955); Chem. Zbl. *1959*, 7747.

[20] *J. B. McPherson* and *G. A. Johnson*, J. agric. Food Chem. *4*, 42 (1956).

[21] *T. R. Fukuto* and *E. M. Stafford*, J. Amer. chem. Soc. *79*, 6083 (1957).

[22] *I.-E. Tammelin*, Acta chem. scand. *11*, 1738 (1957).

[23] *C. R. Noller* and *G. R. Dutton*, J. Amer. chem. Soc. *55*, 424 (1933).

[24] *G. Zemplen* et al., Magyar Kem. Folyóirat *58*, 161 (1952); Chem. Zbl. *1954*, 11410.

[25] *A. D. F. Toy*, J. Amer. chem. Soc. *66*, 499 (1944).

[26] *W. H. C. Rueggeberg* and *J. Chernack*, J. Amer. chem. Soc. *70*, 1802 (1948).

[27] *J. H. Billman*, *A. Radike*, and *B. W. Mundy*, J. Amer. chem. Soc. *64*, 2977 (1942).

[28] *D. G. Thomas*, *J. H. Billman*, and *C. E. Davis*, J. Amer. chem. Soc. *68*, 895 (1946).

[29] *A. Barker* and *C. C. Barker*, J. chem. Soc. (London) *1953*, 2034.

[30] *T. L. Fletcher*, *M. E. Taylor*, and *A. W. Dahl*, J. org. Chemistry *20*, 1021 (1955).

[31] *Hsi-lung Pan* and *T. L. Fletcher*, J. org. Chemistry *27*, 3639 (1962).

[32] *R. Huisgen* and *L. Zirngibl*, Chem. Ber. *91*, 2375 (1958).

[33] *J. B. Parker* and *T. D. Smith*, J. chem. Soc. (London) *1961*, 442.

[34] *H. Teichmann* and *G. Hilgetag*, J. prakt. Chem. [4] *16*, 45 (1962).

[35] German Published Patent Application 1144250 (Jan. 14th, 1961); inventor: *E. Ruf*, Th. Goldschmidt A.-G.; Chem. Zbl. *1964*, 13-2150.

[36] *G. A. Ropp*, J. Amer. chem. Soc. *72*, 2299 (1950).

[37] *A. Rieker*, *K. Scheffler*, and *E. Müller*, Liebigs Ann. Chem. *670*, 23 (1963).

[38] *Th. I. Bieber*, J. Amer. chem. Soc. *74*, 4700 (1952).

[39] *B. P. Lugowkin* and *B. A. Arbusow*, Zh. obshch. Khim. *22*, 2041 (1952).

[40] *W. Gerrard* and *G. J. Jeacocke*, Chem. and Ind. *1954*, 1538.

[41] *G. Hilgetag*, *M. Krüger*, and *H. Teichmann*, unpublished work.

[42] *A. R. Todd*, Angew. Chem. *60 A*, 69 (1948).

[43] *F. R. Atherton*, *H. T. Howard*, and *A. R. Todd*, J. chem. Soc. (London) *1948*, 1106.

[44] *J. Baddiley*, *V. M. Clark*, *J. J. Michalski*, and *A. R. Todd*, J. chem. Soc. (London) *1949*, 815.

[45] *V. M. Clark* and *A. R. Todd*, J. chem. Soc. (London) *1950*, 2023.

[46] *V. M. Clark* and *A. R. Todd*, J. chem. Soc. (London) *1950*, 2030.

[47] *J. Baddiley*, *A. M. Michelson*, and *A. R. Todd*, J. chem. Soc. (London) *1949*, 582.

[48] *R. Anand*, *V. M. Clark*, *R. H. Hall*, and *A. R. Todd*, J. chem. Soc. (London) *1952*, 3665.

[49] Brit. Pat. 675779 (Dec. 8th, 1949), inventors: *A. L. Morrison* and *F. R. Atherton*, Roche Products Ltd.; Chem. Zbl. *1956*, 1973.

[50] *S. M. H. Christie*, *G. W. Kenner*, and *A. R. Todd*, J. chem. Soc. (London) *1954*, 46.

[51] *G. W. Kenner*, *A. R. Todd*, *R. F. Webb*, and *F. J. Weymouth*, J. chem. Soc. (London) *1954*, 2288.

[52] *V. M. Clark*, *G. W. Kirby*, and *A. R. Todd*, J. chem. Soc. (London) *1957*, 1497.

place almost exclusively on the sulfur atom [10, 53–55] unless the conditions used are specially chosen to favor an S_N1 mechanism [55a, b]. This therefore provides an important method of preparing thiol esters of phosphoric acid *(2)*. The nucleophilic agents used for the dealkylation of trialkyl phosphates and thiophosphates, tetraalkyl pyrophosphates, and dialkyl chlorophosphates, chlorothiophosphates, and phosphonates are reviewed in Table 2.

Table 2. List of publications on the dealkylation of esters of pentavalent phosphorus.

Nucleophile	Phosphate triester	Thiophosphate triester	Halogeno-phosphate diester	Halogeno-thiophos-phate diester	Pyrophos-phate tetraester	Phosphonate diester
ArOH	[23, 24, 85]				[50, 51]	
ROH; RO^-	[25, 26, 64, 79, 86]	[4, 11, 12, 41, 101, 120]				[64, 80]
NRR'R''	[44, 45, 56–60]	[10, 12–15, 41, 58, 59, 102–107]	[43, 83, 84]	[61–63, 83]	[44, 47]	
NRR'H	[26, 45]	[41, 105, 108, 109]	[39]			[100]
NRH_2	[27–32, 45, 116, 119]	[41, 104, 105, 109, 110]	[39, 40, 117]			[31, 96–99]
NH_3	[65]	[4, 65]				
NH_2^-	[66]					
$CH_3CO_2^-$	[36, 37, 46, 57]		[82]	[82]		
Cl^-	[7, 35, 45, 46, 50, 67, 68, 72]	[7, 111]			[48]	
Br^-	[35, 71, 72]					[69–71]
I^-	[35, 73–76]	[11, 77]	[82]		[95]	[71, 78]
OCN^-	[38]					
SCN^-	[41, 49, 87]	[41]			[52, 81]	
RS^-	[88, 89]	[3, 88–92]				[88, 89, 93]
ArS^-	[55]	[55, 94]				
$R_2NCS_2^-$	[49, 118]					
$(RO)_2PSO^-$		[9, 111–115]				
R–S–R'		[8, 9, 13]				
$(H_2N)_2CS$	[10, 33, 34]	[10, 13, 41]	[34, 83]	[83]		

[53] *E. I. Hoegberg* and *J. T. Cassaday*, J. Amer. chem. Soc. *73*, 557 (1951).

[54] *M. I. Kabatschnik* and *T. A. Mastrjukova*, Zh. obshch. Khim. *25*, 1924 (1955).

[55] *B. Miller*, Proc. chem. Soc. (London) *1962*, 303.

[55a] *T. A. Mastrjukova* et al., Dokl. Akad. Nauk SSSR *158*, 1373 (1964); Chem. Abstr. *62*, 2700 (1965).

[55b] *G. Kuhlow*, *H. Teichmann*, and *G. Hilgetag*, Z. Chem. *5*, 179 (1965).

[55c] *R. F. Hudson* and *D. C. Harper*, J. chem. Soc. (London) *1958*, 1356.

[56] *P. Chabrier* et al., C. R. hebd. Séances Acad. Sci. *244*, 2730 (1957); *247*, 1014 (1958); *249*, 1240, 2573 (1959); *254*, 2788 (1962).

[57] *J. Cheymoul*, *P. Chabrier*, and *N. T. Thuong*, ibid. *255*, 2451 (1962).

[58] *P. Chabrier* et al., ibid. *257*, 2846 (1963); *258*, 3738 (1964).

[59] *P. Chabrier* et al., Bull. Soc. chim. France *1964*, 1407.

[60] *J. G. Moffatt* and *H. G. Khorana*, J. Amer. chem. Soc. *79*, 3741 (1957).

[61] *Y. Nishizawa*, Agric. biol. Chem. (Tokyo) *25*, 820 (1961); Chem. Abstr. *56*, 8684 (1962).

[62] *H. Cierpka*, Diploma Thesis, Humboldt-Universität Berlin, 1958.

[63] *G. Kowollik*, Diploma Thesis, Humboldt-Universität Berlin, 1959.

[64] *M. Janczak*, Roczniki Chem. *10*, 115 (1930); Chem. Zbl. *1930* I, 2869.

[65] *R. Klement* and *A. Wild*, Chem. Ber. *96*, 1916 (1963).

[66] *O. Schmitz-Dumont* and *H. Reckhard*, Z. anorg. allg. Chem. *294*, 107 (1958).

[67] *E. Hayek* and *E. Rhomberg*, Mh. Chem. *83*, 1318 (1952).

[68] *J. Kennedy*, *E. S. Lane*, and *B. K. Robinson*, J. appl. Chem. *8*, 459 (1958).

[69] *W. S. Abramov*, *E. W. Sergejeva*, and *I. W. Tscholpanova*, Zh. obshch. Khim. *14*, 1030 (1944).

[70] *W. S. Abramov* and *E. A. Militzkova*, Zh. obshch. Khim. *22*, 252 (1952).

[71] *W. S. Abramov* and *O. D. Samoilova*, Zh. obshch. Khim. *22*, 914 (1952).

[72] *M. Miyamo*, J. Amer. chem. Soc. *77*, 3524 (1955).

[73] *L. Zervas* and *I. Dilaris*, J. Amer. chem. Soc. *77*, 5354 (1955).

[74] *C. A. Bunton*, *M. M. Mhala*, *K. G. Oldham*, and *C. A. Vernon*, J. chem. Soc. (London) *1960*, 3293.

[75] *E. Maruszewska-Wieczorkowska*, *J. Michalski*, and *A. Zwierzak*, Chem. and Ind. *1961*, 1668.

[76] Brit. Pat. 912287 (May 12th, 1959), inventors: *J. Mather* and *A. A. B. Browne*, I. C. I. Chem. Abstr. *58*, 8971 (1963).

[77] *A. J. Burn* and *J. I. G. Cadogan*, J. chem. Soc. (London) *1961*, 5532.

[78] *D. W. Grisley*, J. org. Chemistry *26*, 2544 (1961); US.-Pat. 3033891 (27. Nov. 1959), inventor: *D. W. Grisley*, Monsanto Co.; Chem. Zbl. *1964*, 2-2165.

[79] *J. Rabcewicz-Lubowsky*, J. prakt. Chem. [2] *86*, 318 (1912).

[80] *K. A. Andrianow* and *A. S. Shapetin*, Izv. Akad. Nauk SSSR, Ser. Khim. *1962*, 1753; Chem. Abstr. *58*, 7965 (1963).

[81] Brit. Pat. 697473 (Dec. 1st, 1950), Roche Products Ltd.; Chem. Zbl. *1954*, 5399.

[82] *C. Stölzer* and *A. Simon*, Chem. Ber. *96*, 288 (1963).

[83] *C. Stölzer* and *A. Simon*, Chem. Ber. *96*, 453 (1963).

[84] *W. Gerrard*, J. chem. Soc. (London) *1940*, 1464; *W. Gerrard* and *J. M. Z. Gladych*, Chem. and Ind. *1959*, 227.

[85] *G. W. Kenner* and *J. Mather*, J. chem. Soc. (London) *1956*, 3524.

[86] *H. D. Orloff*, *C. J. Worrel*, and *F. X. Markley*, J. Amer. chem. Soc. *80*, 727 (1958).

[87] *T. D. Smith*, J. chem. Soc. (London) *1961*, 5050.

[88] *R. G. Harvey* and *E. V. Jensen*, J. org. Chemistry *28*, 470 (1963).

[89] *R. G. Harvey*, *H. I. Jacobson*, and *E. V. Jensen*, J. Amer. chem. Soc. *85*, 1623 (1963).

[90] *J. Michalski* et al., Roczniki Chem. *33*, 247 (1959).

[91] *J. Michalski* and *J. Wasiak*, J. chem. Soc. (London) *1962*, 5056.

[92] German Published Patent Application 1136328 (Sept. 4th, 1959), inventor: *G. Schrader*, Bayer; Chem. Abstr. *58*, 1350 (1963).

[93] *S. Hirai*, *R. G. Harvey*, and *E. V. Jensen*, Abstr. IUPAC-Symposium "The Chemistry of Natural Compounds". Kyoto *1964*, p. 258.

[94] *B. Miller*, Tetrahedron *20*, 2069 (1964).

[95] *L. Zervas* and *I. Dilaris*, Chem. Ber. *89*, 925 (1956).

[96] *A. E. Jakubowitsch* and *W. A. Ginsburg*, Dokl. Akad. Nauk SSSR *82*, 273 (1952).

[97] *K. C. Kennard* and *C. S. Hamilton*, J. Amer. chem. Soc. *77*, 1156 (1955).

[98] *T.-S. Tung* and *S.-T. Chern*, Acta chim. sinica *24*, 30 (1958); Chem. Zbl. *1963*, 17664.

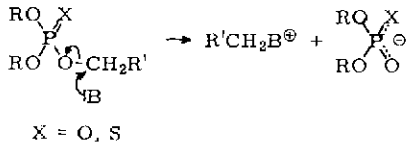
[99] *K. Zieloff*, *H. Paul*, and *G. Hilgetag*, Z. Chem. *4*, 148 (1964).

[100] *T. Reetz*, *D. H. Chadwick*, *E. E. Hardy*, and *S. Kaufmann*, J. Amer. chem. Soc. *77*, 3813 (1955).

[101] *W. E. Bacon* and *W. M. LeSuer*, J. Amer. chem. Soc. *76*, 670 (1954).

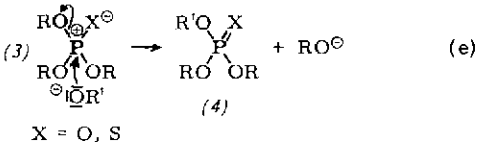
2. Mechanisms of Alkylation and Phosphorylation

There is an important mechanistic difference between the cleavage of esters by alkoxide ions and by the other nucleophilic systems listed in Table 2. Thus nucleophilic agents B generally cause an S_N2 reaction on the α-carbon atom of the ester group, leading to the expulsion of the phosphorus-containing anion, in accordance with Eq. (d) [55c].



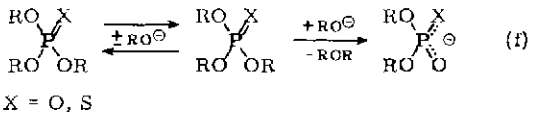
X = O, S (d)

Alkoxide ions, on the other hand, attack preferentially at the phosphorus atom. The transition state *(3)* containing 5-coordinate phosphorus decomposes to form a neutral molecule *(4)*, which can then either react again with the leaving group in the same way, *i.e.* leading to transesterification, or enter into a competing reaction in accordance with Eq. (d). Thus esters of this type have both an alkylating and a phosphorylating action on



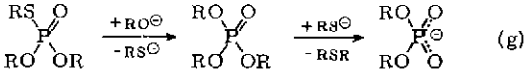
X = O, S (e)

alkoxide ions. Consequently, trialkyl phosphates and thionophosphates can be dealkylated in high yields by means of an alkoxide with the same alkyl group [41,120] [see Eq. (f)], but the same reaction of phosphate esters containing a better leaving group than alkoxy leads to



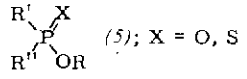
X = O, S (f)

an unwanted modification of the ester molecule. Thus alkyl aryl phosphates lose phenol on reacting with alkoxides [86], and thiolphosphates are largely desulfurized in accordance with Eq. (g) [11,101]. The applicability of alkoxide ions to the dealkylation of esters



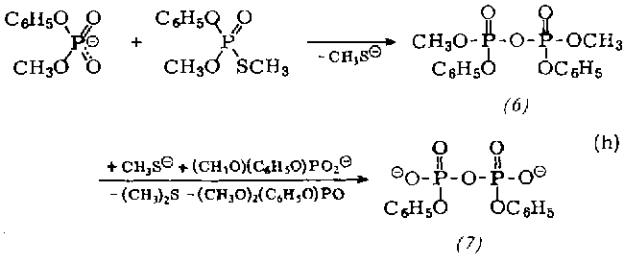
(g)

containing phosphorus is therefore very limited. Hydroxide ions, like alkoxide ions, also react *via* a transition state containing 5-coordinate phosphorus [121]. Phosphates and thiophosphates *(5)* which contain a suitable leaving group R′ or R″ can also react with phosphate ions in accordance with Eq. (e), *i.e.* with phosphorylation of the nucleophile. Suitable phosphorylating agents of this type for the preparation of pyrophosphate and polyphosphate bonds are chlorophosphates (R′ = Cl), amidophosphates (R′ = NH_2), and pyrophosphates [R′ = $OP(O)(OR)_2$] (for further examples see [122]. Thiolphosphates (R′ = SR) can



(5); X = O, S

also have a similar phosphorylating action. Thus *O,S*-dimethyl *O*-phenyl thiophosphate reacts with potassium methyl phenyl phosphate in accordance with Eq. (h) to give high yields of dipotassium *syn*-diphenyl pyrophosphate *(7)*, which is formed by the demethylation of dimethyl diphenyl pyrophosphate *(6)* by the mercaptide and phosphate ions [123].



(h)

The difference in behavior of alkoxide [Eq. (e)] and mercaptide ions [Eq. (d); B = $RS^{\ominus}$] towards phosphates and thiophosphates suggests that a different nucleo-

[102] *G. Hilgetag* and *G. Lehmann*, J. prakt. Chem. [4] *9*, 3 (1959).

[103] *G. Hilgetag*, *A. Martini*, and *I. Eichhorn*, Mber. dtsch. Akad. Wiss. Berlin *1*, 571 (1959).

[104] *N. N. Melnikov* et al., Zh. obshch. Khim. *32*, 2858 (1962).

[105] *N. N. Melnikov* et al., Zh. obshch. Khim. *33*, 2456 (1963).

[106] *N. N. Melnikov* et al., Zh. obshch. Khim. *34*, 40 (1964).

[107] Russ. Pat. 150512 (Oct. 25th, 1961), inventors: *N. N. Melnikov* et al.; Chem. Abstr. *58*, 8974 (1963).

[108] *N. N. Melnikov* et al., Zh. obshch. Khim. *31*, 3605 (1961).

[109] *K. D. Schwetzova-Schilowskaja* et al., Zh. obshch. Khim. *34*, 2138 (1964).

[110] *N. N. Melnikov* et al., Zh. obshch. Khim. *32*, 1836 (1962).

[111] *J. E. Casida* and *D. M. Sanderson*, Nature (London) *189*, 507 (1961); J. agric. Food Chem. *11*, 91 (1963).

[112] *G. Hilgetag* and *G. Lehmann*, J. prakt. Chem. [4] *12*, 6 (1960).

[113] *G. Berkelhammer*, *Sh. DuBreuil*, and *R. W. Young*, J. org. Chemistry *26*, 2281 (1961).

[114] German Published Patent Application 1164408 (Febr. 28th 1961), inventors: *Sh. DuBreuil* et al., Amer. Cyanamid Co.; Chem. Abstr. *60*, 15735 (1964).

[115] *H. Teichmann*, unpublished work; cf. *H. Teichmann*, Z. Chem. *5*, 118 (1965).

[116] *J. I. G. Cadogan*, J. chem. Soc. (London) *1957*, 1079.

[117] *H. Goldwhite* and *B. C. Saunders*, J. chem. Soc. (London) *1957*, 2409.

[118] *T. D. Smith*, J. chem. Soc. (London) *1961*, 3164.

[119] *F. L. Scott*, *R. Riordan*, and *P. D. Morton*, J. org. Chemistry *27*, 4255 (1962).

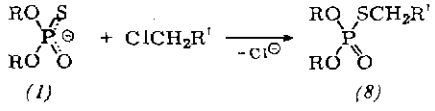
[120] *T. W. Mastin*, *G. R. Norman*, and *E. A. Weilmuenster*, J. Amer. chem. Soc. *67*, 1662 (1945).

[121] Summary: *J. R. Cox* and *O. B. Ramsay*, Chem. Rev. *64*, 317 (1964).

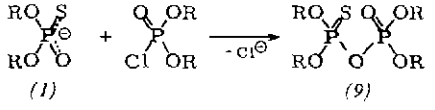
[122] *V. M. Clark*, *D. W. Hutchinson*, *A. J. Kirby*, and *S. G. Warren*, Angew. Chem. *76*, 704 (1964); Angew. Chem. internat. Edit. *3*, 678 (1964).

[123] *G. Hilgetag*, *M. Krüger*, and *H. Teichmann*, Z. Chem. *5*, 180 (1965).

philicity scale [*] applies to phosphorylation, *i.e.* substitution on the phosphorus atom, than to alkylation, *i.e.* S_N2 reactions on the tetrahedral carbon atom [124, 125]. Whereas the nucleophilic constants of anions containing sulfur are particularly high in substitutions on carbon [126], they are lower than those of anions containing oxygen in substitutions on phosphorus, so that in this case there is a closer relationship between nucleophilicity and basicity [125]. The difference in the nucleophilicity scales applying in carbon chemistry and in phosphorus chemistry also explains the fact that the thiophosphate anion *(1)* reacts with alkylating agents to form thiolphosphates *(8)*, and with phosphorylating agents to form thionopyrophosphates *(9)* [127, 138].



(1) *(8)*

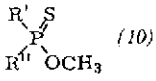


(1) *(9)*

3. Constitution and Alkylating Properties

All the alkylations listed in Table 2 involve the transfer of lower alkyl residues (C_1 to C_4), as well as benzyl and allyl residues. As with other alkylating agents, the heterolysis of benzyl, allyl, and methyl ester linkages proceeds much more readily than that of ethyl and higher alkyl-oxygen bonds.

Since oxygen is more electronegative than sulfur, the phosphorus can be expected to carry a larger positive charge in the phosphates than in the thionophosphates, and the carbon-oxygen bond should therefore be weaker in the former. This is in fact the case, since phosphates are often rather stronger alkylating agents than the isologous thionophosphates, particularly in the absence of solvents and in cases where hydrogen bonding between the substrate and the oxygen of the P=O group occurs [33, 34]. The opposite has, however, been observed in the alkylation of tertiary amines in aprotic solvents [59]. In the heterolysis of carbon-oxygen bonds, however, a much more important factor than the nature of X in a molecule of the type *(5)* is the inductive effect of the substituents R′ and R″. Thus an increase in the attraction of electrons by R′ and R″



(10)

leads to a corresponding decrease in the polarity of the P=O group [128]. The methylating power of the methyl ester *(10)* decreases in the order

R′ p-NO_2-C_6H_4O > C_6H_5O > C_6H_5O > CH_3S > CH_3O > CH_3O > CH_3
R″ p-NO_2-C_6H_4O C_6H_5O CH_3O CH_3O CH_3O CH_3 CH_3

as in the isologous phosphoryl compounds.

It has recently been shown [129a], for the reaction between p-substituted diphenyl methyl phosphates and pyridine, that the effects of substituents on the rate of methylation, as expected, obey the Hammett relation as well as *e.g.* the effects on the dissociation constants of disubstituted phosphoric acids and thiophosphoric acids [129]. Thus the abilities of the esters *(5)* to undergo dealkylation run parallel to the strengths of the parent acids R′R″P(X)OH. Since some disubstituted phosphoric and thiophosphoric acids are stronger acids than phosphoric acid itself, alkyl esters *(5)* with suitable substituents R′ and R″ may be far superior as alkylating agents to the much more commonly used alkyl sulfonates and dialkyl sulfates.

Like dialkyl sulfates, trialkyl phosphates and thiophosphates initially give up only one alkyl cation, since the electron pair remaining in the anion reinforces the other carbon-oxygen bonds. When the dialkyl phosphate anion is protonated, however, the free dialkylphosphoric acid formed can give up another alkyl group [72]. The presence of free dialkylphosphoric and monoalkylphosphoric acids in equilibrium with their salts of weak bases is probably also the reason for the fact that all three alkyl groups can sometimes be used in the alkylation of aromatic amines with trialkyl phosphates under relatively drastic conditions (200 °C and over) [27–30, 119].

In trialkyl phosphates and thiophosphates with only moderate alkylating properties, stronger polarization of the alkyl-ester bond can sometimes be induced artificially by adduct formation with Lewis acids. Esters activated in this way are among the strongest alkylating agents known. Triethyl thiophosphate with antimony (V) chloride, for example, quantitatively alkylates ether to triethyloxonium hexachloroantimonate *(11)* [130].

$(RO)_3PS \rightarrow SbCl_5 + R_2O \rightarrow SbCl_5 \longrightarrow [R_3\overset{\oplus}{O}]SbCl_6^{\ominus} + (RO)_2PSOSbCl_4$

(11)

[*] The reactivity towards tetrahedral carbon decreases in the sequence:

$S_2O_3^{2-} > SH^- > I^- \simeq (CH_3O)_2POS^- > OH^- > Br^- > C_6H_5O^- > Cl^- > F^-$;

for tetrahedral phosphorus the corresponding sequence is:

$F^- > OH^- > C_6H_5O^- > C_6H_5S^- > Cl^-, Br^-, I^-, S_2O_3^{2-}$ [124, 126].

Variously defined nucleophilicity constants, which agree well with one another, have been calculated or experimentally determined for S_N2 reactions on saturated carbon [124, 126]; the sequence for phosphorus follows from the rate constants of comparable reactions [124].

[124] *J. O. Edwards* and *R. G. Pearson*, J. Amer. chem. Soc. *84*, 16 (1962); *R. F. Hudson*, Chimia *16*, 173 (1962).

[125] *B. Miller*, J. Amer. chem. Soc. *84*, 403 (1962).

[126] See, *e.g.*, *C. G. Swain* and *C. B. Scott*, J. Amer. chem. Soc. *75*, 141 (1953); *J. O. Edwards*, ibid. *76*, 1540 (1954); *78*, 1819 (1956).

[127] *G. Schrader*, *W. Lorenz*, and *R. Mühlmann*, Angew. Chem. *70*, 690 (1958).

[128] *J. V. Bell*, *J. Heisler*, *H. Tannenbaum*, and *J. Goldenson*, J. Amer. chem. Soc. *76*, 5185 (1954); *L. L. Burger*, J. phys. Chem. *62*, 590 (1958).

[129] *M. I. Kabatschnik*, *T. A. Mastrjukova* et al., Tetrahedron *9*, 10 (1960); *M. I. Kabatschnik*, Z. Chem. *1*, 289 (1961).

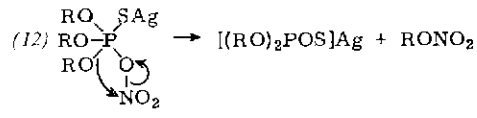
[129a] *D. W. Osborne*, J. org. Chemistry *29*, 3570 (1964).

[130] *G. Hilgetag* and *H. Teichmann*, Chem. Ber. *96*, 1446 (1963).

It is possible, however, that the reaction of trialkyl thiophosphates with silver nitrate, silver nitrite, or silver acetate (which proceeds in accordance with Eq. (i), *via* isolable adducts [131], to form high yields of the silver salts of disubstituted thionophosphoric acids [4, 12, 13, 131]) is not a

$$(C_2H_5O)_3PS + AgNO_3 \rightarrow (C_2H_5O)_3PS{\cdot}AgNO_3 \rightarrow [(C_2H_5O)_2POS]Ag + C_2H_5ONO_2 \quad (i)$$

true dealkylation. The fact that the triaryl esters are also readily converted to silver diaryl thionophosphates suggests that the reaction involves the cleavage of a P–O bond in an intermediate *(12)* which contains 5-coordinate phosphorus.



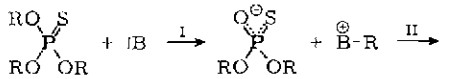
(12) $\rightarrow [(RO)_2POS]Ag + RONO_2$

III. Alkyl Thiophosphates as Unusual Alkylating Agents

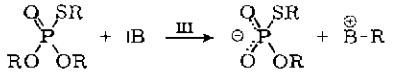
The alkylating behavior of thiophosphates is complicated by the presence of the sulfur atom in two respects. First, the ambident thiophosphate anion *(1)* formed by the dealkylation of a thionophosphate, being a strong nucleophile, can again initiate an S_N2 reaction on the carbon atom of a reaction product, *i.e.* it can be realkylated; the product (see Section II.1) is a thiolphosphate. Second, thiolphosphates can be dealkylated only by the cleavage of carbon-oxygen bonds, but not of carbon-sulfur bonds. Heterolysis of the CS bond is much more difficult than that of the CO bond, since sulfur and carbon have roughly the same electronegativities. As a result of the combination of these two circumstances, thionophosphates frequently isomerize during alkylation. Dealkylations combined in this way with isomerization may occur by the two mechanisms described below.

1. Realkylation

If the transfer of an alkyl residue to the nucleophile B yields a new alkylating agent $\overset{\oplus}{B}$–R, this may realkylate the thionophosphate anion *(1)* [8, 10–14, 77, 132, 133]. The resulting thiol ester *(13)* is a stronger alkylating agent than the thionophosphate *(1a)*, and is immediately dealkylated once more by B. The resultant reaction



(1a) *(1)* (k)



(13) *(14)*

[131] *G. Hilgetag, K.-H. Schwarz, H. Teichmann,* and *G. Lehmann*, Chem. Ber. *93*, 2687 (1960).

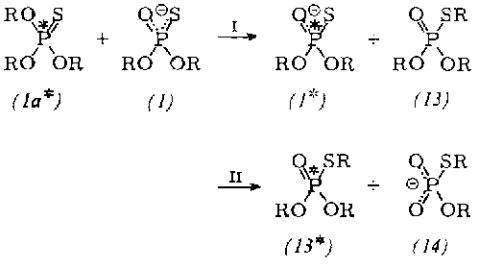
[132] *J. I. G. Cadogan* and *L. C. Thomas*, J. chem. Soc. (London) *1960*, 2248.

[133] *J. I. G. Cadogan*, J. chem. Soc. (London) *1962*, 18.

[Eq. (k)], therefore, is the formation of an *O,S*-dialkyl thiophosphate anion *(14)* from an *O,O,O*-trialkyl thionophosphate *(1a)*; this is the case, for example, when B is $(CH_3)_2S$ or $I^{\ominus}$. The realkylation can be detected *e.g.* when trimethylsulfonium *O,O*-dimethyl thiophosphate is heated in solution; the anion is completely isomerized within a short time. The trimethylphenylammonium salt isomerizes more slowly under the same conditions, whereas the tetramethylammonium salt does so only to a very small extent, and the sodium salt not at all [12]. Trimethylsulfonium *O,O*-diaryl thiophosphates, when heated, form dimethyl sulfide and *S*-methyl *O,O*-diaryl thiophosphates [13]; the realkylation in this case stops at stage II of Eq. (k), since the thiol ester formed is not an alkylating agent.

2. Interaction between Triesters and Diester Anions

If *O,O,O*-trimethyl thiophosphate is treated at room temperature with a nucleophile which is sufficiently strong to bind the methyl group firmly (*e.g.* triethylamine), no realkylation can occur. The product in this case is the *O,O*-dimethyl thiophosphate *(1)* [12]. The same reaction carried out at 80 °C, however, yields only the isomeric *O,S*-dimethyl thiophosphate *(14)* [10]. Since the isomerization of pure tetramethylammonium *O,O*-dimethyl thiophosphate at 80 °C is negligible, so that realkylation can be ruled out, a reaction (l) must have taken place between the *O,O,O*-trimethyl thiophosphate *(1a)* and the *O,O*-dialkyl thiophosphate anion *(1)*.

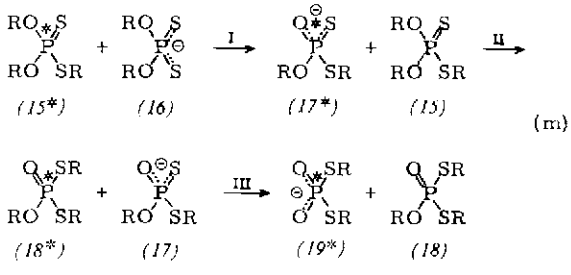


(1a)* *(1)* *(1*)* *(13)* (l)

(13)* *(14)*

In this reaction, the *O,O*-dialkyl thiophosphate anion *(1)* is first alkylated by *(1a)*, with self-regeneration, to form the *S*-ester *(13)*. The latter is then dealkylated by the same anion, with regeneration of the thiol ester *(13*)*, to form the *O,S*-dialkyl thiophosphate anion *(14)* [9, 112]. Eq. (l), together with Equations (k I) and (k II), again gives the overall Eq. (k).

The interaction between a triester *(15)* and an *O,O*-dialkyl dithiophospbate anion *(16)* can even lead to two other isomeric anions *(17)* and *(19)* [114, 115] [Eq. (m)].



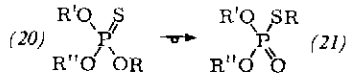
(15)* *(16)* *(17*)* *(15)* (m)

(18)* *(17)* *(19*)* *(18)*

A check on the reaction (m) with R = CH_3 by thin layer chromatography confirms the formation of all the isomers. Reaction (m II) does not go to completion, since the *O,S,S*-trimethyl ester *(18)*, being a stronger alkylating agent, takes over entirely the methylation of the anion *(17)* when the *O,O,S*-triester *(15)* has been about half consumed [115].

IV. The Self-Alkylation of Alkyl Thiophosphates

In the absence of a nucleophile, the alkylating power of tertiary thiophosphates may be directed against the ester molecule itself. The nucleophilic center in the normal case is the thiono sulfur, so that an isomerization *(20)* → *(21)* takes place. Furthermore, if some of the



alkoxy groups in *(20)* are replaced by dialkylaminoalkyl or alkylmercaptoalkyl groups, transalkylation to form ionic products can also take place.

1. Isomerization as a Special Case of Transalkylation

The interpretation of the isomerization of thionophosphates as a self-alkylation explains the following observations:

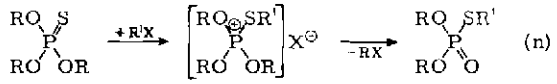
1. Aroxyl groups attached to the phosphorus atom do not take part in isomerizations.

2. The isomerization is favored by the same inductive effects as other alkylations. For an ester $RP(S)(OCH_3)_2$, the rate of isomerization decreases in the following order [14,134]:

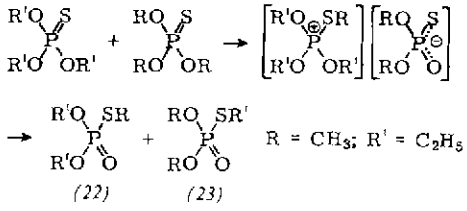
$$R = p\text{-}NO_2\text{-}C_6H_4O > C_6H_5O > CH_3O > CH_3.$$

3. Alkyl esters isomerize extremely slowly. The most readily isomerized trimethyl ester must be heated for 28 h at 130 °C before the thione sulfur disappears completely [8]. Allyl esters react much more rapidly [135].

In general, *O,O,O*-triesters of thiophosphoric acid with no nucleophilic center require temperatures of 120 to 180 °C for isomerization. This isomerization may be regarded as a special case of the Pistschimuka reaction (n) [4], which takes place under similar conditions, and which, like the thermal isomerization [18], is accelerated by polar solvents [77,136]. When a mixture of trimethyl and triethyl thionophosphate is heated, the formation of the two isomeric trialkyl thiolphosphates is accompanied by that of *O,O*-dimethyl *S*-ethyl *(23)* and *O,O*-diethyl *S*- methyl *(22)* thiophosphates. The thiono sulfur in this case is alkylated not only by the thiono esters, but above all by the thiol esters formed [137].



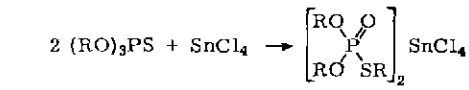
R'≠R; X = Cl, Br, I



(22) *(23)*

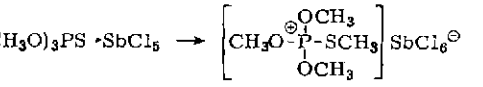
Since ethyl iodide, for example, is a stronger alkylating agent than *O,O,O*-triethyl thiophosphate, the Pistschimuka reaction (n) with alkyl iodides having the same alkyl residue (R′ = R) can sometimes be used to "catalyse" the thermal isomerization [4,138]; the same effect can be achieved by using the isomeric thiolphosphates. The thermal isomerization can also be accelerated by nucleophilic reagents such as dimethyl sulfide or thiourea, since these split off alkyl groups to form thiophosphate ions, which then initiate mechanisms such as that shown in Eq. (l) [8,9,14]. In general, impure thionophosphates isomerize more readily than the purified esters.

A non-catalytic acceleration of the isomerization is also observed with Lewis acids such as $FeCl_3$, $AlCl_3$, or $SnCl_4$, which react quantitatively, even at or below room temperature, to form thiolphosphate adducts such as *(24)* [139,140].

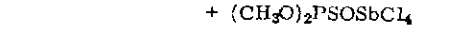


(24)

In contrast to the thermal isomerization, the intermediate *O,O,O,S*-tetraalkyl thiophosphate acidium ions can be isolated in this case. Thus the hexachloroantimonate *(25)* can be quantitatively isolated with $SbCl_5$



(25)



[141]; in the presence of nucleophilic reagents, the cation of *(25)* suffers immediate dealkylation to form *O,O,O*-trimethyl thiophosphate [141,142].

[134] *G. Hilgetag* and *G. Schramm*, unpublished work.

[135] *A. N. Pudowik* and *I. M. Aladschewa*, Zh. obshch. Khim. *30*, 2617 (1960).

[136] *A. J. Burn*, *J. I. G. Cadogan*, and *A. B. Foster*, Chem. and Ind. *1961*, 591.

[137] *H. Teichmann*, unpublished work.

[138] *R. A. McIvor*, *G. D. McCarthy*, and *G. A. Grant*, Canad. J. Chem. *34*, 1819 (1956).

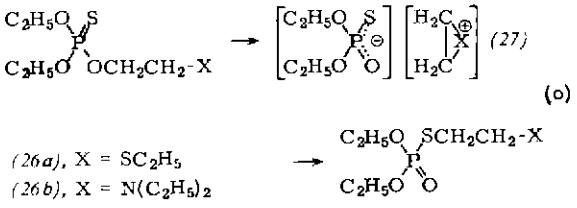
[139] *H. Teichmann* and *G. Hilgetag*, Chem. Ber. *98*, 856 (1965).

[140] *G. Hilgetag*, *H. Teichmann*, and *M. Krüger*, Chem. Ber. 98, 864 (1965).

[141] *H. Teichmann* and *G. Hilgetag*, Chem. Ber. *96*, 1454 (1963).

[142] *G. Hilgetag* and *H. Teichmann*, Chem. Ber. *96*, 1465 (1963).

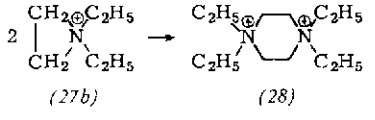
Dialkyl β-alkylthioethyl *(26a)* [17,18] and dialkyl β-dialkylaminoethyl *(26b)* [21,22,62,143] thionophosphates isomerize much more readily than unsubstituted alkyl or alkyl aryl thionophosphates. In this case, owing to a neighboring-group effect, it is not the smallest alkyl residue, but the nucleophilically substituted alkyl residue that migrates onto the sulfur atom, *e.g.* in accordance with Eq. (o).



(o)

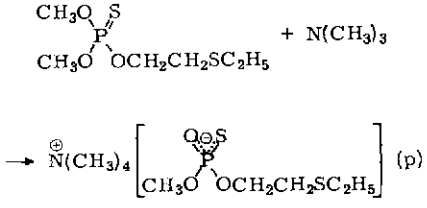
(26a), X = SC_2H_5
(26b), X = $N(C_2H_5)_2$

The first step in this reaction is an intramolecular self-alkylation to form a cyclic sulfonium [17] or immonium *O,O*-dialkyl thiophosphate *(27)* [21,22,62,143], which then undergoes a realkylation similar to reaction (k II), with formation of the thiolphosphate. Tetraethylpiperazinium salts *(28)*, which are formed from the cycloimmonium cation *(27b)* by a side reaction, have occasionally been isolated [62,132].



(27b) *(28)*

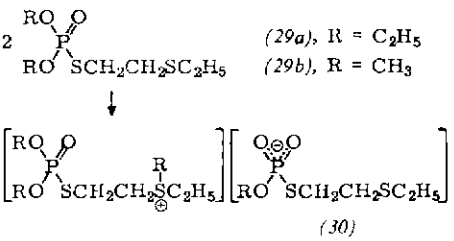
If an ester of the type *(26)* is offered a stronger nucleophile than the nitrogen or sulfur atom in its own molecule, the self-alkylation is suppressed, and once more only the smallest alkyl group is split off [103]; an example is shown in Eq. (p).



(p)

2. Transalkylation

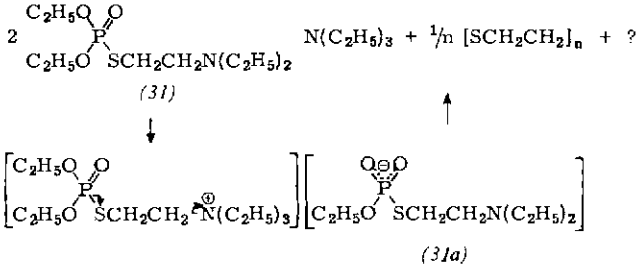
Esters of the type *(26)*, and above all their thiol isomers, tend to change into salt-like products. *O*-Ethyl *O*-β-diethylaminoethyl *O*-methyl thiophosphate, for example changes on standing at room temperature into a substance which is insoluble in ether [62]. This reaction has been investigated in detail in the case of the compounds *(29a)* (Isosystox®) and *(29b)* (Isometasystox®) [144]. It is accelerated by higher temperatures or polar solvents. Oxidation of the thioether group to the sulfone group leads to stable thiolphosphates. According to *Heath* [144], the reaction is essentially a transalkylation with formation of *(30)*.



(29a), R = C_2H_5
(29b), R = CH_3

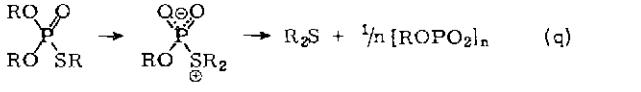
(30)

A similar explanation applies to the formation of triethylamine when the insecticide Amiton® *(31)* is heated [133].



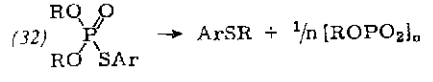
(31) *(31a)*

The sulfur of the thiol ester group in simple alkyl and alkyl aryl thiolphosphates can also become alkyl acceptor for transalkylations at temperatures somewhat higher than 130 °C. Thus considerable quantities of dimethyl sulfide are liberated from *O,O,S*-trimethyl thiophosphate [8] or *O*-aryl *O,S*-dimethyl thiophosphates



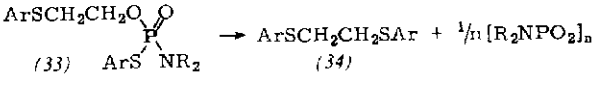
(q)

[134], probably in accordance with Eq. (q). *O,O*-Dialkyl *S*-aryl thiophosphates *(32)* give high to quantitative yields of alkyl aryl sulfide at 170 °C [145]. 1,2-Di-



(32)

arylthioethanes *(34)* can be readily obtained in a similar manner from amido thiophosphates of the type *(33)* [146].



(33) *(34)*

3. Interference in Syntheses

The alkylating properties of thiophosphates are not only of preparative interest, but are equally important in the preparation and use of these compounds.

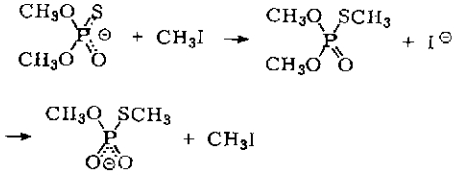
The yields of thiophosphates are considerably reduced if their synthesis involves the formation of *e.g.* iodide

[143] *A. Calderbank* and *R. Ghosh*, J. chem. Soc. (London) *1960*, 637.

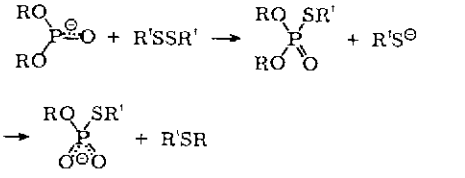
[144] *D. F. Heath*, Nature (London) *179*, 377 (1957); J. chem. Soc. (London) *1958*, 1643; *D. F. Heath* and *M. Vandekar*, Biochem. J. *67*, 187 (1957).

[145] *K. Pilgram* and *F. Korte*, Tetrahedron *21*, 203 (1965).

[11] or mercaptide ions [89–91] which dealkylate the esters according to Eq. (r) and (s).

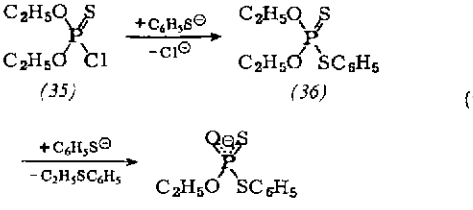


(r)



(s)

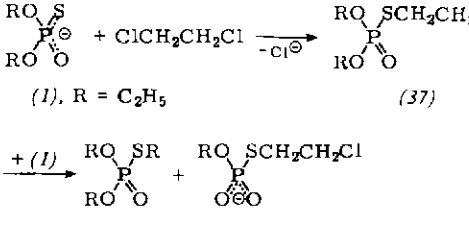
In reactions of chlorophosphates with mercaptides or thiophenolates, the "esterifying reagent" can itself dealkylate the triester formed. Thus the reaction of *O,O*-diethyl chlorothiophosphate *(35)* with sodium thiophenolate [Eq. (t)] [94] yields only 32 % of *O,O*-diethyl *S*-phenyl dithiophosphate *(36)*, whereas the more



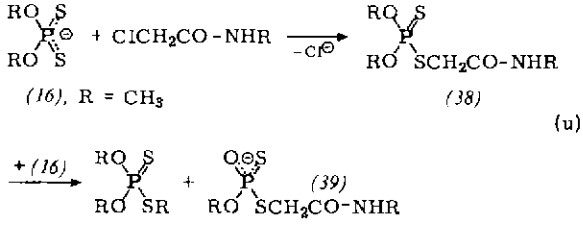
(t)

weakly nucleophilic phenoxide under the same conditions gives 80% of *O,O*-diethyl *O*-phenyl thiophosphate. The dealkylation by tertiary amines during the esterification of alcohols with chlorophosphates has already been mentioned [Eq. (c)]; similar behavior is found with chlorothionophosphates [62, 63].

Another complication is introduced by the interaction between the thiophosphate anion and the triester produced [Eq. (l)]. In the reaction of *O,O*-diethyl thiophosphates *(1)* with ethylene dichloride, for example, instead of the expected *S*-β-chloroethyl ester *(37)*, the

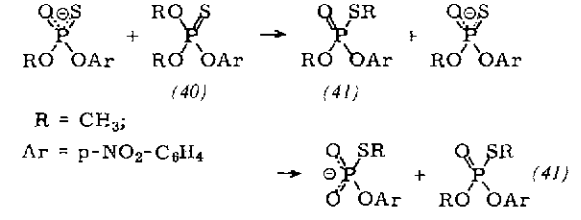


product consists of a mixture of *(37)* with *O,O*-diethyl *S*-ethyl thiophosphate [147]. The anion *(39)* formed by dealkylation in the synthesis of the insecticide Rogor® *(38)* [Eq. (u)] [111, 113–115] can be realkylated to form an isomer of the insecticide which is more toxic to warmblooded animals.



(u)

It is sometimes possible to make preparative use of such generally undesirable reactions. For example, a patent [114] describes the preparation of *O,S*-dimethyl *O*-(*p*-nitrophenyl) thiophosphate *(41)* in high yields by the reaction of the isomeric methyl parathion *(40)* with its dealkylation product.



Thiophosphates can also change as a result of careless storage, formulation, and use, with consequent influence on the pharmacological and insecticidal properties.

The isomerization of thionophosphates of the type *(26)*, which is appreciable on prolonged storage even at room temperature, is generally associated with an increase in toxicity. In particular, the salts *(30)* and *(30a)* formed by transalkylation are very efficient choline esterase inhibitors, whose structural relationship to acetylcholine is obvious. Polar solvents such as water greatly accelerate such transalkylations [144].

The toxicity of phosphate and thiophosphate insecticides has formerly been ascribed mainly to their inhibitory action on choline esterase. It now seems certain that this property does not suffice to explain the toxicity. In this connection, it is probably more than mere coincidence that all toxic phosphoric acid and thiophosphoric acid insecticides are strong alkylating agents [148].

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Translated by Express Translation Service, London

[146] *K. Pilgram, D. D. Phillipp,* and *F. Korte,* J. org. Chemistry *29*, 1848 (1964).

[147] *T. A. Mastrjukova, T. B. Sacharova,* and *M. I. Kabatschnik,* Zh. obshch. Khim. *34*, 94 (1964).

[148] See, *e.g., G. Schrader,* Z. Naturforsch. *18b*, 965 (1963).

Recent Advances in the Theory of Liquids

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In this paper, the methods of calculation of liquid properties using cluster integrals or the radial distribution function are not discussed. Rather, the theories using a model approach are presented. The basic principles involved in the cell theory, tunnel theory, and significant structure theory are reviewed, and the merits of the three theories are examined by comparing theoretical and experimental values of the pressures, molar volumes, compressibility factors, and excess entropies of real liquids. – The thermodynamic properties of two- and three-dimensional arrays of hard discs and spheres are also calculated, and compared with the machine calculation. – One finds that the significant structure theory gives the best results in every case.

A. Introduction

The purpose of this paper is to review the lattice theories developed to describe the liquid state. In this category belong the free-volume theory or cell theory [1,2], the tunnel theory [3], which is an improved version of the cell theory, and the significant structure theory of liquids [4]. The first two theories are based more on a fundamental approach [5,6], while the last has more obvious physical significance. All three theories involve assumptions in formulating the partition function, Z_N, which is related to the Helmholtz free energy, A, according to:

$$A = -kT \ln Z_N \tag{1}$$

Thermodynamic properties such as pressure, P, entropy, S, and internal energy, E, can be obtained from the Helmholtz free energy as follows:

$$P = -\left(\frac{\partial A}{\partial V}\right)_T$$

$$S = -\left(\frac{\partial A}{\partial T}\right)_V$$

$$E = -kT^2\left[\frac{\partial}{\partial T}\left(\frac{A}{kT}\right)\right]_V \tag{2}$$

First we shall discuss the formulations of Z_N according to the various theories and the assumptions introduced, and then compare the numerical results obtained with experiment.

B. Theories

I. Cell Theory or Free Volume Theory

This theory was first developed by *Eyring* and *Hirschfelder* [1], and by *Lennard-Jones* and *Devonshire* [2]. They assumed that a molecule in a liquid spends much of its time in the cell which is formed by its neighboring molecules fixed at their equilibrium positions. In order to simplify the calculation of the free volume, they further assumed that the z nearest neighbors can be treated as if uniformly smeared over a spherical surface of radius equal to the nearest neighboring distance, a. Then the partition function (for a system of N molecules) becomes

$$Z_N = \lambda^{-3N} \exp\left[-\frac{z}{2}\frac{N\Psi(a)}{kT}\right] v_f^N \left[J(T)\right]^N \tag{3}$$

where $\lambda = h/(2\pi mkT)^{1/2}$, J(T) is the partition function for the internal degrees of freedom of the molecule, and v_f is the free volume and is given by

$$v_f = \int_{cell} \exp\left[-z\frac{\Psi(\vec{r}) - \Psi(\vec{a})}{kT}\right] d\vec{r} \tag{4}$$

In the above equations, Ψ is a pair interaction potential.

II. Tunnel Theory

The tunnel theory is a one-dimensionally disordered cell theory proposed by *Barker* [3]. Instead of one molecule in a cell, the theory assumes that a whole line of molecules is in a tunnel. The partition function is the product of the partition functions for longitudinal and transverse motions in the tunnel. The partition function for the one-dimensional longitudinal motion can be evaluated exactly, and is

$$Z_M = \lambda^{-M}\left[\frac{1}{M!}\int_0^{lM}\cdots\int_0^{lM}\exp\left[-\frac{U(x)}{kT}\right]dx_1\cdots dx_M\right] \tag{5}$$

where U(x) is the potential energy of the one-dimensional system of M molecules in length *l*M. When there are

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[1] (a) *H. Eyring*, J. chem. Physics *4*, 283 (1936). (b) *H. Eyring* and *J. O. Hirschfelder*, J. physic. Chem. *41*, 249 (1937).

[2] *J. E. Lennard-Jones* and *A. F. Devonshire*, Proc. Roy. Soc. (London) *A 163*, 53 (1937).

[3] (a) *J. A. Barker* in: The International Encyclopedia of Physical Chemistry and Chemical Physics: Topics 10, The Fluid State, *J. S. Rowlinson*, ed., Vol. 1, Lattice Theories of the Liquid State (MacMillan, New York 1963). (b) *J. A. Barker*, Proc. Roy. Soc. (London) *A 259*, 442 (1961).

[4] (a) *H. Eyring* and *T. Ree*, Proc. nat. Acad. Sci. U.S.A., *47*, 526 (1961). (b) *H. Eyring* and *R. P. Marchi*, J. chem. Educat. *40*, 526 (1963). (c) *H. Eyring*, *T. S. Ree*, and *T. Ree*, Int. J. Engng. Sci. *3*,285 (1965).

[5] *J. G. Kirkwood*, J. chem. Physics *18*, 380 (1950).

[6] *H. S. Chung* and *J. S. Dahler*, J. chem. Physics *40*, 2868 (1964).

K such tunnels in a system, the total partition function will be Z_M^K.

The partition function for the transverse motion can be evaluated in terms of a "free area", a_f, exactly analogous to the "free volume" in the cell model. Therefore, the total partition function is

$$Z_N = \lambda^{-3N}\left[a_f \cdot \exp\left(-\frac{V(a)}{2kT}\right)\right]^N \cdot Z_M^K\,[J(T)]^N \qquad (6)$$

where

$$a_f = \int \exp\left\{-[V(\vec{r})-V(\vec{a})]/kT\right\} d\vec{r} \qquad (7)$$

In the above equation, $V(\vec{r})$ is the potential energy of interaction of a given molecule at a distance $\vec{r}$ from the axis of its tunnel, and this is summed over all molecules except those in the tunnel.

III. The Significant Structure Theory of Liquids [4]

The significant structure theory of liquids was developed in this laboratory, and its concept amounts to picking out *a priori* what one considers to be the regions of phase space that give the major contribution to the partition function and neglecting the rest of phase space. The significant structures that we choose for the liquid state are: (a) solid-like degrees of freedom; (b) a configurational degeneracy associated with the solid-like degrees of freedom; and (c) gas-like degrees of freedom for molecules maneuvering voids through the solid-like regions.

Assuming that the binding energy of the liquid is attributable solely to solid-like degrees of freedom, the fraction of the latter is estimated to be V_s/V, where V_s is the volume of the solid at the melting point and V is liquid volume. Then the partition function is written as:

$$Z_N = \{Z_s[1 + n_h \exp(-\varepsilon_o/kT)]\}^{NV_s/V} Z_g^{N(V-V_s)/V} \qquad (8)$$

where Z_s and Z_g are the partition function for solid and gas, respectively. Presumably n_h is proportional to the total number of holes present in the fluid. Hence,

$$n_h = n(V-V_s)/V_s \qquad (9)$$

The energy necessary to occupy one of the degenerate positions, ε_o, is assumed to be proportional to the potential energy of the lattice, E_c, and inversely proportional to n_h. Thus,

$$\varepsilon_o = a' E_c V_s/(V-V_s) \qquad (10)$$

where a′ is a proportionality constant.

C. Calculations

In order to obtain numerical results, we shall introduce the following two special potential functions into the partition functions:

I. The Lennard-Jones 6-12 Potential

A simple spherical molecule, such as argon, interacts with an identical molecule according to the Lennard-Jones 6–12 potential energy, *i.e.*,

$$\Psi(\vec{r}) = 4\varepsilon\left[\left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^{6}\right] \qquad (11)$$

where ε and σ are energy and distance parameters and are listed by *Hirschfelder et al.* [7]. With the 6–12 potential energy, the partition functions of the three theories mentioned above assume the following forms:

1. Cell Theory

When hexagonal close-packing is assumed, then

$$z = 12$$
$$V/N = a^3/\sqrt{2} \qquad (12)$$

With Equations (11) and (12), $\Psi(a)$ and v_f in Equation (3) become, respectively,

$$\frac{z\Psi(a)}{2} = 6\varepsilon\left[\frac{1.0109}{v^{*4}} - \frac{2.4090}{v^{*2}}\right] \qquad (13)$$
$$v_f = 2\sqrt{2}\,(V/N)\,G$$

where

$$v^* = V/N\sigma^3,$$

and

$$G = \int_0^{0.30544} y^{1/2} \exp\{-z[\Psi(y)-\Psi(a)]/kT\}\, dy \qquad (14)$$

The term $\Psi(y)-\Psi(a)$ in Equation (14) is written as

$$z[\Psi(y)-\Psi(a)] = 12\varepsilon\left[\frac{L(y)}{v^{*4}} - 2\,\frac{M(y)}{v^{*2}}\right] \qquad (15)$$

where

$$L(y) = l(y) + \frac{1}{128}\,l\left(\frac{1}{2}\,y\right) + \frac{2}{729}\,l\left(\frac{1}{3}\,y\right)$$

$$M(y) = m(y) + \frac{1}{16}\,m\left(\frac{1}{2}\,y\right) + \frac{2}{27}\,m\left(\frac{1}{3}\,y\right)$$

and

$$l(y) = (1 + 12y + 25.2y^2 + 12y^3 + y^4)\,(1-y)^{-10} - 1$$
$$m(y) = (1 + y)\,(1-y)^{-4} - 1 \qquad (16)$$
$$y = (r/a)^2$$

In Equations (13) and (15), non-nearest neighbor interactions are also counted. Hence, with Equation (1), the pressure equation for the cell theory becomes:

$$\frac{PV}{NkT} = 1 - \frac{12}{T^*}\left[\frac{2.4090}{v^{*2}} - \frac{2.0219}{v^{*4}}\right] - \frac{48}{T^*}\left[\frac{1}{v^{*2}}\cdot\frac{g_M}{G} - \frac{1}{v^{*4}}\cdot\frac{g_L}{G}\right] \qquad (17)$$

where $T^* = kT/\varepsilon$.

[7] *J. O. Hirschfelder, C. F. Curtiss,* and *R. V. Bird*: Molecular Theory of Gases and Liquids. Wiley, New York 1964, pp. 1110 to 1113 and 1212–1215.

The excess of a property is defined as the difference between the real property and the ideal gas property; hence, the excess reduced entropy, S^E/Nk, and the excess reduced energy, $E^E/N\varepsilon$, for the cell theory is derived from Equations (2) by using Equation (3) as:

$$\frac{S^E}{Nk} = \ln\left[2\sqrt{2}\,\pi\frac{G}{e}\right] + \frac{12}{T^*}\left[\frac{1}{v^{*4}}\cdot\frac{g_L}{G} - 2\frac{1}{v^{*2}}\cdot\frac{g_M}{G}\right] \tag{18}$$

and

$$\frac{E^E}{NkT} = \frac{6}{T^*}\left[\frac{1.0109}{v^{*4}} - \frac{2.4090}{v^{*2}}\right] + \frac{12}{T^*}\left[\frac{1}{v^{*4}}\cdot\frac{g_L}{G} - 2\frac{1}{v^{*2}}\cdot\frac{g_M}{G}\right] \tag{19}$$

In the above equations,

$$\left.\begin{aligned} g_L &= \int_0^{0.30544} y^{1/2} L(y)\exp\{-[\Psi(y)-\Psi(a)]/kT\}\,dy \\ g_M &= \int_0^{0.30544} y^{1/2} M(y)\exp\{-[\Psi(y)-\Psi(a)]/kT\}\,dy \end{aligned}\right\} \tag{20}$$

The values of G, g_L, and g_M have been tabulated by *Wentorf et al.* [8].

2. Tunnel Theory

The one-dimensional partition function defined in Equation (5) is written as:

$$-\frac{1}{N}\ln\left(Z_M\lambda^M\right) = \frac{A_1^*}{RT} + \frac{4}{T^*}\left[0.0003\left(\frac{\sigma}{l}\right)^{12} - 0.0173\left(\frac{\sigma}{l}\right)^6\right] \tag{21}$$

The second term on the right in Equation (21) is the Helmholtz free energy due to the non-nearest neighbor interaction, and the first term is that due to nearest neighbor interaction and is

$$A_1^* = -\frac{P_1 l}{kT} - \ln\left[\int_0^\infty \exp\{-[\Psi(x) + P_1 x]/kT\}\,dx\right] \tag{22}$$

Here P_1 is the one-dimensional pressure which is related to the intermolecular distance l by Equation (23):

$$l = \frac{\int_0^\infty x\exp\{-[\Psi(x) + P_1 x]/kT\}\,dx}{\int_0^\infty \exp\{-[\Psi(x)+P_1 x]/kT\}\,dx} \tag{23}$$

The hexagonal close-packed lattice with the lattice distance a is assumed for obtaining V(a) and a_f in Equation (6). Then the following equations are obtained:

$$V/N = (\sqrt{3}/2)a^2 l \tag{24}$$

$$V(a)/kT = 4.652C - 7.925B \tag{25}$$

where

$$B = \frac{4\varepsilon a}{lkT}\left(\frac{\sigma}{a}\right)^6,\quad C = \frac{4\varepsilon a}{lkT}\left(\frac{\sigma}{a}\right)^{12} \tag{26}$$

and a_f is given by

$$a_f = a^2 S \tag{27}$$

where

$$S = 2\pi\int_0^{0.25}\exp-\left[\frac{V(y)-V(a)}{kT}\right]y\,dy \tag{27a}$$

and

$$y = r/a \tag{27b}$$

From Equation (1) with Equations (6) and (21)–(27b), the pressure equation (28) is obtained:

$$\frac{PV}{NkT} = \frac{1}{T^*}\left(\frac{V_o}{V}\right)^4\left(20.938 + 9\frac{S_C}{S}\right) - \frac{1}{T^*}\left(\frac{V_o}{V}\right)^2\left(23.880 + 6\frac{S_B}{S}\right) + \frac{0.3497}{W}\left(\frac{V_o}{V}\right)^{-1/3} + \frac{2}{3} \tag{28}$$

In the above equation the relation $l = a = \sigma(2V/\sqrt{3}\,V_o)^{1/3}$ has been introduced, where

$$S_B = \frac{\partial S}{\partial B};\quad S_C = \frac{\partial S}{\partial C};\quad W = \frac{kT}{P_1\sigma};\quad \text{and } V_o = N\sigma^3 \tag{29}$$

S, S_B, S_C and W have been tabulated by *Barker* [3b].

3. Significant Structure Theory of Liquids

According to the significant structure theory, the partition funktion for simple liquids is written as:

$$Z_N = \left[e^{E_c/RT}\left(\frac{T}{\Theta}\right)^3\left(1 + n_h\cdot e^{-\varepsilon_0/kT}\right)J(T)\right]^{NV_s/V}\left[\left(\frac{2\pi mkT}{h^2}\right)^{3/2}(V-V_s)J(T)\right]^{N(V-V_s)/V}\left[\frac{N(V-V_s)}{V}!\right]^{-1} \tag{30}$$

The first set of brackets represents the solid-like portion of the partition function. The remaining portion is the gas-like part. Here, J(T) is again the partition function for the internal degrees of freedom. E_c is the configurational energy and can be written as

$$E_c = \frac{Z}{2}N\varepsilon\left[2.4090\left(\frac{V_s}{N\sigma^3}\right)^{-2} - 1.0109\left(\frac{V_s}{N\sigma^3}\right)^{-4}\right] \tag{31}$$

At the nearest neighbor distance a in the solid state, the interaction energy, Equation (11), attains the least value. Thus we have the following relation:

$$2^{1/6}\sigma = a \tag{32}$$

By applying equation (32) to hexagonal close packing, one obtains

$$V_s = Na^3/\sqrt{2} = N\sigma^3 \tag{33}$$

In Equation (30), Θ is the Einstein characteristic temperature and is given by

$$\Theta = \frac{h\nu}{k} = \frac{h}{k}\cdot\frac{1}{2\pi}\left(\frac{k_r}{m}\right)^{1/2} \tag{34}$$

where k_r is the force constant which can be approximated using the 6–12 potential as

$$k_r^2/2 \approx Z[\Psi(r)-\Psi(a)] \tag{35}$$

Hence,

$$k_r = 2z\varepsilon\sigma^{-2}\left[22.106\left(\frac{N\sigma^3}{V_s}\right)^4 - 10.559\left(\frac{N\sigma}{V_s}\right)^2\right]\left[1.414\left(\frac{V_s}{N\sigma^3}\right)\right]^{-2/3} \tag{36}$$

The n and a' in Equations (9) and (10) are 10.7 and 0.0052 for simple liquids, respectively, and are derived as follows:

[8] *R. H. Wentorf, R. J. Buehler, J. O. Hirschfelder*, and *C. F. Curtiss*, J. chem. Physics *18*, 1484 (1950).

Near the melting point the fraction of the neighboring positions, z, which are available for occupancy is $z(V_m-V_s)/V_m$, where V_m is the volume of the liquid at the melting point. Therefore, we have the following relation:

$$z(V_m-V_s)/V_m = (zV_s/V_m)(V_m-V_s)/V_s = n(V_m-V_s)/V_s \quad (37)$$

Hence for simple liquids, which expand about 12% on melting, one obtains

$$n = zV_s/V_m = 12/1.12 = 10.7 \quad (38)$$

Next, we calculate the proportionality constant a'. The occupancy of a vacancy in a liquid by neighbors to the vacancy is competitive. One molecule can exclude others from a vacancy providing it is at a higher pressure, *i.e.* if it is at a higher density of translational kinetic energy than its neighbors. Now the average translational kinetic energy of a solid molecule is (3/2)kT. If an average molecule divides its time equally between two neighboring positions, this will cut the energy density in two, and effective pressure will be cut in two. Now if a competing neighbor wants to exclude such average competitors from a vacancy and still hold its old position, it needs (3/2)kT to hold the old position and an additional (1/2) (3/2)kT to preempt the vacancy. Since (3/2)k is very near the entropy of melting of rare-gas solids, and since (3/2)kT is very closely equal to the energy of melting E_m/N, we provide the justification for Equation (39):

$$\frac{a'F_cV_s}{V_m-V_s} = \frac{n-1}{z}\frac{1}{2}E_m \simeq \frac{n-1}{z}\frac{1}{2}\frac{V-V_s}{V_m}E_c \quad (39)$$

Here the factor $(n-1)/z$ comes in from the consideration that there are $n-1$ competitors each contributing $(1/z)$th of the energy (1/2) (3/2)kT to the vacancy; in the second equality of Equation (39), it has been assumed that $E_m \simeq E_c(V_m-V_s)/V_m$. Hence,

$$a' = \frac{n-1}{z}\frac{1}{2}\frac{V_m-V_s}{V_m}\frac{V_m-V_s}{V_s} = 0.0052 \quad (40)$$

By substituting Equations (31) through (39) in Equation (30), and applying Stirling's approximation to $[N(V-V_s)/V]!$, we obtain:

$$Z_N = \left[\frac{(2\pi mkT)^{3/2}}{h^3}\frac{eV}{N}J(T)\right]^N \left[\frac{e\,8.388/T^*}{eV^*}\left(\frac{T^*}{35.01}\right)^{3/2}(1+10.7(V^*-1)\exp\frac{-0.0436}{T^*(V^*-1)}\right]^{N/V^*} \quad (41)$$

Pressure, excess entropy, and excess energy for the significant structure theory of liquids are obtained from the above partition functions as:

$$\frac{PV}{NkT} = 1-\frac{8.388}{V^*T^*}+\frac{\ln V^*}{V^*}-\frac{3}{2V^*}\ln\frac{T^*}{35.01}-\frac{1}{V^*}\ln\left[1+10.7(V^*-1)\exp\frac{-0.0436}{T^*(V^*-1)}\right]$$
$$+\frac{10.7}{T^*(V^*-1)}\frac{0.436+T^*(V^*-1)}{10.7(V^*-1)+\exp[0.436/T^*(V^*-1)]} \quad (42)$$

$$\frac{S_E}{Nk} = \frac{1}{V^*}\ln\left[1+10.7(V^*-1)\exp\frac{-0.0436}{T^*(V^*-1)}\right]$$
$$+\frac{(0.4665/T^*V^*)\exp-0.0436/T^*(V^*-1)}{1+10.7(V^*-1)\exp-[0.0436/T^*(V^*-1)]}+\frac{1.5}{V^*}\ln\left(\frac{T^*}{35.01}\right)+\frac{0.5}{V^*}-\frac{\ln V^*}{V^*} \quad (43)$$

$$\frac{E^E}{Ne} = -\frac{8.388}{V^*}+\frac{15T^*}{V^*}+\frac{[0.4665/V^*]\exp-[0.0436/T^*(V^*-1)}{1+10.7(V^*-1)\exp-[0.0436/T^*(V^*-1)]} \quad (44)$$

4. Results

In Figures 1 and 2, we compare the reduced experimental vapor pressure ($P^* = P\sigma^3/\varepsilon$) and volume ($V^*$) for simple liquids such as Ne [9,10], Ar [11], N_2 [9,12], and CH_4 [11,12] with the calculated values from the three theories.

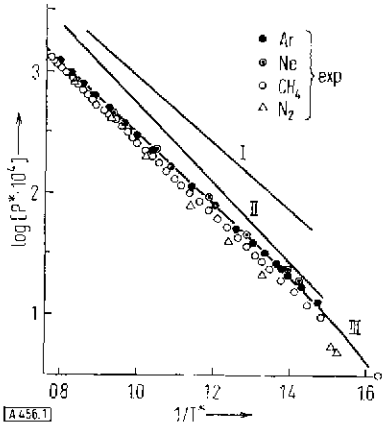

Fig. 1. Logarithm of reduced pressure *versus* the reciprocal of reduced temperature. Curve I, tunnel theory; Curve II, cell theory; Curve III, significant structure theory; points experimental.

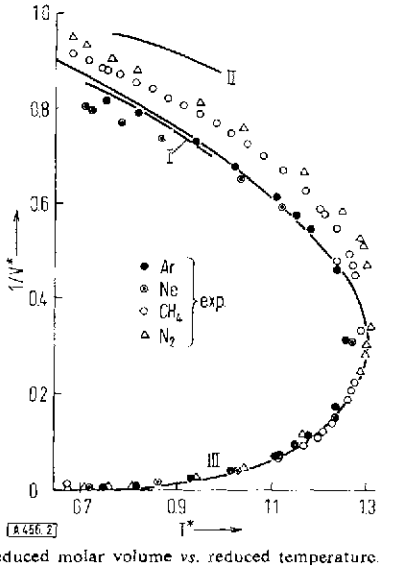

Fig. 2. Reciprocal of reduced molar volume *vs.* reduced temperature. Curve I, tunnel theory; Curve II, cell theory; Curve III, significant structure theory; points experimental.

[9] Handbook of Chemistry and Physics, 41st ed. Chemical Rubber Publishing Co., Cleveland, Ohio, 1959–60.

[10] International Critical Tables. McGraw-Hill, New York 1926.

[11] Thermodynamic Functions of Gases, *F. Din*, ed. Butterworths, London 1961–62.

[12] Landolt-Börnstein, Physikalisch-chemische Tabellen. Springer, Berlin 1923.

One obtains vapor pressure and volume from the cell theory and the tunnel theory as follows: The volume at zero pressure of the liquid phase can be determined by setting P in Equations (17) and (28) equal to zero and solving for V*. In equilibrium between a liquid and its vapor, the Gibbs free energy, F, for the two phases are equal, *i.e.*

$$F_l = F_g \tag{45}$$

where $F_l = A_l + P_l V_l$ and $F_g = A_g + P_l V_g$, and the subscripts l and g indicate the liquid and gas phase, respectively. When the ideal gas law is applicable to the vapor, V_g is expressed by

$$V_g = NkT/P_l \tag{46}$$

With Equations (45) and (46), and the condition $V_g \gg V$ one obtains

$$RT\ln(P_l/kT) = RT\ln\frac{(2\pi mkT)^{3/2}}{h^3} J(T) + A_l \tag{47}$$

The vapor pressure and volume for the significant structure theory of liquids are obtained as follows:

In general, a plot of the Helmholtz free energy against V* by using Equation (1) with Equation (41) yields a curve with two minima for the solid and liquid phases, as shown by the isotherm in Figure 3.

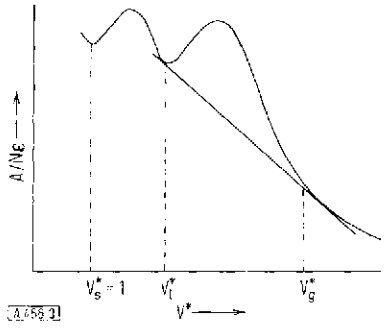

Fig. 3. Reduced Helmholtz free energy *vs.* reduced molar volume (isotherm).

Since the slope gives the pressure, the slope of the common tangent to the curve at the two points corresponding to the liquid and gaseous phases gives the vapor pressure, and the tangential point near the minimum corresponding to the liquid phase yields the liquid volume, while the one at a larger volume indicates the vapor volume. The melting temperature is the temperature at which the slope of the common tangent between the solid and liquid minima is $P^* = \sigma^3/\varepsilon$, *i.e.* P = 1 atmosphere. In Table I, the melting properties for the significant structure theory are compared with experimental data for liquid argon [3a]. The results of the other two theories at $T^* = 0.70$ are also shown. In columns 4 and 5 of Table I, a comparison is made of the calculated reduced excess entropy and excess energy at the melting temperature with the corresponding experimental quantities for liquid argon [3a]. The comparison between the data for the cell theory and for solid argon confirms the fact that the cell theory is a theory of super-heated solids rather than a theory of liquids.

Table 1. Theoretical and experimental properties at the melting point.

	T*	V*	S^E/Nk	$E^E/N\varepsilon$
Significant structure theory	0.711	1.159	−3.89	−6.19
Tunnel theory		1.184	−4.8	−5.9
Liquid argon	0.701	1.178	−3.64	−5.96
Theory of *Lennard-Jones* and *Devonshire*		1.037	−5.51	−7.32
Solid argon	0.701	1.035	−5.53	−7.14

The critical constants are obtained by using the conditions $(\partial P/\partial V)_T = 0$ and $(\partial^2 P/\partial V^2)_T = 0$. In Table II, we compare the critical constants for the three theories and the experimental data for simple liquids [13]. The agreement between experiment and significant structure theory is far better than for the other two theories. The tunnel theory values are in slightly worse agreement with experiment than the cell theory. This is almost certainly due to the approximation of treating the motion in the tunnels as strictly one-dimensional.

Table 2. Experimental and theoretical critical constants.

	T_c^*	P_c^*	V_c^*	$(PV/RT)_c$
Mean values for Ne, Ar, N_2, CH_4	1.277	0.121	3.09	0.292
Significant structure theory	1.306	0.141	3.36	0.362
Tunnel theory	1.07	0.37	1.8	0.6
Theory of *Lennard-Jones* and *Devonshire*	1.30	0.434	1.77	0.591

II. Hard-Sphere Potential

The potential of interaction between hard spheres of diameter d is

$$\Phi(r) = \infty \qquad r < d$$
$$\Phi(r) = 0 \qquad r \geq d \tag{48}$$

This intermolecular potential is of great theoretical interest because it is amenable to comparatively simple calculations, and the results of extensive machine calculations by the Monte Carlo [14] and the molecular dynamics [15] methods for large systems of hard spheres and hard discs are available. As a result, the hard sphere potential is a very useful test case for a theory of liquids. Hence it is interesting to compare the three theories with the machine calculations.

1. Cell Theory

For a system of hard spheres, the free volume is equal to the volume of a sphere of radius a−d. In obtaining this result the smearing approximation has been used. Hence Equation (3) becomes

$$Z_N = \left[\lambda^{-3}\frac{4}{3}\pi(a-d)^3\right]^N \tag{49}$$

[13] *T. L. Hill*: Statistical Mechanics. McGraw-Hill, New York 1956, p. 389.

[14] *W. W. Wood*, *F. R. Parker*, and *J. D. Jacobson*, Nuovo Cimento Suppl. *9*, 133 (1958).

[15] *B. J. Alder* and *T. E. Wainwright*, J. chem. Physics. *27*, 1208 (1957); *31*, 459 (1959); *33*, 1439 (1960); Nuovo Cimento Suppl. *9* 116 (1958).

The resulting equation of state and the equation for the excess entropy are, respectively:

$$\frac{PV}{NkT} = \frac{1}{1-(V_o/V)^{1/3}} \tag{50}$$

and

$$\frac{S^E}{Nk} = \ln\left\{\frac{4\pi/2}{3}\left[1-\left(\frac{V_o}{V}\right)^{1/3}\right]^3\right\} - 1 + \ln\frac{PV}{NkT} \tag{51}$$

where $V_o = Nd^3/\sqrt{2}$ is the molar volume of hexagonal closest packing.

In parallel with a three-dimensional system, the partition function for two-dimensional hard discs is

$$Z_N = \left[\lambda^{-2}\pi(a-\sigma)^2\right]^N \tag{52}$$

Hence the equation of state and excess entropy are given by:

$$\frac{\Pi}{NkT} = \frac{1}{1-(\mathfrak{A}_o/\mathfrak{A})^{1/2}} \tag{53}$$

$$\frac{S^E}{Nk} = \ln\frac{2\pi}{\sqrt{3}}\left[1-\left(\frac{\mathfrak{A}_o}{\mathfrak{A}}\right)^{1/2}\right]^2 - 1 + \ln\left(\frac{\Pi\mathfrak{A}}{NkT}\right) \tag{54}$$

where $\mathfrak{A}$ is the molar area and $\mathfrak{A}_o = (\sqrt{3}/2)\,Nd^2$ is the molar area of closest packing; Π is the surface pressure.

2. Tunnel Theory

When the rigid sphere potential is applied, Equation (5) becomes

$$Z_M = e^M(l-d)^M \tag{55}$$

and a_f in Z_n [cf. Eq. (6)] together with the smearing approximation gives

$$a_f = \pi(a-d)^2 \tag{56}$$

Hence

$$Z_N = \lambda^{-3N}[\pi(a-d)^2(l-d)e]^N \tag{57}$$

Consequently, the equation of state and excess entropy for the tunnel theory are, respectively:

$$\frac{PV}{NkT} = \frac{1}{1-[\sqrt{3/2}\cdot V_o/V]^{1/3}} \tag{58}$$

and

$$\frac{S^E}{Nk} = \ln\left\{\frac{2\pi}{3}\left[1-\left(\sqrt{\frac{3}{2}}\,\frac{V_o}{V}\right)^{1/3}\right]^2\right\} \tag{59}$$

In Equations (58) and (59), the condition

$$a = l = \left(\frac{2}{\sqrt{3}}\,\frac{V}{N}\right)^{1/3} \tag{60}$$

has been introduced. This equality can be derived by maximizing Equation (57) subject to Equation (24).

3. The Significant Structure Theory of Liquids

Henderson [16] used the cell theory partition function rather than the Einstein partition function for Z_s in Equation (8). This is theoretically permissible, because the cell theory is the theory for metastable solids rather than for liquids, as pointed out previously. Then the partition function for hard spheres becomes:

$$Z_N = \left[\lambda^{-3}\frac{eV}{N}\right]^N\left[0.00967\left(8-11\,\frac{V_o}{V}\right)\right]^{(3/2)NV_o/V} \tag{61}$$

In the above equation, $n = 12$ and $V_s = 1.5\,V_o$ have been introduced, and the value of v_f for $V_s = 1.5\,V_o$ has been obtained by an interpolation of the results tabulated by *Buehler et al.* [17]. The relation $V_s = 1.5\,V_o$ has been observed by *Wood* and *Jacobson* [14] and *Alder* and *Wainwright* [15] by means of machine calculations. Consequently, the equation of state is written as

$$\frac{PV}{NkT} = 1 - \frac{3}{2}\left(\frac{V_o}{V}\right)\ln\left\{0.00967\left[8-11\left(\frac{V_o}{V}\right)\right]\right\} + \frac{3}{2}\,\frac{11(V_o/V)^2}{8-11(V_o/V)} \tag{62}$$

and the excess entropy is given by

$$\frac{S^E}{Nk} = \frac{3}{2}\,\frac{V_o}{V}\ln\left[0.00967\left(8-11\,\frac{V_o}{V}\right)\right] - \ln\left\{1-\frac{3V_o}{V}\ln\left[0.00967\left(8-11\,\frac{V_o}{V}\right)\right] + \frac{3}{2}\,\frac{11(V_o/V)^2}{8-11(V_o/V)}\right\} \tag{63}$$

Wang et al. [18] applied the significant structure theory to two-dimensional discs and obtained

$$Z_N = \left[\lambda^{-2}\frac{e\mathfrak{A}}{N}\right]^N\left[0.02358\,(6-5\,\mathfrak{A}_s/\mathfrak{A})\right]^{N\mathfrak{A}_s/\mathfrak{A}} \tag{64}$$

Here, $\mathfrak{A}$ is the molar area of a liquid of hard discs and $\mathfrak{A}_s$ is the corresponding quantity of solid, and the values $a_f = 0.05552a^2$ and $n = 6$ have been introduced. The equations for pressure Π and excess entropy become:

$$\frac{\Pi\mathfrak{A}}{NkT} = 1 - 1.312\,\frac{\mathfrak{A}_o}{\mathfrak{A}}\ln\left[0.02358\left(6-6.56\,\frac{\mathfrak{A}_o}{\mathfrak{A}}\right)\right] + \left(1.312\,\frac{\mathfrak{A}_o}{\mathfrak{A}}\right)^2\left[\frac{5}{6-6.56\mathfrak{A}_o/\mathfrak{A}}\right] \tag{65}$$

and

$$\frac{S^E}{Nk} = \ln\frac{\Pi\mathfrak{A}}{NkT} + 1.312\,\frac{\mathfrak{A}_o}{\mathfrak{A}}\ln\left[0.02358\left(6-6.56\,\frac{\mathfrak{A}_o}{\mathfrak{A}}\right)\right] \tag{66}$$

In Equations (65) and (66), the relation $\mathfrak{A}_s = 1.312\,\mathfrak{A}_o$ obtained by machine calculation [15], has been introduced.

[16] *D. Henderson*, J. chem. Physics *39*, 1857 (1963).

[17] *R. J. Buehler, R. H. Wentorf, J. O. Hirschfelder*, and *C. F. Curtiss*, J. chem. Physics *19*, 61 (1951).

[18] *Y. Wang, T. Ree, T. S. Ree*, and *H. Eyring*, J. chem. Physics *42*, 1926 (1965).

4. Results

The results of molecular dynamics calculations [15] are compared with the three theories in Figure 4 and 5. For the equation of state, both significant structure theory and tunnel theory agree very well with "experiment".

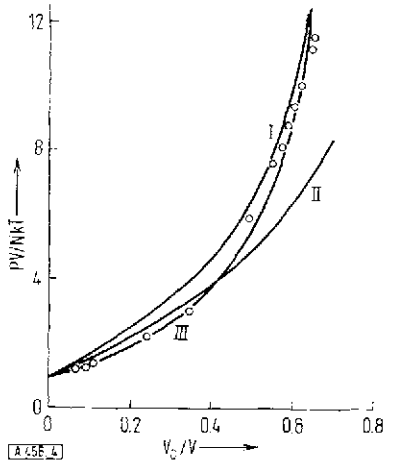

Fig. 4. Compressibility factor *vs.* V_0/V. V and V_0 are the molar liquid volume and the molar volume of closest packing, respectively. Curve I, tunnel theory; Curve II, cell theory; Curve III, significant structure theory; o calculated by the molecular dynamics method.

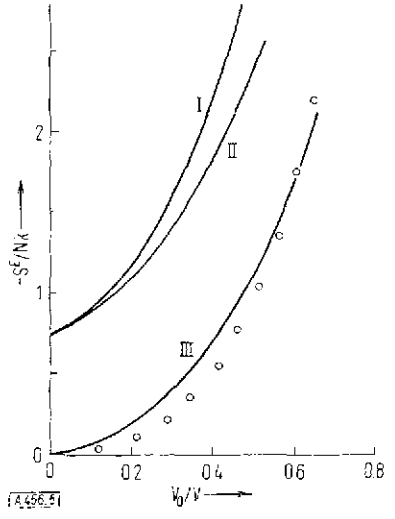

Fig. 5. Excess entropy *vs.* V_0/V. Curve I, tunnel theory; Curve II, cell theory; Curve III, significant structure theory; o calculated by the molecular dynamics method.

For the excess entropy, the tunnel theory agrees with "experiment" slightly less well than the cell theory, while the significant structure theory agrees very well.

In Figures 6 and 7, the theoretical equation of state and the excess entropy for a hard disc system are compared with the results obtained by machine calculations [15].

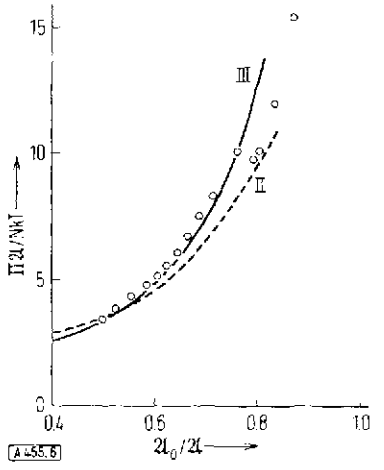

Fig. 6. Compressibility factor of a two-dimensional liquid *vs.* $\mathfrak{A}_0/\mathfrak{A}$. $\mathfrak{A}$ and $\mathfrak{A}_0$ are the molar area of the two-dimensional liquid and the molar area of closest packing, respectively. The data (o) of molecular dynamics calculations at $\mathfrak{A}_0/\mathfrak{A}$ higher than 0.8 correspond to the two-dimensional solid. Curve II, cell theory; Curve III, significant structure theory.

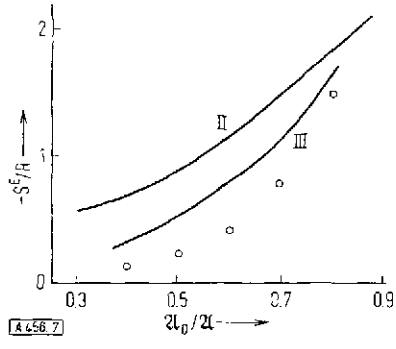

Fig. 7. Excess entropy of two-dimensional liquid versus $\mathfrak{A}_0/\mathfrak{A}$. Curve II, cell theory; Curve III, significant structure theory; o molecular dynamics method.

Here the tunnel theory is omitted because two-dimensional tunnel theory is the same as the cell theory.

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Phosphorescence Spectroscopy as an Analytical Method for Aromatic and Heterocyclic Compounds

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The phosphorescence of aromatic and heterocyclic compounds at low temperatures can be utilized for their identification and determination. The theoretical and experimental basis of phosphorimetry, which represents a valuable addition to the better-known analytical methods, is described, and examples of its application to coal-tar chemistry are discussed.

A. Introduction

Under suitable conditions, numerous aromatic and heterocyclic compounds exhibit a long-lived phosphorescence after irradiation with ultraviolet light. The spectrum, mean lifetime, and quantum yield of this phosphorescence are characteristic properties of the substance.

Analytical application of phosphorescence spectroscopy has so far been directed to the characterization of some biologically important indole derivatives[1], to the determination of small amounts of aspirin in blood[2], to coal-tar chemistry[3], to the direct determination of inhibitors in polymers[4], and to paper chromatography[5]. Experimental aspects of phosphorimetry have been discussed[6,7].

In the present work, the theoretical and experimental basis of phosphorescence, which is surveyed elsewhere[8], is described insofar as it is needed to appraise and plan phosphorimetric methods of analysis.

B. Theoretical and Experimental Principles

Aromatic and heterocyclic compounds are π-electron systems having a singlet ground state and several singlet and triplet excited states. A general principle of the spectroscopy of unsaturated compounds states that only the lowest excitated state of a given multiplicity is capable of emission[9]. The electronic transition from the lowest singlet excited state to the ground state leads to fluorescence, while the analogous transition from the lowest triplet state leads to phosphorescence[10] (low-temperature phosphorescence).

The long lifetime of the phosphorescence, which may amount to several seconds, is explained by the intercombination selection rule for radiative transitions between terms with different multiplicity. This also explains why the triplet state can be occupied by absorption of radiation to only a very small extent; instead, its occupation occurs predominantly by a radiationless transition from the lowest singlet excitation state.

The relationships can be represented by means of the Jablonski term scheme[11] (Fig. 1). When an aromatic or heterocyclic compound is irradiated with light corresponding to the longest-wavelength absorption band, the electronic transition to the lowest singlet excited state S′ (process 1) takes place. From S′, two competing processes occur: return to the ground state

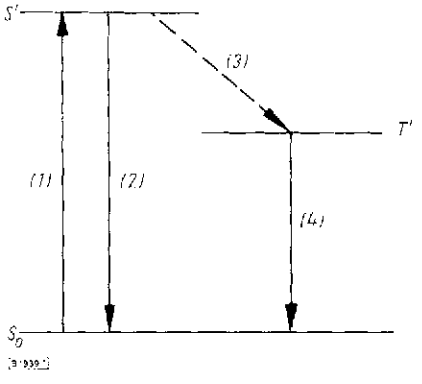


Fig. 1. Jablonski term diagram. (The excitation scheme is somewhat simplified, e.g. by omission of the radiationless transition $S' \rightarrow S_0$). 1. Transition to the lowest singlet excited state S′. 2. Fluorescence emission. 3. Radiationless transition. 4. Spin-forbidden transition (phosphorescence).

with emission of fluorescence (process 2) and radiationless transition to the lowest triplet excitation state T′ (process 3). The spin-forbidden transition T′ → ground state (process 4) leads to emission of phosphorescence. Because of the long lifetime of the triplet state, phosphorescence can usually be observed only under conditions where collisions between molecules and the

[1] *S. Freed* and *W. Salmre*, Science (Washington) *128*, 1341 (1958).

[2] *J. D. Winefordner* and *H. W. Latz*, Analytic. Chem. *35*, 1517 (1963).

[3] *M. Zander*, Erdöl u. Kohle – Erdgas – Petrochemie *15*, 362 (1962).

[4] *H. V. Drushel* and *A. L. Sommers*, Analytic. Chem. *36*, 836 (1964).

[5] *A. Szent-Györgyi*, Science (Washington) *126*, 751 (1957); *M. Zander* and *U. Schimpf*, Angew. Chem. *70*, 503 (1958); *M. P. Gordon* and *D. South*, J. Chromatog. *10*, 513 (1963).

[6] *R. J. Keirs*, *R. D. Britt jr.*, and *W. E. Wentworth*, Analytic. Chem. *29*, 202 (1957).

[7] *S. P. McGlynn*, *B. T. Neely*, and *C. Neely*, Anal. chim. Acta *28*, 472 (1963).

[8] *Th. Förster*: Fluoreszenz organischer Verbindungen. Vandenhoek & Ruprecht, Göttingen 1951, pp. 261 *et seq.*; Naturwiss. *36*, 240 (1949); *M. Kasha*, Chem. Rev. *41*, 401 (1947).

[9] *M. Kasha*, Disc. Faraday Soc. *1950*, 14.

[10] *G. N. Lewis* and *M. Kasha*, J. Amer. chem. Soc. *66*, 2100 (1944).

[11] *A. Jablonski*, Nature (London) *131*, 839 (1933); Z. Physik *94*, 38 (1935).

associated radiationless deactivation can be substantially eliminated. The most general method is the measurement of phosphorescence spectra in solid solutions at low temperatures. Particularly organic solvents or solvent mixtures which set to a glass at the temperature of liquid nitrogen are used. Only very short-lived phosphorescences have been observed in liquids at room temperature [12].

Many unsaturated compounds exhibit a "delayed" fluorescence under various experimental conditions, in addition to phosphorescence [13]. A special case of delayed fluorescence is the "high-temperature phosphorescence" of organic dyes [8], particularly of the triphenylmethane series. Among aromatic hydrocarbons this phenomenon has so far been observed only with coronene [14]. Delayed fluorescence is unlikely to find important analytical applications [*].

The mean decay period of phosphorescence (= mean lifetime of the triplet state) in aromatic and heterocyclic compounds is of the order of 10^{-3} to several seconds. Because of this longevity, phosphorescence spectra can be measured with a mechanical phosphoroscope, *e.g.* of the Becquerel type, in which exciting radiation and fluorescence are eliminated. The phosphorescence decay process in a solid solution is of the first order. Since the mean decay time at constant temperature in a given solvent is characteristic of the material, *i.e.* independent of concentration [15], it can be used to identify phosphorescent compounds, together with the spectra themselves. Examples are given below. – Table 1 lists the lifetime of the phosphorescence of various compounds. A marked decrease in the lifetime is observed [16] in the series naphthalene, fluoro-, chloro-, bromo-, and iodonaphthalene, *i.e.* with increasing atomic number of the substituent.

In addition to its spectrum and lifetime, the phosphorescence of a particular compound is characterized by the quantum yield. This value varies widely for different compounds (Table 2). A decrease both in the quantum yield and in the lifetime is found with a shift towards longer wavelengths of the phosphorescence spectrum of aromatic hydrocarbons. Phosphorescence spectra in the blue or green regions are generally very intense; in the red or near infrared they are as a rule extremely

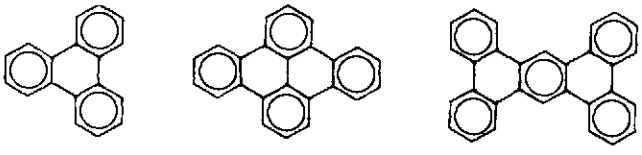
Table 1. Mean phosphorescence lifetimes [sec] of various compounds.

Compound	Lifetime and reference
Benzene	7.0 [16]; 8.0 [12b]
Naphthalene	2.4 [16a]; 2.5 [16b, 30c]; 2.6 [16]; 2.8 [12b]; 2.9 [16c]
Anthracene	0.09 [33]
Phenanthrene	3.0 [30c]; 3.3 [16, 16b]; 3.4 [16c]; 3.6 [16a]; 4.3 [12b]
Chrysene	2.3 [16c]; 2.5 [16]; 2.6 [16b]
Triphenylene	15.9 [16]
Pyrene	0.2 [16]; 0.3 [16c]; 0.7 [16b]
Coronene	9.0 [16c]; 9.3 [16a]; 9.4 [16]
1-Fluoronaphthalene	1.5 [16]
1-Chloronaphthalene	0.3 [16]
1-Bromonaphthalene	0.018 [16]
1-Iodonaphthalene	0.0025 [16]
Phenol	2.6 [12b]; 2.9 [16]
Aniline	4.7 [16]
Benzoic acid	2.0 [12b]; 2.5 [16]
2-Naphthol	1.3 [16]; 1.4 [16d]
2-Naphthoic acid	2.5 [16]
4-Phenanthrol	2.1 [16d]
Indole	4.8 [16d]; 5.0 [28]
Benzo[*b*]naphtho-[1,2-*d*]furan	4.0 [16d]

Table 2. Phosphorescence quantum yields of various compounds [16e].

Compound	Quantum yield
Benzene	0.17
Naphthalene	0.06
Triphenylene	0.37
Chlorobenzene	0.04
Acetophenone	0.43
Benzophenone	0.52

weak and frequently cannot be measured with conventional techniques. In addition to these general relationships, constitutional factors play a part. Among polycyclic aromatic hydrocarbons, compounds which like triphenylene *(1)*, 4,5;9,10-dibenzopyrene *(2)*, 1,2;3,4;5,6;7,8-tetrabenzanthracene *(3)*, *etc.* can be regarded as "fused polyphenylenes" [17], exhibit particularly intense phosphorescence with long lifetimes.



(1) *(2)* *(3)*

The phosphorescence spectrum of a compound occurs at longer wavelengths than its fluorescence spectrum, and in many cases in the visible region, which is particularly accessible experimentally. Its relationship to

[12] *C. A. Parker* and *C. G. Hatchard*, a) Trans. Faraday Soc. *57*, 1894 (1961); b) Analyst *87*, 664 (1962).

[13] *R. Williams*, J. chem. Physics *28*, 577 (1958); *H. Sponer*, *Y. Kanda*, and *L. A. Blackwell*, *ibid.* *29*, 721 (1958); *N. W. Blake* and *D. S. McClure*, *ibid.* *29*, 722 (1958); *B. Stevens* and *E. Hutton*, Nature (London) *186*, 1045 (1960); *E. C. Lim* and *G. W. Swenson*, J. chem. Physics *36*, 118 (1962); *J. Kern*, *F. Dörr*, and *G. Scheibe*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *66*, 462 (1962); *T. Azumi* and *S. P. McGlynn*, J. chem. Physics *38*, 2773 (1963); *M. Zander*, Naturwiss. *50*, 327 (1963); Z. Elektrochem., Ber. Bunsenges. physik. Chem. *68*, 301 (1964).

[14] *M. Zander*, Naturwiss. *47*, 443 (1960).

[*] Note added in proof: Recently *C. A. Parker*, *C. G. Hatchard*, and *T. A. Joyce*, Analyst *90*, 1 (1965), reported a useful application of sensitized delayed fluorescence.

[15] The author's unpublished measurements of the mean phosphorescence decay time of phenol, phenanthrene, and triphenylene in EPA (77 °K), at concentrations between 10^{-2}–10^{-6} mole/l, indicated no appreciable variation with concentration; see also *G. N. Lewis*, *D. Lipkin*, and *T. T. Magel*, J. Amer. chem. Soc. *63*, 3005 (1941).

[16] *D. S. McClure*, J. chem. Physics *17*, 905 (1949).

[16a] *J. Czekalla* and *K. J. Mager*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *66*, 65 (1962).

[16b] Determined from the decay of triplet-triplet absorptions: *D. P. Craig* and *J. G. Ross*, J. chem. Soc. (London) *1954*, 1589.

[16c] *A. Martinez*, C. R. hebd. Séances Acad. France *255*, 491 (1962).

[16d] *M. Zander*, unpublished data.

[16e] *E. H. Gilmore*, *G. E. Gibson*, and *D. S. McClure*, J. Chem. Physics *20*, 829 (1952).

[17] *E. Clar* and *M. Zander*, J. chem. Soc. (London) *1958*, 1861; cf. also *E. Clar*: Polycyclic Hydrocarbons. Academic Press (London-New York) and Springer-Verlag (Berlin-Göttingen-Heidelberg) 1964, Vol. 1, p. 37 *et seq.*; *M. Zander*, Angew. Chem. *72*, 513 (1960).

the ultraviolet spectrum has been thoroughly investigated, especially for fused polycyclic aromatic hydrocarbons. A red-shift of the ultraviolet absorption is accompanied by a displacement of the phosphorescence spectrum towards longer wavelengths. Since the lowest triplet state has the classification ^{3}La, *i.e.* is coupled with the para-band [*], the positions of the para-absorption and the phosphorescence transition are related. For hydrocarbons with more than five fused benzene nuclei, the difference of the 0, 0 bands [cm^{-1}] of para-absorption and phosphorescence spectrum is constant to a close approximation (10000–11000 cm^{-1}). With hydrocarbons containing less than 5 nuclei the positional difference is found to vary with the size of the molecule [19]. Fig. 2 shows this difference plotted

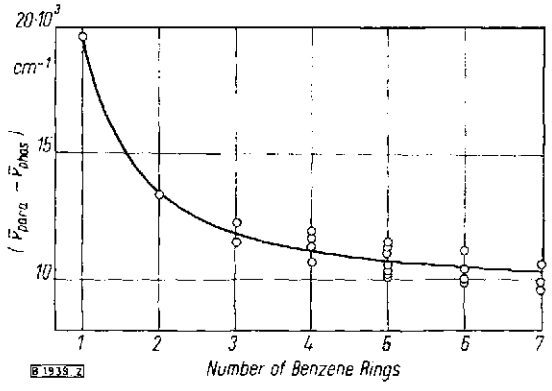


Fig. 2. Relationship between the wavenumber difference of 0,0-bands of the para-absorption and phosphorescence spectrum of aromatic hydrocarbons and the number of fused benzene rings.

against the number of the benzene rings in the hydrocarbons. It is therefore possible to predict the position of the phosphorescence spectrum of an aromatic hydrocarbon from its ultraviolet spectrum with fair accuracy.

Typical phosphorescence spectra (phenanthrene and carbazole) are shown in Fig. 3. In general, the spectra exhibit a symmetry-allowed structure with a strong 0,0-band. Only in a few cases (*e.g.* benzene [20]) is there a symmetry prohibition in addition to the spin prohibition. Position and vibrational structure of the phosphorescence spectra of aromatic hydrocarbons depend only little on the solvent [21].

Phosphorimetric analysis demands a knowledge of the spectra, decay times, and quantum yields of the phosphorescent emissions of the relevant compounds. Complete phosphorescence spectra of polycyclic aromatic hydrocarbons and data concerning the positions of the phosphorescence maxima are given in several publi-

[*] For a classification of the electronic transitions of aromatic hydrocarbons see [18].

[18] *E. Clar*: Polycyclic Hydrocarbons. Academic Press (London-New York) and Springer-Verlag (Berlin-Göttingen-Heidelberg) 1964, Vol. 1, pp. 50 and 87; *A. Streitwieser, jr.*: Molecular Orbital Theory for Organic Chemists. John Wiley & Sons Inc., New York-London 1961, p. 215.

[19] *M. Zander*, unpublished work.

[20] *H. J. Shull*, J. chem. Physics *17*, 295 (1949).

[21] *R. V. Naumann*, Dissertation, University of California, Berkeley 1947.

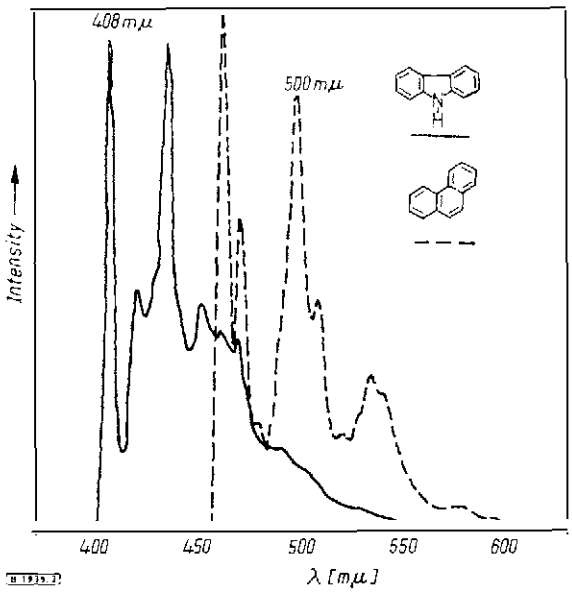


Fig. 3. Phosphorescence spectra (in EPA, 77°K) of carbazole (· · ·) and phenanthrene (- · - · -).

cations [10, 16, 22]. Quantum yields and lifetimes have been measured by various authors (see Tables 1 and 2). The phosphorescence spectra of numerous derivatives of aromatic hydrocarbons are known: methyl homologues [23], halogen compounds [10, 24], phenols [10], nitro compounds [10, 25], amino compounds [10, 25], carboxylic acids [10], *etc.* Among the heterocycles, the phosphorescence spectra particularly of aza-hydrocarbons [26] and of carbazoles [27] have been investigated in some detail; data on sulfur and oxygen heterocycles are also available [28]. Aromatic amino-acids are examples of phosphorescent, biologically important compounds [29].

C. Experimental Details

I. Instrumental

Devices for the measurement of phosphorescence spectra consist of an excitation light source, a low-temperature cell, a phosphoroscope, and a spectrograph or spectrometer. Several constructions have been described [6, 10, 12, 24, 30]. In order to obtain particularly

[22] *E. Clar* and *M. Zander*, Chem. Ber. *89*, 749 (1956).

[23] *M. M. Moodie* and *C. Reid*, J. chem. Physics *22*, 252 (1954).

[24] *J. Ferguson, T. Iredale*, and *J. A. Taylor*, J. chem. Soc. (London) *1954*, 3160.

[25] *R. Foster, D. L. Hammick, G. M. Hoode*, and *A. C. E. Sande*, J. chem. Soc. (London) *1956*, 4865.

[26] *Y. Kanda* and *R. Shimada*, Spectrochimica Acta *1959*, 211; *F. Dörr* and *H. Gropper*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *67*, 193 (1963); *F. Dörr, H. Gropper*, and *N. Mika*, *ibid. 67*, 202 (1963).

[27] *M. Zander*, Chem. Ber. *97*, 2695 (1964).

[28] *R. C. Heckman*, J. Molecular Spectroscopy *2*, 27 (1958).

[29] *P. Debye* and *J. D. Edwards*, Science (Washington) *116*, 143 (1952).

[30] a) *B. Muel* and *M. Hubert-Habart*, J. Chimie Physique *1958*, 377; b) *J. Czekalla, G. Briegleb, W. Herre*, and *R. Glier*, Z. Elektrochem. Ber. Bunsenges. physik. Chem. *61*, 537 (1957); c) *J. Czekalla, G. Briegleb, W. Herre*, and *H. J. Vahlsensiek*, *ibid. 63*, 715 (1959).

well-resolved spectra, or for the measurement of extremely weak phosphorescences, spectrographs are the most suitable devices. For routine phosphorimetric analysis, *e.g.* in a control laboratory, recording spectrometers are the recommended instruments. We used an instrument of the latter type, *viz.* an Aminco-Keirs Spectrophosphorimeter [*]. Its construction is shown schematically in Fig. 4.

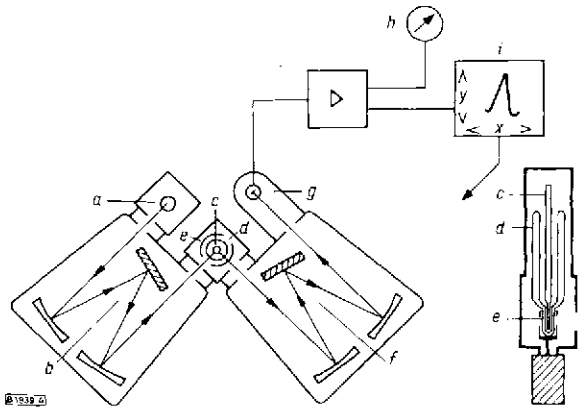


Fig. 4. Schematic view of the Aminco-Keirs spectrophosphorimeter. Right: side-view of the sample cell arrangement.

a = xenon lamp, *b* = grating monochromator (200—800 mμ), *c* = quartz sample cell, *d* = quartz Dewar vessel, *e* = phosphoroscope (eliminates scattered light and fluorescence), *f* = grating monochromator (200—800 mμ), *g* = photomultiplier, *h* = galvanometer, *i* = recorder.

The resulting curves can be evaluated with the aid of calibration measurements on fluorescence standards or light sources of known energy distribution in the form of energy spectra (quantum spectra) [31]. In general, however, this is not necessary for analytical purposes.

Frequently, the knowledge of the phosphorescence lifetime τ of a compound is useful. Phosphorescence lifetimes can be readily determined with the Aminco-Keirs instrument or similar arrangements. For this purpose, the phosphorescence excitation is interrupted, and the change in the intensity of a suitable band of the phosphorescence spectrum is directly recorded as a function of time. An exponential fall in intensity is obtained. To determine τ, the logarithm of the intensity is plotted against time. The slope of the resulting straight line is $2.303\,\tau$.

The two-coordinate recorder fitted with a time base, supplied with the instrument, can measure lifetimes down to about 0.5 sec. For more rapidly decaying phosphorescences, an oscillograph must be employed. The screen picture is conveniently photographed with a Polaroid camera. The reproducibility of the determination of τ (using the two-coordinate recorder) is about 5 %, as found by us in numerous measurements.

[*] Developed by *R. J. Keirs* and manufactured by American Instrument Co. Inc., Silver Spring, Md., U.S.A.

[31] *E. Lippert, W. Nägele, J. Seibold-Blankenstein, U. Staiger,* and *W. Voss,* Z. analyt. Chem. *170,* 1 (1959); *O. Dann* and *P. Nickel,* Liebigs Ann. Chem. *667,* 101 (1963).

[32] *H. Sternlicht, G. C. Niemann,* and *G. W. Robinson,* J. chem. Physics *38,* 1326 (1963).

[33] *S. P. McGlynn, M. R. Padhye,* and *M. Kasha,* J. chem. Physics *23,* 593 (1955).

[34] *H. D. Sauerland,* Brennstoffchemie *45,* 55 (1964).

[35] *H. G. Franck,* Angew. Chem. *63,* 260 (1951).

II. Solvents

For phosphorescence spectroscopy, solvents or solvent mixtures are required which at low temperature (liquid nitrogen or liquid air) set to a glass, *i.e.* do not crystallize or fracture. Clearly, the solvents used should have no marked intrinsic phosphorescence. The mixture

Table 3. Solvents for phosphorescence spectroscopy [36].

Components	Volume ratio
EPA/chloroform	12:1
Triethylamine/ether/n-pentane	2:5:5
n-Pentane/n-heptane	1:1
Methylcyclohexane/n-pentane	4:1 or 3:2
Di-n-propyl ether/isopentane [30c]	3:1

ethanol/isopentane/ether (2:5:5 by volume) (EPA) [10] is most frequently used. This solvent was employed for all measurements in this work. Other solvent mixtures which are potentially useful for phosphorescence spectra are shown in Table 3. Liquid nitrogen (−196 °C) was used as the coolant in all measurements.

III. Identification of Compounds and Determination of Purity

The phosphorescence spectrum and the mean decay time of the phosphorescence are unique for a given substance, and can therefore be used for identification purposes, similarly to ultraviolet or fluorescence spectra. Identification of individual phosphorescent substances in mixtures is frequently successful provided the phosphorescence spectra are sufficiently different. The choice of exciting wavelength is simplified by the fact that phosphorescence intensity increases with the intensity of absorption at the exciting wavelength. When a mixture is irradiated with a wavelength at which one of the components absorbs appreciably more strongly than the others, predominantly the phosphorescence spectrum of this substance will be obtained. Excitation of phosphorescence of the mixture successively with several wavelengths thus makes it possible to obtain the spectra of the individual components more or less free from interference, provided the ultraviolet spectra of the components present show adequate differences. Recognition of individual components in mixtures is made easier by the fact that the phosphorescence quantum yields of the substances present are generally unequal. For the identification of individual components the lifetimes can be utilized in addition to the spectra, as will be shown later.

To test the purity of a phosphorescent substance, its observed spectrum is compared with its known spectrum in the pure state. This spectrum must be independent of the exciting wavelengths. A frequently useful criterion of purity is the mean decay time. A pure substance alone will show a straight-line plot of log intensity against time. With mixtures, a curved plot is obtained

[36] *J. D. Winefordner* and *P. A. St. John,* Analytic. Chem. *35,* 2211 (1963).

since several decay processes with different rates are superimposed.

Often the impurities in a substance exhibit intense phosphorescence while the substance itself does not phosphoresce or exhibits intensities too low to be measured. In aromatic hydrocarbons it is generally just these impurities which cannot be recognized in the ultraviolet spectrum, because of the superposition of the main component. In this respect, ultraviolet and phosphorescence spectroscopy form excellent complementary methods of testing for purity. Limits of detection of strongly phosphorescent substances are roughly of the same order of magnitude as for strongly fluorescent compounds. Examples are given in Table 4. The values were obtained with the Aminco-Keirs Spectrophosphorimeter at a spectral resolution adequate for the quantitative determination of the compounds. The limits of detection were set largely by the intrinsic phosphorescence of the solvent (EPA, American Instr. Corp.) and the noise in the instrument.

Table 4. Limits of detection by phosphorimetric analysis.

Compound	Excitation wavelength [mμ]	Key band [mμ]	Limit of detection [g/ml]
Phenanthrene	290	500	10^{-8}
Triphenylene	258	463	10^{-9}
1,2-Benzopyrene	332	540	10^{-7}
Carbazole	290	408	10^{-8}
Benzil	285	505	10^{-7}

An interesting method of testing the purity of aromatic and heterocyclic compounds is provided by solid-state spectroscopy. On the basis of theoretical work [32] it can be assumed that unsaturated organic compounds – apart from a few exceptions such as benzophenone – will show no phosphorescence in the crystalline state (even at very low temperatures) when absolutely pure.

It seems therefore that phosphorescence observed in crystalline aromatic and heterocyclic compounds is usually due to impurities. The limits of detection of phosphorescent impurities are extremely low, and the absence of crystal phosphorescence may in many cases well be the most sensitive criterion of purity known today.

IV. Quantitative Determination of Compounds

The basic equations of fluorimetry can be applied to phosphorescence spectroscopy without modification. Phosphorescence intensity P and concentration c are related by the equation [6]:

$$P = \text{const}\ (2.30\ \varepsilon cd - 2.65\ \varepsilon^2 c^2 d^2 + 2.04\ \varepsilon^3 c^3 d^3 - \ldots)$$

where ε is the extinction coefficient of the compound, and d the thickness of the cell. For extinctions $E < 0.01$ ($E = \varepsilon cd$) the higher terms of the series can be neglected, and one obtains:

$$P' = \text{const}' \cdot c \qquad (\text{const}' = \text{const} \cdot 2.30\ \varepsilon d)$$

In sufficiently dilute solutions there is therefore a linear relation between phosphorescence intensity and concentration.

For aromatic hydrocarbons, with irradiation in the relatively low-intensity α-bands ($\varepsilon = 10^2 - 10^3$ l mole^{-1} cm^{-1}) and using the cells of the Amino-Keirs spectrophosphorimeter (d about 0.1 cm) the straight-line region is obtained with dilutions of $c < 10^{-3}$ mole/l. With irradiation in the more intense para and β-bands ($\varepsilon = 10^4 - 10^5$), higher dilutions are necessary ($< 10^{-5}$ mole/l).

The phosphorescence intensity of a solution under otherwise identical conditions depends on the excitation intensity as well as on the concentration of the dissolved, phosphorescent substance. In solutions of a pure substance A, the exciting radiation is absorbed only by this material. When other absorbing substances B, C, D, *etc.*, are present, absorbing part of the exciting radiation, the full intensity is no longer available for the excitation of A. For the same concentration of A, the phosphorescence of A in the presence of B, C, D, *etc.* is therefore less than in a solution of the pure material. This effect is more marked the smaller the ratio of the extinction of A to those of B, C, D, *etc.* at the exciting wavelength, and the higher the concentrations.

For a phosphorimetric analysis, it is initially necessary to construct a phosphorescence intensity *vs.* concentration calibration curve with solutions of known concentrations of the component to be determined. For this purpose, both the key band and the exciting wavelength must be matched to the relevant problem. Where the compounds present in addition to the component to be analysed are known, and where they are available in pure form, they can be added in known amounts during the construction of the calibration curve to eliminate the above effect of a partial absorption of the exciting radiation. This is no longer possible for multicomponent mixtures or where the qualitative composition of the samples is not completely established. In such cases it is necessary to work with dilute samples, in which the above effect is negligible. After calibration, the phosphorescence intensity of the key band in the sample is determined under identical conditions and the relevant concentration is read from the calibration curve. Two examples of such analyses are described below.

The mean relative error of phosphorimetric analyses with present techniques is 5–10 %. This is adequate for many applications, *e.g.* for the determination of impurities in a relatively pure product. Of the possible factors which can affect the reproducibility of determination with the Aminco-Keirs Spectrophosphorimeter, we have found that fluctuations in the lamp brightness, noise in the recording section, and deviations in the adjustment of wavelength have only a slight effect. The greatest error is introduced by non-reproducible changes in the position of the sample cell from one experiment to the next. An improvement in the sample tube holder, which we are attempting, should provide a remedy. The sensitivity of phosphorimetric analyses to such influences is smaller the higher the measured intensities.

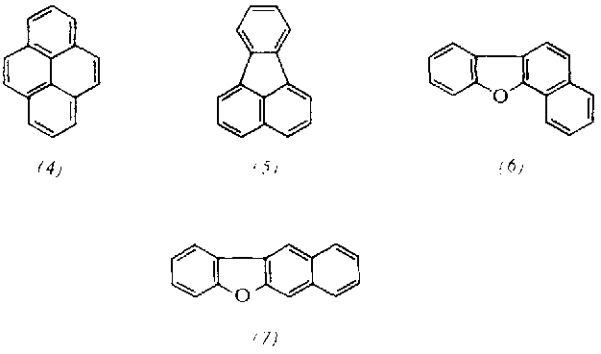
The few results of phosphorimetric analyses so far available already predict a wide field of application for this method. In connection with the present work, special experience in the phosphorimetry of polynuclear aromatic hydrocarbons has been gathered. For this reason, the question of establishing in which cases the phosphorimetric method of analysis can be successfully employed, and where it offers advantages over other methods, will be discussed specially for this class of compounds. In general, weakly fluorescent compounds exhibit strong phosphorescence, and *vice versa*. Therefore weakly fluorescing aromatic compounds such as triphenylene can be determined by phosphorimetry with greater accuracy and with lower limits of detection than by

fluorimetry. In most cases the phosphorescence spectrum of an aromatic hydrocarbon is much more characteristic than its fluorescence spectrum and therefore more suitable for the identification of the compound.

In analyses of mixtures of polynuclear aromatic hydrocarbons, the ultraviolet spectrum is particularly suitable for the identification and determination of the longest-wavelength absorbing components. Thus, for example, very small quantities of anthracene can be determined in phenanthrene. In the short-wavelength region, the ultraviolet spectra of all the substances present in the mixture overlap substantially, and unambiguous identification and quantitative determination of hydrocarbons absorbing at low wavelengths is seldom possible in complex mixtures. Since these hydrocarbons are often strongly phosphorescent, phosphorimetry is particularly suitable for the identification and determination of these components in mixtures. For example, as little as about 50 ppm of phenanthrene can be determined in anthracene, while the ultraviolet-spectroscopic determination encounters difficulties at appreciably higher concentrations. To summarize, it is found that ultraviolet, fluorescence, and phosphorescence spectroscopy are excellent complementary techniques for the analysis of aromatic hydrocarbons. According to the particular problem involved, one or another of the methods is particularly suitable, and offers appreciable advantages over the others.

impurities, the conditions for study by phosphorescence spectroscopy were particularly favorable.

In the ultraviolet spectrum, a single redundant band was found at 288 mμ in addition to those of pyrene.



(4) *(5)* *(6)* *(7)*

This was possibly due to fluoranthene *(5)*. The measurement of phosphorescence on irradiation into a strong absorption band of fluoranthene (360 mμ) gave the almost undisturbed phosphorescence spectrum of this compound. Fig. 5 shows the impurity spectrum (curve 1) next to that of pure fluoranthene (curve 2). As a check, the phosphorescence lifetimes of the pyrene-accompanying substance and of pure fluoranthene were measured (using the 545 mμ band). They agreed (0.8 and 0.9 sec respectively) within the experimental error. Measurement of the phosphorescence of technical

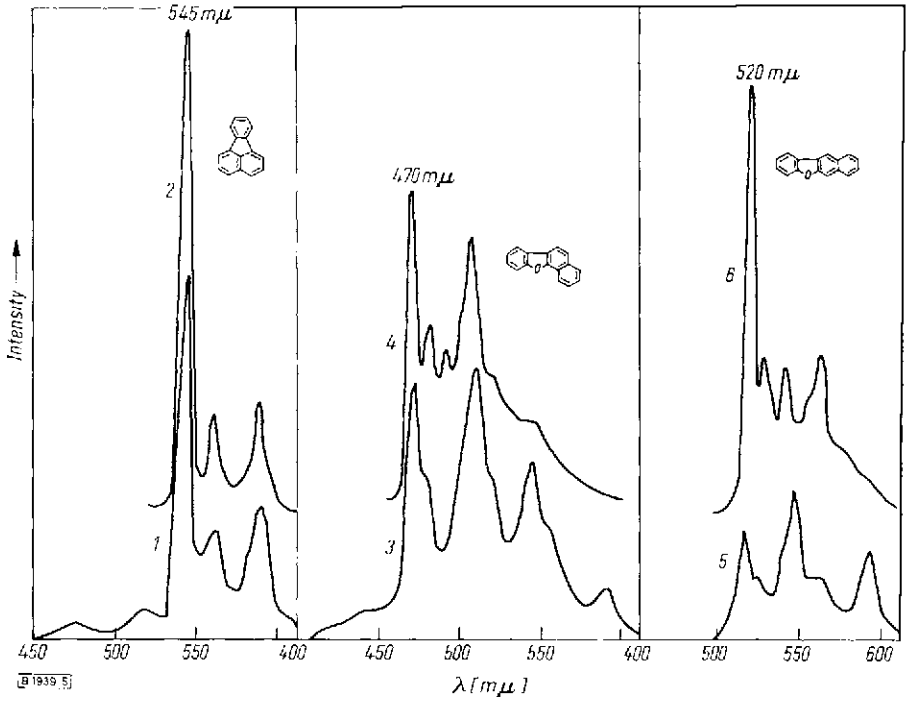


Fig. 5. Phosphorescence spectra (in EPA, 77°K) of technical pyrene on excitation with 360 mμ (curve 1), 290 mμ (curve 3) and 340 mμ (curve 5) radiation and of pure fluoranthene (curve 2), benzo[*b*]naphtho-[1,2-*d*]furan (curve 4) and benzo[*b*]naphtho[2,3-d]furan (curve 6).

D. Some Analytical Applications in Coal-Tar Chemistry

I. Identification of Impurities in Technical Pyrene

Technical (about 95%) pyrene *(4)* was investigated by ultraviolet and phosphorescence spectroscopy to determine the nature of the impurities. Since pyrene itself is appreciably less intensely phosphorescent than its pyrene on irradiation at 290 mμ gave spectrum 3, which belongs to a further impurity. Comparison with the phosphorescence spectra of several tar constituents in the pyrene boiling-point range makes it very likely that this impurity is benzo[*b*]naphtho[1,2-*d*]furan *(6)* (phosphorescence spectrum 4 in Fig. 5). For confirmation, the

lifetimes of both pure *(6)* and of the pyrene impurity were again measured, and agreed within experimental error (3.9 and 4.0 sec respectively). Finally, excitation of the phosphorescence of technical pyrene with 340 mμ radiation gave a third impurity spectrum (curve 5). Since the long-wavelength part of the spectrum is overlapped by that of fluoranthene, only the first two bands could be utilized for identification purposes. It seems probable that this impurity is benzo[*b*]naphtho-[2,3-*d*]furan (β-brazan) *(7)*. The spectrum of the pure substance *(7)* (curve 6) is reproduced for comparison.

To summarize, study of the phosphorescence spectra of technical pyrene *(4)* unambiguously revealed two impurities [fluoranthene *(5)*, benzo[*b*]naphto[1,2-*d*]-furan *(6)*] and very probably a third substance, benzo-[*b*]naphto[2,3-*d*]furan *(7)*. In contrast, ultraviolet investigation gave only a weak indication of a single impurity (fluoranthene).

II. Quantitative Determination of Impurities in Purified Anthracene

Anthracene obtained from coal tar (purity > 97 %) contains carbazole and phenanthrene as principal impurities. Since the ultraviolet spectrum of the main constituent overlaps the spectra of carbazole and phenanthrene over the entire spectral region, their determination by this method is very difficult. In contrast, carbazole and phenanthrene exhibit intense phosphorescence in the blue and green spectral regions, respectively, whereas anthracene phosphoresces very weakly in the red (680 mμ) [10, 33]. Conditions for the phosphorimetric determination of these impurities in pure anthracene are therefore ideal.

The phosphorescence spectra of carbazole and phenanthrene are shown in Fig. 3. The shortest-wavelength carbazole phosphorescence band at 408 mμ is a suitable key band, while for phenanthrene the one at 500 mμ, which is only little overlapped by the carbazole spectrum, can be used. Trial analyses show that, with the proportions encountered in anthracene, no allowance need be made for the carbazole phosphorescence at 500 mμ.

The spectra in Fig. 3 were measured with small slit widths and correspondingly high resolution. For the determination of small concentrations of carbazole and phenanthrene, a lower resolution is acceptable for the sake of increased sensitivity. The following selection of slit widths has proved suitable when the Aminco-Keirs instrument is used for quantitative analysis (see Fig. 4): exit slit of the excitation monochromator *b*: 3 mm; entrance and exit slits of the phosphoroscope housing: 3 and 2 mm, respectively; entrance and exit slits of the emission monochromator *f*: 3 and 2 mm, respectively.

The excitation wavelength for the carbazole and phenanthrene determination is 290 mμ. At this wavelength the extinction coefficients of carbazole and phenanthrene are greater than that of anthracene by a factor of about 40. The concentration of anthracene in the samples is about 50–100 times greater than that of the impurities, so that the extinctions of the three components are of comparable magnitude. Consequently an appreciable part of the exciting radiation is absorbed by the anthracene. It is therefore necessary for the calibration solutions used to contain anthracene as well as carbazole and phenanthrene, in concentrations which approximately match the actual conditions.

To carry out the analysis, calibration solutions containing 0.1–2 % each of phenanthrene and carbazole in EPA are initially prepared from 0.002 M stock solutions. The relative phosphorescence intensities of the key band are then measured, suitably by excitation with 290 mμ radiation. These intensities may then be plotted against concentration (directly as % of the weight taken) to give the calibration curve. Fig. 6 shows such calibration curves for the range 0.1–2 % phenanthrene or carbazole in anthracene. This is followed by a measurement of the relative intensities of the key bands of a

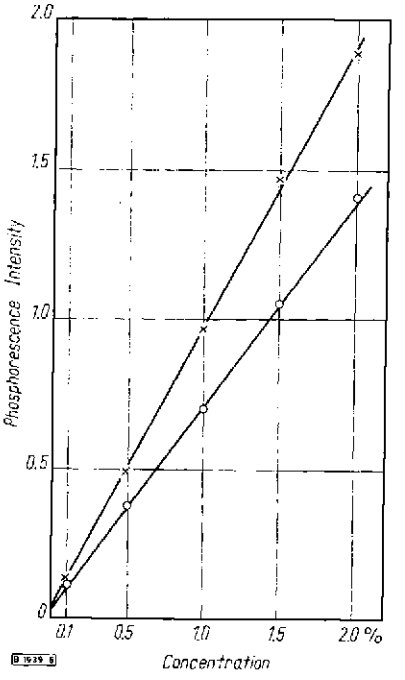


Fig. 6. Phosphorescence calibration curves for the determination of carbazole (×) and phenanthrene (○) in pure anthracene.

likewise 0.002 M solution in EPA of the material to be investigated and the reading-off of the corresponding percentage concentrations of phenanthrene and carbazole.

In highly purified coal-tar anthracene, the impurities amount to less than 0.1 %. As little as about 0.005 % of carbazole and of phenanthrene can be determined by the above procedure. Calibration curves for the range 0.1–0.005 % must be constructed. The required solutions are suitably prepared from 0.002 M anthracene and 2×10^{-5} M carbazole and phenanthrene. Obviously, the carbazole and phenanthrene contents of the anthracene used for the calibration curve must lie below the limit of detection.

Table 5 shows the results of a series of test analyses. The mixtures investigated were prepared from very pure anthracene, carbazole, and phenanthrene, and the anthracene content of the solutions was adjusted to between 99.6 and 96 %. To test the reproducibility of the method, several anthracene samples were each analysed six times for their carbazole and phenanthrene contents. The results are shown in Table 6.

As expected, the mean relative error of the method depends on the concentrations measured. At 0.1 % carbazole or phenanthrene it is about 10 %; at 0.005 % carbazole or phenanthrene it amounts to about 50 %. The procedure is superior to chemical methods of

Table 5. Phosphorimetric determination of carbazole and phenanthrene in the presence of anthracene.

Anthracene	Carbazole		Phenanthrene	
present [%]	present [%]	found [%]	present [%]	found [%]
99.60	0.20	0.23	0.20	0.23
99.00	0.50	0.56	0.50	0.53
99.00	1.00	0.90	—	—
99.00	—	—	1.00	1.13
98.80	1.00	0.93	0.20	0.25
98.50	1.00	1.05	0.50	0.67
98.50	0.50	0.45	1.00	0.90
98.00	1.00	1.00	1.00	0.93
97.50	2.00	2.10	0.50	0.57
97.00	1.00	1.05	2.00	2.00
96.50	0.50	0.47	3.00	2.83
96.00	3.00	2.95	1.00	1.17

Table 6. Phosphorimetric determination of carbazole and phenanthrene in the presence of anthracene. Δ = Deviation from the mean.

	% Carbazole found	$\lvert\Delta\rvert$	% Phenanthrene found	$\lvert\Delta\rvert$
Sample 1				
	0.59	0.00	0.90	0.02
	0.59	0.00	0.90	0.02
	0.56	0.03	0.86	0.02
	0.59	0.00	0.83	0.05
	0.63	0.04	0.90	0.02
	0.59	0.00	0.86	0.02
Average	0.59		0.88	
Sample 2				
	0.55	0.02	0.70	0.00
	0.49	0.04	0.72	0.02
	0.54	0.01	0.72	0.02
	0.54	0.01	0.67	0.03
	0.52	0.01	0.70	0.00
	0.56	0.03	0.67	0.03
Average	0.53		0.70	
Sample 3				
	0.52	0.01	0.63	0.01
	0.52	0.01	0.64	0.00
	0.49	0.04	0.64	0.00
	0.54	0.01	0.63	0.01
	0.56	0.03	0.67	0.03
	0.54	0.01	0.63	0.01
Average	0.53		0.64	
Sample 4				
	0.52	0.01	0.80	0.00
	0.53	0.00	0.80	0.00
	0.52	0.01	0.77	0.03
	0.54	0.01	0.80	0.00
	0.52	0.01	0.77	0.03
	0.56	0.03	0.83	0.03
Average	0.53		0.80	

analysis in regard to sensitivity and precision, and is probably equivalent to gas-chromatographic methods[34].

III. Determination of Triphenylene in Tar Fractions

The number of compounds which occur in coal tar is estimated at about 10000[35]. Evidently even narrow cuts from coal tar still contain a large number of compounds. The determination of individual compounds in coal-tar fractions is therefore often extremely difficult.

Quantitative determination of small amounts of triphenylene in relatively wide cuts was of interest in connection with the processing of higher-boiling tar fractions. While the longest-wavelength absorbing hydrocarbons like tetracene and 1,2-benzanthracene in such fractions can be readily determined in the ultraviolet region, triphenylene, which absorbs at shorter wavelengths, cannot even be detected reliably if present in small concentrations. Gas chromatography is likewise difficult in such cases, because of the overlapping of different constituents, while paper chromatography, which is frequently superior to gas chromatography for the separation and identification of individual hydrocarbons in coal tar fractions, takes longer and is more laborious, (elution of the spots, measurements of the spectra). In contrast, phosphorescence spectroscopy quickly and simply leads to an answer. Triphenylene phosphoresces particularly strongly and has a very characteristic spectrum. When the phosphorescence of a triphenylene-containing coal tar fraction is excited by irradiation in a strong-band region (285 or 258 mμ), the almost undisturbed phosphorescence spectrum of triphenylene is obtained (cf. Fig. 7). Spectrum 1 in Fig. 7 was measured with an excitation at 258 mμ using a tar fraction with boiling range of 470–490 °C. Although this fraction containing largely five-ring compounds contains only about 2 % of triphenylene, its phosphorescence spectrum is substantially identical with that of pure triphenylene (curve 2 in Fig. 7).

For the determination of triphenylene in tar fractions, the intense band at 463 mμ serves as a suitable key band; irradiation with the 258 mμ wavelength, *i.e.* the

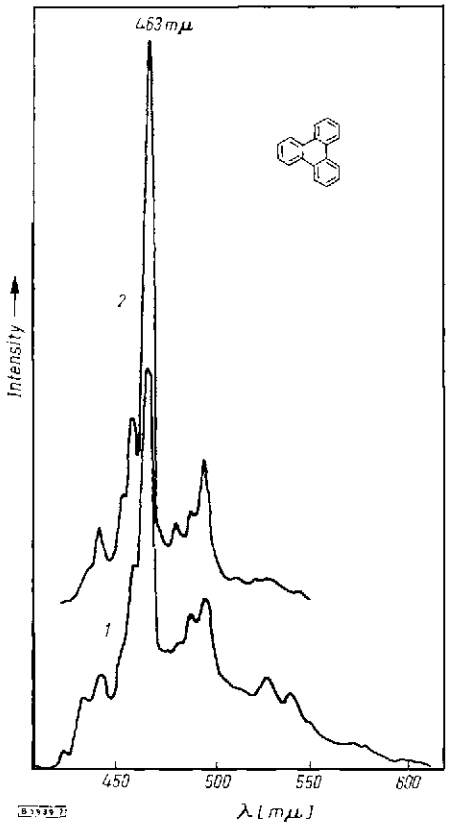


Fig. 7. Phosphorescence spectra (in EPA, 77°K) of a tar fraction containing triphenylene (curve 1) and of pure triphenylene (curve 2)

β-band of triphenylene, is a suitable excitation procedure. In addition to triphenylene, the tar fractions investigated contain numerous other phosphorescing components, but no marked overlapping of the 463 mμ band with other spectra was observed. The partial absorption of excitation radiation by accompanying substances, leading to a weakening of the phosphorescence intensity as compared to calibration solutions of equal concentration, is kept negligibly small by working at concentrations below 10^{-5} mole/l.

Table 7. Phosphorimetric determination of triphenylene in hydrocarbon mixtures.

Compound	% present	% found
3,4-Benzopyrene	25.0	
1,2-Benzopyrene	25.0	
Perylene	10.0	
1,2-Benzanthracene	15.0	
Triphenylene	25.0	23.5
3,4-Benzopyrene	35.0	
1,2-Benzopyrene	15.0	
Perylene	14.0	
1,2-Benzanthracene	21.0	
Triphenylene	15.0	14.5
3,4-Benzopyrene	40.0	
1,2-Benzopyrene	10.0	
Perylene	16.0	
1,2-Benzanthracene	24.0	
Triphenylene	10.0	10.0
3,4-Benzopyrene	35.0	
1,2-Benzopyrene	20.0	
Perylene	14.0	
1,2-Benzanthracene	21.0	
Triphenylene	10.0	10.0
3,4-Benzopyrene	40.0	
1,2-Benzopyrene	15.0	
Perylene	16.0	
1,2-Benzanthracene	24,0	
Triphenylene	5.0	4.5

Some test mixtures were made up from pure substances (triphenylene, 1,2-benzanthracene, 3,4-benzopyrene, 1,2-benzopyrene and perylene) and analysed for triphenylene. The results are shown in Table 7. In a second series, known amounts of triphenylene were added to a triphenylene-free tar fraction (boiling range of five-ring compounds) and the mixtures were analysed as above.

Table 8. Phosphorimetric determination of triphenylene in coal-tar fractions.

% present:	5.0	5.0	10.0	10.0	15.0	15.0	20.0	20.0	30.0	30.0
% found:	5.3	5.7	11.5	11.0	18.5	17.0	21.0	20.0	27.0	28.0

Table 8 contains the results. The analyses indicate a mean relative error of about 10 % for the phosphorimetric determination of triphenylene in tar fractions.

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Thermal Fragmentation and the Determination of the Structure of Organic Compounds [*]

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A pyrolysis apparatus with high-frequency induction heating has been developed, which, owing to the small dead volume in the pyrolysis zone (≥ 5 μl), can be used for pyrolysis gas chromatography utilizing capillary columns without a sample split system. Thin films of the samples are deposited on ferromagnetic conductors, and can be reproducibly heated in routine operation to an accurately defined temperature (the Curie point) in from 20 to 40 msec. Microgram quantities of natural amino acids can be identified by this method with the aid of standard pyrolysis gas chromatograms. When a thin film of the sample is used on the ferromagnetic conductor, the fragments are closely related to the structure of the original compound.

Introduction

Pyrolysis gas chromatography is used for the qualitative and quantitative analysis of non-volatile organic compounds [1, 2]. The samples are thermally fragmented in a stream of an inert carrier gas, and the reaction products are passed directly into a gas chromatography column where they are separated. The principal methods used for the pyrolysis are the filament method [3–12] and the furnace method [2, 13–18]. In the former the sample is

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[1] Reviews on pyrolysis gas chromatography: *J. Dandoy*, Ind. chim. belge *1962*, 355; *Anon:* Pyrolysis-Gas-Chromatography Methods, Supplemental Data Sheet to Bulletin 2382, American Instrument Co., October 1962; *S. G. Perry*, J. Gas-Chromatog. *2*, 54 (1964); *R. W. McKinney*, Pyrolysis-Gas-Chromatography: A Bibliography (1960 to 1963). W.R. Grace & Co., Clarksville 1964.

directly or indirectly brought into contact with a wire situated in a carrier gas stream, and which is rapidly heated by means of an electric current. In the furnace method the pyrolysis is carried out in a heated tube through which carrier gas is flowing. The samples are injected [2, 15, 17], thrown in [19, 20], pushed into the tube in boats [13, 14, 16, 18], or introduced *via* gas-inlet valves [17]. With few exceptions [6, 7, 15–18, 21], the relatively new method of pyrolysis gas chromatography has been studied only in relation to very specific analytical problems. The fundamental relationships are elucidated in only a few papers [7, 10, 17, 22].

Conditions for the Use of Pyrolysis Gas Chromatography

The successful use of pyrolysis gas chromatography in the structural elucidation of organic compounds and in the qualitative and quantitative analysis of mixtures is possible under the following conditions.

a) The fragmentation of the sample must be carried out at such a high dilution, and the fragments must be so quickly stabilized by migration into cooler zones, that no undesirable secondary reactions can occur between the starting materials, between these and the fragments, or between the fragments themselves.

b) The sample must be heated to a constant pyrolysis temperature as quickly and as reproducibly as possible, to ensure that the relative yields of the fragments are not affected by the different reaction rates or mechanisms at different temperatures.

c) The pyrolysis temperature must not be too high, since uncharacteristic fragments (methane, carbon, hydrogen) may otherwise be formed [23–25].

If conditions a) to c) are satisfied, the fragments should be closely related to the structure of the original compound, and the pyrolysis chromatogram of a mixture can be deduced by adding together the signals of the pyrolysis chromatograms of the individual components.

The Pyrolysis Apparatus

A pyrolysis method which combines the advantages of the filament and furnace methods without possessing any of their disadvantages consists in depositing a thin film of the sample on a ferromagnetic conductor, which is heated in a stream of carrier gas by high-frequency induction heating [26–28]. Fig. 1 shows the design of the pyrolysis apparatus, which may be connected to any gas chromatograph.

The power consumption, N [watt/cm], per unit length of a conductor located along the axis of the high-frequency induction coil [29] is

$$N = 2\pi\sqrt{2}\,H^2\rho\frac{r}{s}F(r,s) \qquad (1)$$

where

$$s = \sqrt{\frac{\rho}{\pi\mu_0\mu_r\nu}} \qquad (2)$$

H [oersted] is the magnetic field inside the coil; r [cm] is the radius of the conductor; ρ [Ω cm] is the specific resistance of the conductor; s [cm] is the skin depth of the eddy current; F is a function of s and r; $\mu_0 = 4\pi\times10^{-9}$ V sec/A cm is the permeability of free space; μ_r is the relative permeability ($\gg 1$ for ferromagnetic conductors below the Curie temperature, ~ 1 for non-ferromagnetic conductors); ν [sec^{-1}] is the frequency.

Values of F(s,r) have been tabulated as a function of r/s [29,30]. The relative permeability μ_r of a ferromagnetic conductor suddenly drops when it is heated to the Curie

[2] *R. J. Kokes, H. Tobin jr.*, and *P. H. Emmett*, J. Amer. chem. Soc. *77*, 5860 (1955).

[3] *J. Strassburger, G. M. Brauer, M. Tryton*, and *A. F. Forzati*, Analytic. Chem. *32*, 454 (1960).

[4] *F. A. Lehman* and *G. M. Brauer*, Analytic. Chem. *33*, 673 (1961).

[5] *A. Barlow, R. S. Lehrle*, and *J. C. Robb*, Makromolekulare Chem. *54*, 230 (1964).

[6] *J. Janák*, Nature (London) *185*, 684 (1960).

[7] *J. Janák*, Collect. czechoslov. chem. Commun. *25*, 1780 (1960); *J. Janák* in: Gaschromatography 1960, Proceedings on the 3rd Symposium (*R. P. W. Scott*, Ed.). Butterworths, London 1960, p. 387.

[8] *B. Groten*, Analytic. Chem. *36*, 1206 (1964).

[9] *C. E. R. Jones* and *A. F. Moyles*, Nature (London) *191*, 663 (1961).

[10] *D. F. Nelson* and *P. L. Kirk*, Analytic. Chem. *36*, 875 (1964).

[11] *J. Úlehla*, Sbornik československ. Akad. Zemedelske *7*, 567 (1960).

[12] *J. Voigt*, Kunststoffe *54*, 2 (1964).

[13] *E. M. Barrall, R. S. Porter*, and *J. F. Johnson*, J. Chromatogr. *11*, 177 (1963).

[14] *E. M. Barrall, R. S. Porter*, and *J. F. Johnson*, Analytic. Chem. *35*, 73 (1963).

[15] *J. H. Dhont*, Analyst *89*, 71 (1964).

[16] *K. Ettre* and *P. F. Varadi*, Analytic. Chem. *35*, 69 (1963).

[17] *A. I. M. Keulemans* and *S. G. Perry*, Papers presented at the 4th International Symposium on Gaschromatography, Hamburg 1962, p. 103; *A. I. M. Keulemans* and *S. G. Perry* in: Gaschromatography 1962 (*M. van Swaay*, Ed.), Butterworths, London 1963, p. 356.

[18] *C. C. Luce, E. F. Humphrey, L. V. Guild, H. H. Norrish, J. Coull*, and *W. W. Castor*, Analytic. Chem. *36*, 482 (1964).

[19] *B. C. Cox* and *B. Ellis*, Analytic. Chem. *36*, 90 (1964).

[20] *G. C. Hewitt* and *B. T. Whitham*, Analyst *86*, 643 (1961).

[21] *J. H. Dhont*, Nature (London) *200*, 882 (1963).

[22] *G. G. Smith* and *D. F. Brown*, Canad. J. Chem. *42*, 294 (1964).

[23] *R. S. Lehrle* and *J. C. Robb*, Nature (London) *183*, 1671 (1959).

[24] *S. B. Martin*, J. Chromatogr. *2*, 272 (1959).

[25] *S. B. Martin* and *R. W. Ramstad*, Analytic. Chem. *33*, 982 (1961).

[26] *H. Szymanski, C. Salinas*, and *P. Kwitowski*, Nature (London) *188*, 403 (1960).

[27] *T. D. Andrew, C. S. G. Phillips*, and *J. A. Semlyen*, J. Gas-Chromatogr. *1*, 27 (1963).

[28] *H. Giacobbo* and *W. Simon*, Pharmac. Acta Helvetiae *39* 162 (1964); *H. Giacobbo* and *W. Simon* in: Festschrift zum 60. Geburtstag von *Jakob Büchi* (*X. Perlia*, Ed.). Verlag Schweizer Apothekerverein, Zürich 1963, p. 199.

[29] *W. Brunst*, Die induktive Wärmebehandlung, Springer 1962, p. 40/45.

[30] *G. H. Brown, C. N. Hoyler*, and *R. A. Bierwirth*: Theory and Application of Radio-Frequency Heating. Van Norstrand Company, New York 1947, p. 27.

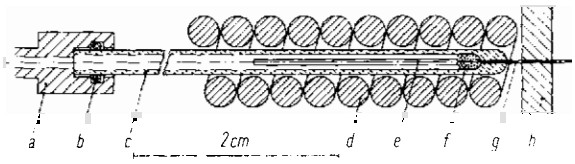

Fig. 1. Diagram of the pyrolysis apparatus.
a Connection for the introduction of carrier gas; *b* O-ring; *c* glass capillary; *d* high-frequency induction coil (copper); *e* ferromagnetic conductor (piece of wire 0.5×20 mm); *f* glass beads (sintered); g hollow platinum-iridium needle (diameter 0.3 mm); *h* rubber cap of the injection system of a gas chromatograph.

point [31]. This results in a sudden increase in the skin depth s [cf. Eq. (2)], so that r/s and F(s,r) become smaller, and the heating power supplied to the conductor decreases approximately with the fourth power of the temperature [cf. Eq. (1)].

To illustrate this, Table 1 [32] shows the values of the product ρF(r,s) r/s for various temperatures and radii of the ferromagnetic conductor. This product may be taken as a measure of the heating power supplied. The results are plotted in Fig. 2; if the frequency and the radius of the conductor are suitably chosen, the heating power supplied to the wire decreases very rapidly to a minute fraction when the Curie point is reached.

In order to obtain the greatest possible rate of decrease in power at the Curie point, the radius and the frequency must be matched in such a way that the ratio r/s > 2.5 below the Curie point, but is as small as possible above the Curie point [29, 30]. With a generator (Fig. 3) working at 0.45 Mc/s and equipped with two T 350–1 transmitter triodes (Brown, Boveri & Cie.AG. Baden, Switzerland) having an output of 0.7 kW each, the ferromagnetic conductors listed in Table 2 give the heating curves shown in Fig. 4. For example, iron is heated in approximately 20 msec to a constant temperature which, since it is governed by a constant of the material (the Curie point), is accurately reproducible. Thus from 1 kg of wire, it is possible to produce some

Table 1. Heating power in arbitrary units of ρF(s/r)r/s as a function of temperature for iron wires of various diameters (ν = 0.5 Mc/s).

Temperature [°C]	10^6 ρ [31] [Ω^{-6} cm]	μ_r [a]	s [mm]	ρ r/s			ρ·F (s,r)·r/s [b]		
				r = 0.1 [mm]	r = 0.25 [mm]	r = 0.5 [mm]	r = 0.1 [mm]	r = 0.25 [mm]	r = 0.5 [mm]
0	10	100	0.022	4.52	11.4	22.7	29.0	79	159
200	20	100	0.031	3.23	8.06	16.1	38.8	108	
400	40	100	0.045	2.22	5.55	11.1	48.8	144	
600	70	100	0.062	1.61	4.04	8.06	48.4	175	373
700	85	80	0.073	1.37	3.42	6.85	40.8	175	385
770	90	50	0.094	1.06	2.66	5.3	19.1	136	310
770	90	1	0.67	0.15	0.375	0.75	0.0081	0.030	5.06
800	105	1	0.73	0.14	0.34	0.68	0.0078	0.026	4.00

[a] The permeability values used were estimated, since there are no data available on the behavior of the relative permeability with temperature for the high field strengths which are used in high-frequency induction heating [13, 32].

[b] The values of F(s,r) were taken from [29].

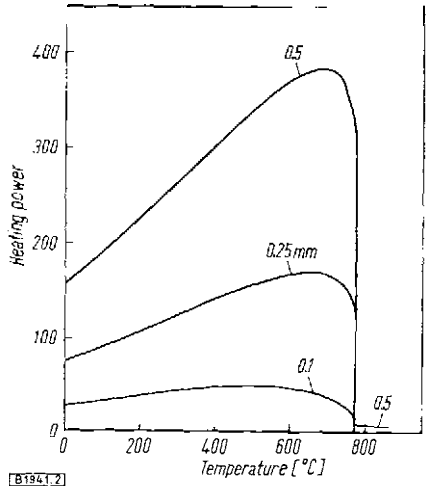

Fig. 2. Dependence of the heating power in arbitrary units [ρ×r/s×F(s,r)] on the temperature for iron wires of various radii.

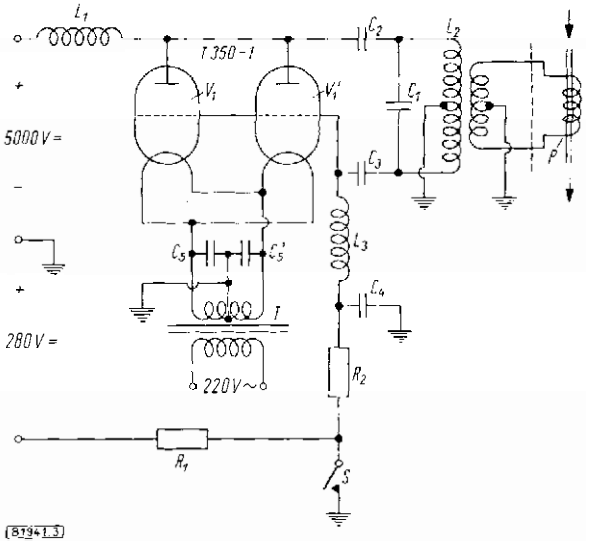

Fig. 3. Circuit diagram of the high-frequency generator.
P: pyrolysis apparatus; V_1, V_1': transmitter triodes T 350–1; T: 220 V/5V, 30A transformer; L_1, L_3: chokes, ≃ 200 μH; L_2: coil, ≃ 20 μH; S: time switch (Bohrer & Co., Solothurn, Switzerland) for setting the transmission time; R: resistances (R_1: 100 kΩ, 5W; R_2: 2 kΩ, 200 W); C: condensers (C_1, C_2, C_3: 1200 pF; C_4: 1000 pF; C_5, C_5': 10 nF).

[31] *R. M. Bozorth*: Ferromagnetism. Van Norstrand Company, Toronto, New York, London 1951, p. 55, 714.

[32] *H. Sobotka*: Hochfrequenz-Industriegeneratoren für induktive Erwärmung. Philips Technische Bibliothek, Eindhoven 1962, p. 7.

Table 2. Data on ferromagnetic conductors used in pyrolysis gas chromatography.

Material	Abbreviation	Curie point [°C]	Diam. [mm]	Source
Soft iron, galvanized	Fe(Zn)	770	0.6	Leuthold & Co., Zürich
Iron	Fe	770	0.6	Pestalozzi & Co., Zürich
Nickel	Ni	358	0.6	Nickel-Contor A.G., Zürich
Nickel/iron (45/55 %)	NiFe (45/55%)	400 [a]	0.5	Vacuumschmelze A.G., Hanau (Germany)
Nickel/chromium/iron (51/1/48 %)	NiCrFe (51/1/48%)	480 [a]	0.5	
Nickel/iron (60/40 %)	NiFe (60/40%)	590 [a]	0.5	
Cobalt/nickel (33/67 %)	CoNi (33/67%)	700 [a]	0.5	
Cobalt/nickel (45/55 %)	CoNi (45/55%)	800 [a]	0.5	
Cobalt/nickel (60/40 %)	CoNi (60/40%)	900 [a]	0.5	

[a] Private communication from Messrs. Vacuumschmelze A.G., Hanau

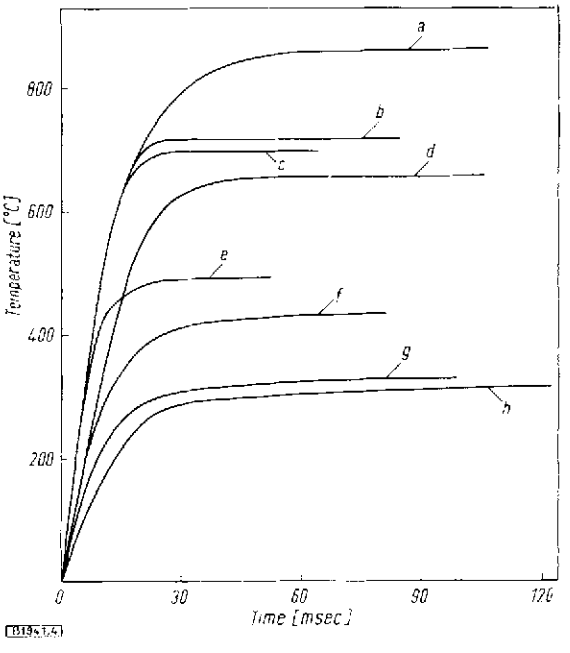

Fig. 4. Heating curves for the surfaces of wires (diameter 0.5 to 0.6 mm) of various materials.
a CoNi (60/40 %); *b* Fe(Zn); *c* Fe; *d* CoNi (33/67 %); *e* NiFe (60/40 %); *f* NiCrFe (51/1/48 %); *g* NiFe (45/55 %); *h* Ni.

obtained with capillary columns of diameter 0.25 mm without a sample split system (cf. Fig. 5).

Pyrolysis of Sodium Benzoate

As can be seen from Fig. 6, the pyrolysis of 28 ± 5 µg of benzoic acid (deposited from a 5 % solution in 1 N NaOH onto the ferromagnetic conductor [Fe(Zn) 0.6×20 mm] and dried in air at 25 °C) under similar conditions to those described above yields mainly benzene, accompanied by small quantities of substances formed in unwanted secondary reactions. This is not

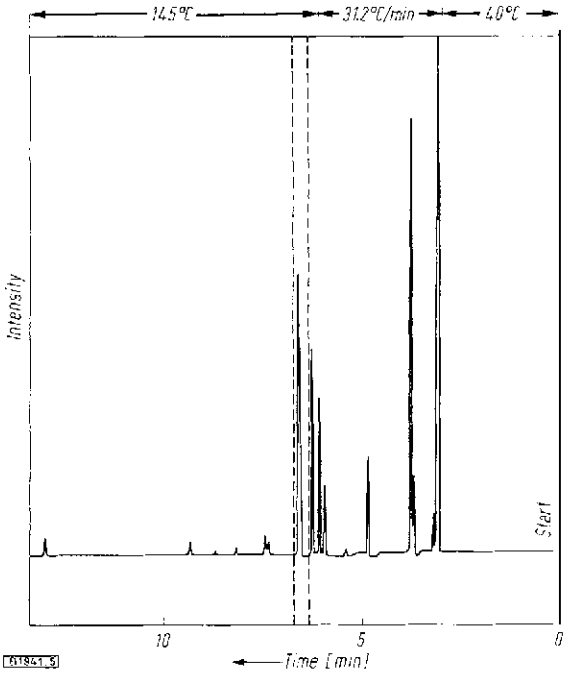

Fig. 5. Temperature-programmed pyrolysis gas chromatogram (5 µg of methionine deposited from a 2 % solution in 1N NaOH) obtained with a capillary column without sample split system. Ferromagnetic conductor: Fe(Zn) (cf. Table 2); gas chromatograph: Perkin-Elmer 226; Golay column K 1540 (150'; 0.01"), 1.2 ml of N_2/min; 3 min at 40 °C; progr. 31.2 °/min; 145 °C. Between the two broken lines the sensitivity was decreased by a factor of 5.

surprising, since even if the distribution of the sample on the surface of the wire were uniform, the thickness of the film would be of the order of 1000 molecules [*].

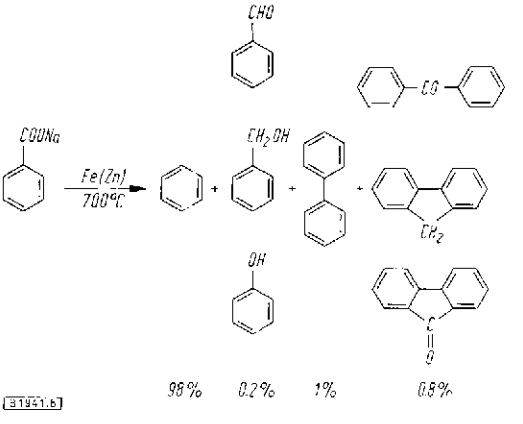

Fig. 6. Fragmentation of sodium benzoate on galvanized iron wire.

The probability for such secondary reactions decreases with decreasing sample size. Thus the relative yield of biphenyl decreases as the quantity of sodium benzoate on the ferromagnetic wire is reduced (cf. Fig. 7). The decrease in the yield of benzene with increasing sample size is probably due to the fact that the hydrogen atom used to form benzene from the benzoate presumably comes from the water retained by excess NaOH on the surface of the conductor after evaporation of the solvent. The relative amount of water present decreases with increasing sample size.

[*] Assuming an area of the of molecule 10×6 Å²; dimensions of the wire: 0.6×20 mm; size of sample: 10 µg, molecular weight: 100.

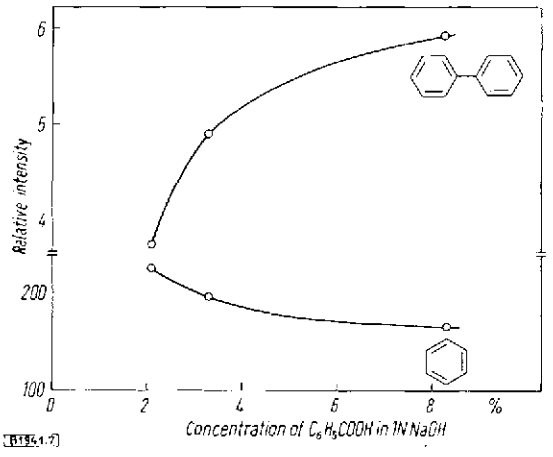

Fig. 7. Dependence of the relative peak heights on the sample size in the pyrolysis of sodium benzoate.

It can be seen from Fig. 8 that the fragmentation is strongly affected by the radius of the metal ion in the salt. This dependence indicates that both simple fragmentations (formation of benzaldehyde) and undesirable secondary reactions (formation of biphenyl) take place in the vicinity of the solid on the surface of the wire.

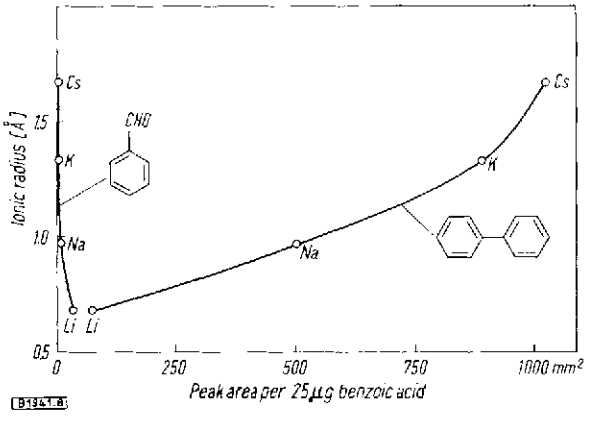

Fig. 8. Yields of biphenyl and of benzaldehyde (expressed as the area of the peak/25 µg of benzoic acid) in the pyrolysis of benzoates, as a function of the cation radius [Å].

Pyrolysis of Amino Acids

For the elucidation of the structures of organic compounds by pyrolysis gas chromatography, it is desirable that the structure of the fragments is closely related to that of the starting material. As expected, this is the case when thin films of the sample are used. The fragmentations of the sodium salts of phenylalanine and of proline, for instance, lead to the products shown in Fig. 9, provided that the salts are deposited on the ferromagnetic conductor as a roughly monomolecular layer [28].

Contrary to *Úlehla*'s opinion [11], naturally occurring amino acids can be identified in samples of about 3 µg by their pyrolysis chromatograms (cf. Fig. 10). As can be shown by chromatography on stationary phases of various polarities, fragments with the same retention data in Fig. 10 are not necessarily indentical.

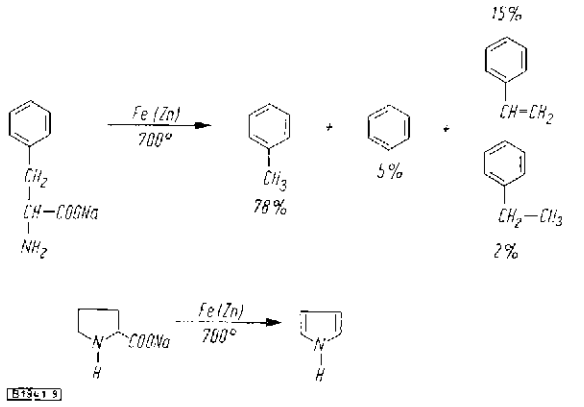

Fig. 9. Fragmentation of the sodium salts of phenylalanine and of proline on a galvanized iron wire.

The fragments found in the pyrolysis of amino acids are also formed in the fragmentation of the corresponding peptides [6, 7, 11, 27, 33] (cf. Fig. 11). However, the relative intensities of the signals seem to be affected by the peptide linkage. The weak signals observed in the pyrolysis of prolylphenylalanine (Fig. 11A), but which are absent in the pyrolysis chromatogram of a 1:1 mixture of proline and phenylalanine (Fig. 11B), are probably due to impurities in the dipeptide.

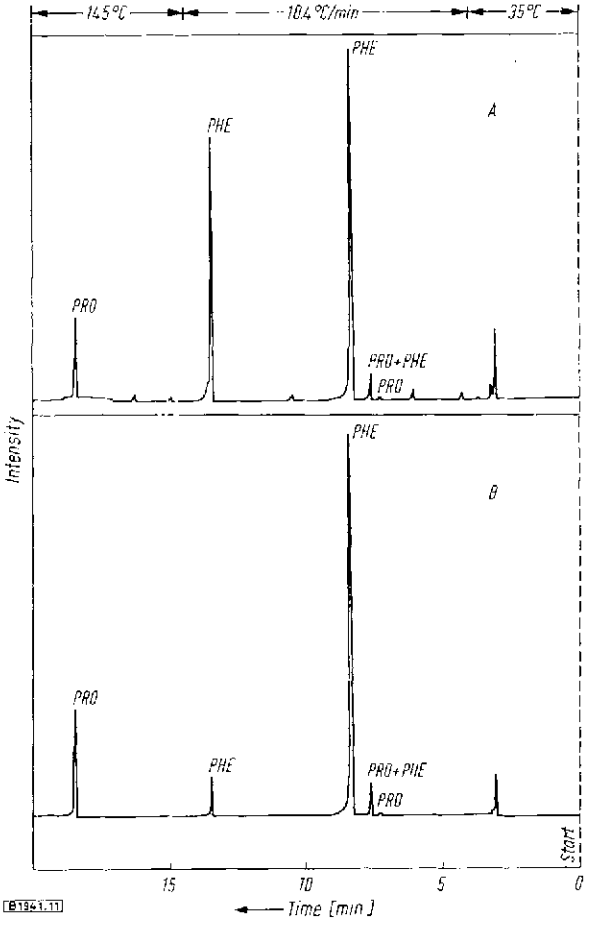

Fig. 11. Comparison of the pyrolysis gas chromatograms of prolylphenylalanine (A) and a 1:1 mixture of proline and phenylalanine (B). GLC: Perkin-Elmer 226; Golay K 1540 (150'; 0.01"); 1.2 ml of N_2/min; 4 min at 35 °C; progr. 10.4 °C/min; 145 °C.

[33] *L. N. Winter* and *P. W. Albro*, J. Gas-Chromatogr. *2*, 1 (1964).

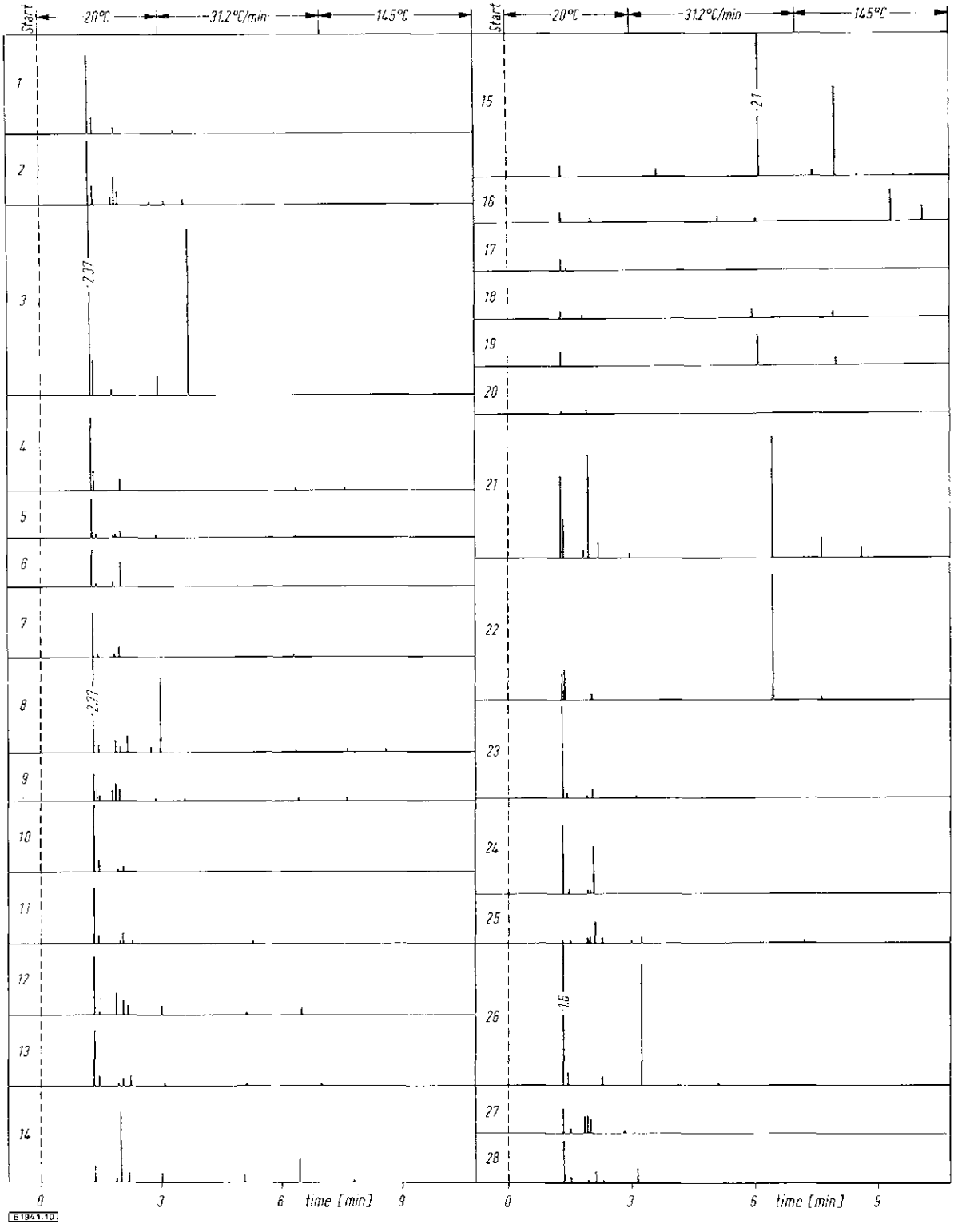

Fig. 10. Comparison of the pyrolysis gas chromatograms of 28 amino acids (the lengths of the lines are proportional to the area under the peak at that retention).

G.L.C: Perkin-Elmer 226; Golay DC 550 (100', 0.01"); 2.5 ml of N_2/min; 3 min at 20 °C; progr. 31.2 °C/min; 145 °C; 3 μg of amino acid (1 % in 1 N NaOH).

1. Glycine; 2. alanine; 3. valine; 4. serine; 5. threonine; 6. cysteine; 7. cystine; 8. methionine; 9. aspartic acid; 10. glutamic acid; 11. arginine; 12. ornithine; 13. lysine; 14. citrulline; 15. phenylalanine; 16. tyrosine; 17. diiodotyrosine; 18. thyronine; 19. diiodothyronine; 20. thyroxine; 21. proline; 22. hydroxyproline; 23. djenkolic acid; 24. lanthionine; 25. β-alanine; 26. α-aminobutyric acid; 27. γ-amino butyric acid; 28. α,γ-diaminobutyric acid.

The method described has important advantages over the conventional pyrolysis gas chromatography procedure. In order to fully exploit its possibilities, however, a systematic study of the pyrolysis reaction is essential.

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Extreme Values of the Pressure Coefficient of Viscosity [*]

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The pressure coefficients of viscosity of hydrocarbons and ethers containing two to four phenyl groups linked either directly, via methylene bridges, or via $CH(CH_3)$ bridges, were studied with a view to elucidating the reason for the extreme viscosity-pressure behavior of certain mineral oils. Measurements were made in the range of 1 to 2000 atm at 25, 40, 60, and 80 °C. The results show the existence of a simple relationship between molecular structure and viscosity-pressure coefficient, and suggest applications in control engineering and lubrication technology.

A. Statement of Problem

The viscosity of a liquid generally increases exponentially with pressure [1]. Thus as a first approximation we may write:

$$\eta_p = \eta_0 e^{\alpha p}$$

The quantity α given by

$$\alpha_t = \frac{1}{\eta_p}\left(\frac{\partial \eta_p}{\partial p}\right)_t$$

can then be used to characterize the dependence of the viscosity of the substance on pressure.

On this basis the viscosity-pressure behavior of all liquids is qualitatively the same; quantitatively, however there are substantial differences between various types of substances. Thus for simple substances with low molecular weights, the viscosity at 2000 atm is 3 to 7 times as great as at atmospheric pressure, whereas the corresponding factors for mineral oils and oil extracts are between 30 and 20000.

This strong dependence of viscosity on pressure and the very different behavior of the various oils is important for technical applications in which the oil is subject to very high local pressures [2–5], as in driving gears. It is therefore desirable to establish the reasons for the extreme pressure-dependence of the viscosities of certain oils. For the examination of technical problems it is also desirable to have available series of defined substances having different viscosities and different viscosity-pressure behavior.

Mineral oils are unsuitable for fundamental research, since the structures of the various oil components are in most cases unknown, and since the behavior with pressure may also be influenced by the complexity of the oil mixture. In order to explain the dependence of the viscosity on pressure, therefore, chemically uniform substances with systematically modified molecular structures were studied. It was found that the pressure coefficient of the viscosity depends on the structural characteristics of the molecule in the following ways [6].

a) *Effect of chain length*: In a homologous series, the absolute viscosity increases with chain length, whereas the pressure coefficient remains constant (except for the lower members of the series). By varying the chain length it is therefore possible, within certain limits, to vary the viscosity without affecting the viscosity-pressure coefficient.

b) *Effect of internal mobility of the molecule*: If ether linkages are built into a long-chain molecule, its internal mobility is increased and the dependence of the viscosity on pressure is substantially decreased. In molecules with very long chains, the various molecular segments move almost independently, like the segments of a caterpillar [7].

c) *Effect of side groups*: The pressure coefficient of viscosity depends strongly on the degree of branching in the molecule. In accordance with the predictions of *Eyring*'s hole theory [8,9], α is considerably increased by the introduction of rigid or bulky side groups.

d) *Effect of functional groups*: The pressure coefficient of viscosity can also be raised by the introduction of certain functional groups (*e.g.* Cl or OH).

With a view to the synthesis of compounds having pressure coefficients of viscosity as high as possible, hydrocarbons and ethers containing two and three phenyl groups per molecule were studied. Since substances containing condensed rings are solid under normal conditions, the investigations were carried out on compounds in which the phenyl groups are linked either by C–C bonds, by methylene bridges, or by $CH(CH_3)$ bridges.

[*] Lecture to the Colloquium held in honour of Prof. Dr. *Gg. R. Schultze* on the occasion of his 60th birthday.

[1] *E. Kuss*: Erdöl-Ztg. *78*, 678 (1962); Materialprüfung *2*, 189 (1960).

[2] *H. A. Everett*, S.A.E. Journal *41*, 531 (1937).

[3] *L. J. Bradford* and *M. Wetmiller*, Machine Design *9*, 37 (1937).

[4] *B. Sternlicht*, Trans. ASME *80*, 1108 (1958).

[5] *W. Fleck*, Maschinenbautechnik (Schmiertechn.) *12*, 602 (1963).

[6] *E. Kuss*, Z. angew. Physik *7*, 372 (1955); *10*, 566 (1958); *E. Kuss* and *G. R. Schultze*, Proceedings of the IVth World-Petroleum Congress, Sect. V/A 5, 101 (1955/56).

[7] *G. Gee*, Proc. chem. Soc. (London) *1957*, 111.

[8] *H. Eyring* and *N. J. Hirai*, Appl. Physics *29*, 810 (1958); *J. F. Kincaid*, *H. Eyring*, and *A. E. Stearn*, Chem. Rev. *28*, 301 (1941).

[9] *A. Bondi*: Physical Chemistry of Lubricating Oils. Reinhold, New York 1951.

Attempts were then made to further increase the pressure coefficient of viscosity by hydrogenation and by cleavage of the ether linkages, and to pass progressively in this way to substances with extremely high pressure-viscosity coefficients.

B. Experimental Techniques

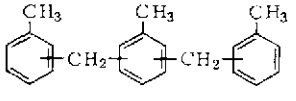
I. The High-Pressure Viscometer

Viscosities were measured at 25, 40, 60, and 80 °C at pressures up to 2000 atm, using a high-pressure falling sphere viscometer described earlier[1].

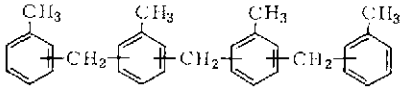
An important improvement was made with respect to the determination of the time of fall. The jacketed induction coils built into the pressure tube and consisting of 2000 turns each are operated at 1.8 kc/s by a two-stage oscillator. The potential differences across the two coils are applied to the two inputs of a bridge amplifier (twice 3 stages), which is detuned when the ball enters one of the coils. This actuates a flip-flop circuit which starts or stops an electronic clock having 6 decimal counters and an output printer[*]. In this way the time of fall can be measured automatically with an accuracy of 0.01 sec.

II. Hydrogenation

Three groups of substances were studied before and after hydrogenation: (a) biphenyl and terphenyls, (b) bis(tolylmethyl)toluene *(1)* and bis(tolylmethyltolyl)methane *(2)*, and (c) substituted methoxybenzenes containing one to three phenyl groups per molecule.



(1)



(2)

Since the pressure coefficient of viscosity is greatly increased on replacement of phenyl groups by cyclohexyl groups, all the substances studied were hydrogenated. This adds considerably to the range of pressure coefficients previously covered.

The hydrogenations were carried out in a rocking autoclave[*] under the mildest possible conditions, *i.e.* in cyclohexane solution with 5 % of Pd on $BaSO_4$ as catalyst at 210 to 240 °C (depending on the substance) and 800 atm. The course of the hydrogenation was always followed by infrared spectroscopy. The characteristic bands between 1490 and 1510, at 1600, and in the region between 1700 and 2000 cm^{-1} disappeared completely in every case. The proportion of unhydrogenated substance was therefore much less than 1 %.

III. Ether Cleavage

In the first two groups of substances, *i.e.* bi- and terphenyl and compounds *(1)* and *(2)*, the pressure coefficient of viscosity could only be increased by hydrogenation. In the phenyl methyl ethers, on the other hand, a substantial increase was obtained on conversion of the methoxy to hydroxy groups.

The first method used to cleave the ether linkage was *Zeisel*'s hydrogen iodide method[10]. This method was specially developed for the determination of CH_3O groups, and is not suitable for preparative purpose, particularly for substances containing three phenyl groups per molecule.

The method developed by *Prey*[11] was found to be suitable for use on the preparative scale, even for complex substances. In this method, freshly prepared pyridinium chloride is used instead of hydrogen iodide for the cleavage of the ether. The substance can be completely converted into the desired alcohol and methyl chloride, which is readily distilled off. The pyridine is removed with water.

C. Viscosity-Pressure Isotherms

I. Bicyclohexane and Tercyclohexanes

Since biphenyl and *o*-, *m*-, and *p*-terphenyl are solid under normal conditions, only the viscosity-pressure isotherms of the hydrogenated substances can be given (Fig. 1). The data for *p*-tercyclohexane have been omitted, since this substance occurs as a mixture of two isomers with very different melting points and unknown difference in conformation.

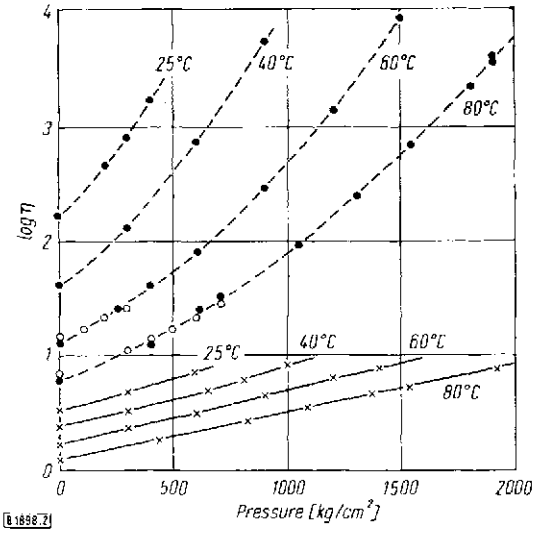


Fig. 1. Viscosity-pressure isotherms of bicyclohexane and tercyclohexanes (η in centipoise).

× Bicyclohexane (m.p. 2.7°C); ● *o*-tercyclohexane (m.p. 38.5–39.0°C); ○ *m*-tercyclohexane (m.p. 66°C).

The curves terminate where the substances solidify.

In the plot of the logarithm of viscosity against pressure (Fig. 1), bicyclohexane gives linear isotherms in accordance with the exponential law. The viscosity changes by a factor of 7 to 10, depending on the temperature, between

[*] The author is grateful to *W. Siegmann* at this Institute, who constructed this apparatus.

[*] For a description of the hydrogenation apparatus, see the original article: Chemie-Ing.-Techn. *37*, 465 (1965).

[10] See, *e.g.*, *L. Gattermann* and *H. Wieland*: Die Praxis des organischen Chemikers. 34th ed., *W.* De Gruyter, Berlin 1952, p. 74; *K. H. Bauer* and *H. Moll*: Die organische Analyse. 4th ed. Akadem. Verlagsges., Leipzig 1960, p. 123; *H. Krauch* and *W. Kunz*: Namenreaktionen der organischen Chemie, Dr. Hüthig Verlag, Heidelberg 1961, p. 519.

[11] *V. Prey*, Ber. dtsch. Chem. Ges. *74*, 1219 (1941); *75*, 350, 445 (1942).

1 and 2000 atm. The pressure coefficient of viscosity increases markedly if the number of cyclohexyl groups per molecule is increased, *i.e.* on passing to the tercyclohexanes.

The absolute value and the pressure-dependence of the viscosity are practically identical for *o*- and *m*-tercyclohexanes. Owing to the high melting point (66 °C) of *m*-tercyclohexane, however, only parts of the 60 °C and 80 °C isotherms can be given. Even at these temperatures *m*-tercyclohexane solidifies at relatively low pressures; consequently, the highest viscosity reached is more than two orders of magnitude lower than that of *o*-tercyclohexane, for which the measurements could be extended well into the supercooled range. At 80 °C the viscosity changes by a factor of 750 between 1 and 2000 atm.

Another striking feature of the viscosity-pressure isotherms of tercyclohexanes is that they are convex towards the pressure axis. Thus the pressure coefficient α increases with pressure. This behavior is observed only for substances with several rings in the molecule.

II. Bis(tolylmethyl)toluene and Bis(tolylmethyltolyl)methane

These substances, which are used as heating and cooling liquids over a very wide temperature range, can be prepared from technical (chloromethyl)toluene and toluene [12]. The *o*-, *m*-, and *p*-isomers were not separated, but were studied as a mixture. In contrast to bi- and tercyclohexanes (Fig. 1), however, the viscosity behavior of both the hydrogenated and the unhydrogenated substances can be studied in this case, since they are liquids under normal conditions.

The effects of both chain length and hydrogenation are clearly visible in Fig. 2. The pressure coefficients α are given for a reference temperature of 40 °C to permit comparisons with other groups of substances. The increase in the chain length of both the hydrogenated and the unhydrogenated substances leads to an increase of 1.6×10^{-3} atm^{-1} in α_{40}, whereas hydrogenation of both starting substances gives an increase of about 2.2×10^{-3}. It was also confirmed that, as had been observed previously [12a], hydrogenation of the phenyl groups leads to a decrease in density and to a considerable increase in the viscosity at atmospheric pressure.

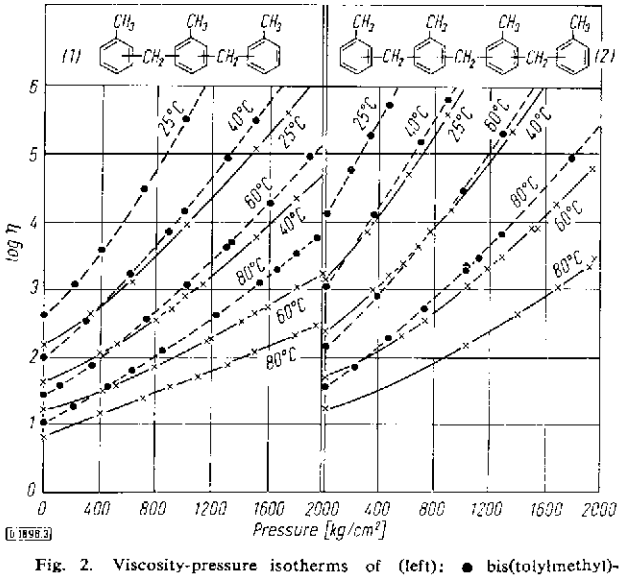


Fig. 2. Viscosity-pressure isotherms of (left): ● bis(tolylmethyl)-toluene *(1)* ($\alpha_{40} = 3.54\times10^{-3}$ atm^{-1}), × perhydro-*(1)* ($\alpha_{40} = 5.77\times10^{-3}$); (right): ● bis(tolylmethyltolyl)methane *(2)* ($\alpha_{40} = 5.18\times10^{-3}$), × perhydro-*(2)* ($\alpha_{40} = 7.35\times10^{-3}$). The α_{40} values refer to a pressure of 1000 atm.

III. Phenylethylphenols and Phenylethylanisoles

By far the widest range of pressure coefficient is found in a group of substituted phenols and anisoles [13]. Data for three anisoles are shown in Fig. 3.

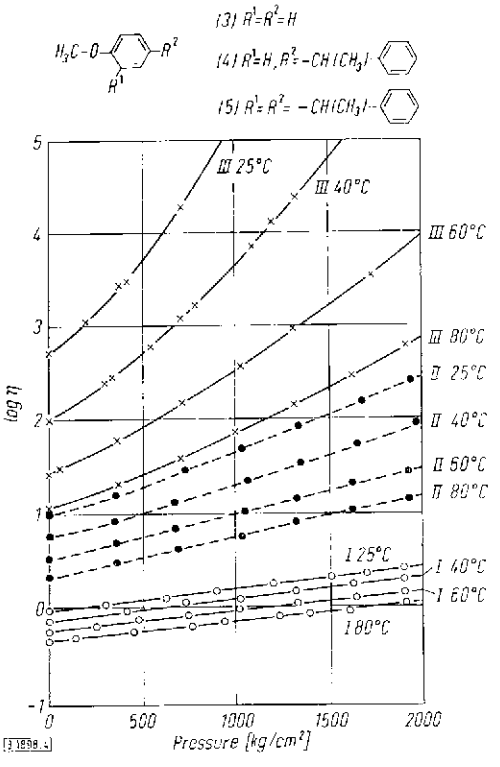


Fig. 3. Viscosity-pressure isotherms of: I anisole *(3)*, II 4-(1-phenylethyl) anisole *(4)*, and III 2,4-bis-(1-phenylethyl)anisole *(5)*.

In the case of anisole (curve I in Fig. 3), $\alpha_{25} = 0.55\times10^{-3}$ atm^{-1}, *i.e.* the viscosity at 2000 atm is 3 times that at 1 atm. Thus $\alpha\times10^3$ falls in the range 0.5–1.0 given above for simple substances with low molecular weights.

To a first approximation, the pressure coefficients are given by:

$$\alpha = \Delta V/RT$$

where ΔV is the local increase in volume required to permit the movement of the molecules past one another in viscous flow. In agreement with this interpretation, α decreases by about 15 % between 25 and 80 °C for methoxybenzene.

[12] *W. Glaß*, Erdöl u. Kohle *17*, 118 (1964).

[12a] *E. Kuss*, Z. angew. Physik *7*, 372 (1955).

[13] German Patent Application C 31800 IV c/23c (Dec. 12th, 1963), Chemische Werke Hüls AG.; inventor: *E. Kuss*.

If another phenyl group is now attached to the molecule *via* a $CH(CH_3)$ bridge, ΔV increases and so also does α. In the case of 4-(1-phenylethyl)anisole *(4)*, the viscosity at 2000 atm is 28 times that at 1 atm ($\alpha_{25} = 1.66 \times 10^{-3}$). The normal viscosity is also about one order of magnitude greater than that of anisole. As can be seen from Fig. 3, the isotherms fan out to a greater extent, *i.e.* α is much more dependent on the temperature.

As in simple substances with low molecular weights, by far the highest pressure coefficients are found for substances having bulky groups in the side chain. A high pressure coefficient can be obtained by the introduction of another phenylethyl substituent to form 2,4-bis-(1-phenylethyl)anisole *(5)*. At 25 °C, the viscosity is so high at pressures above 1000 atm that it could no longer be measured. The pressure coefficient is 5.75×10^{-3} atm^{-1}, corresponding to an extrapolated viscosity at 2000 atm of about 10^5 times that at 1 atm. As can be seen from Fig. 3, the isotherms are convex towards the abscissa; thus this compound exhibits the characteristic behavior of substances containing several rings in the molecule, *i.e.* α increases with pressure. It is also strongly dependent on the temperature.

From the compounds *(3)–(5)* groups of substances were prepared by hydrogenation, ether cleavage, and hydrogenation + ether cleavage, using the methods described above. These groups of compounds should cover the range of pressure coefficients as evenly as possible, and should include substances in which the viscosity is very strongly pressure-dependent.

1. Compounds with One Ring

This group includes methoxybenzene, methoxycyclohexane, phenol, and cyclohexanol. Since phenol melts at 41 °C at atmospheric pressure, only the 60 °C and 80 °C isotherms are given for the two hydroxy compounds (Fig. 4).

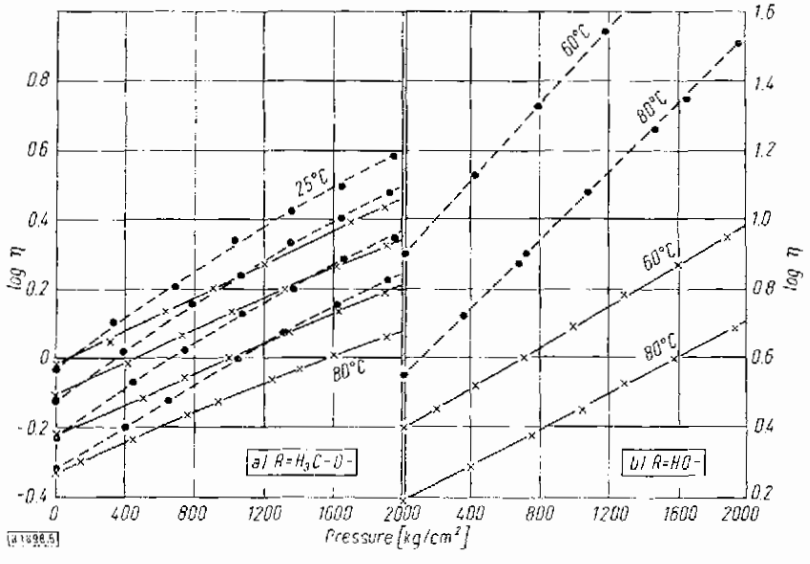


Fig. 4. Viscosity-pressure isotherms of methoxy and hydroxy compounds containing one ring.

(a): Isotherms at 25, 40, 60, and 80°C for: × anisole ($\alpha_{60} = 0.50 \times 10^{-3}$), ● methoxycyclohexane ($\alpha_{60} = 0.66 \times 10^{-3}$); (b): × phenol ($\alpha_{60} = 0.67 \times 10^{-3}$), ● cyclohexanol ($\alpha_{60} = 1.28 \times 10^{-3}$).

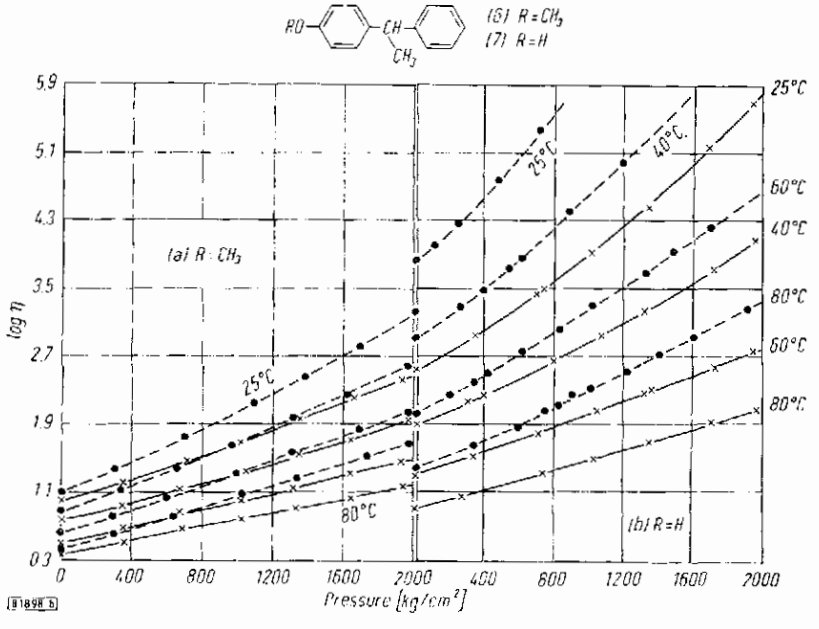


Fig. 5. Viscosity-pressure isotherms at 25, 40, 60, and 80°C of methoxy and hydroxy compounds containing two rings.

(a): × *p*-Phenylethylanisole *(6)*, ● perhydro-*(6)*; (b): × *p*-phenylethylphenol *(7)*, ● perhydro-*(7)*.

Fig. 4 shows that the hydrogenation of the phenyl group of the methoxy compounds has little effect on the viscosity at atmospheric pressure, but leads to a considerable increase in α. The pressure coefficient is also larger for the hydroxy compounds than for the corresponding methoxy compounds. The dependence of the viscosity on pressure is even more strongly affected if hydrogenation is combined with conversion into the hydroxy compound.

2. Compounds with Two Rings

Similar behavior is observed on hydrogenation, ether cleavage, and ether cleavage + hydrogenation of 4-(1-phenylethyl)anisole *(4)*.The viscosity-pressure isotherms of the four substances of this group are shown in Fig. 5. The pressure coefficients α follow on well from those of the compounds containing one ring, covering the wide range of from 1.36×10^{-3} to 3.56×10^{-3} atm^{-1}. Thus at 40 °C the viscosities of these substances increase by factors of 15 to 1250 between 1 and 2000 atm.

The increase in α with increasing content of the phenol in the mixture obtained by partial cleavage of the methoxy groups is faster than linear (Fig. 6). Intermediate values of the pressure coefficient can evidently be obtained by partial cleavage.

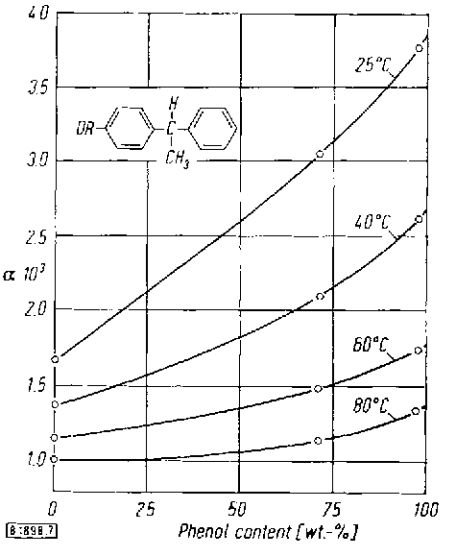


Fig. 6. Pressure coefficient of viscosity α as a function of the degree of conversion of 4-(1-phenylethyl)anisole (R = CH_3) into 4-(1-phenylethyl)phenol (R = H).

The isotherms extend over five decades and are convex towards the pressure axis. They fan out strongly, particularly in the hydroxy compounds, showing that α for these compounds is highly temperature-dependent.

The mean viscosity-pressure coefficient α at 40 °C extends from 3.8×10^{-3} to about 8×10^{-3} atm^{-1} for this group of compounds. The latter value corresponds to an increase in viscosity by a factor of several million between 1 and 2000 atm.

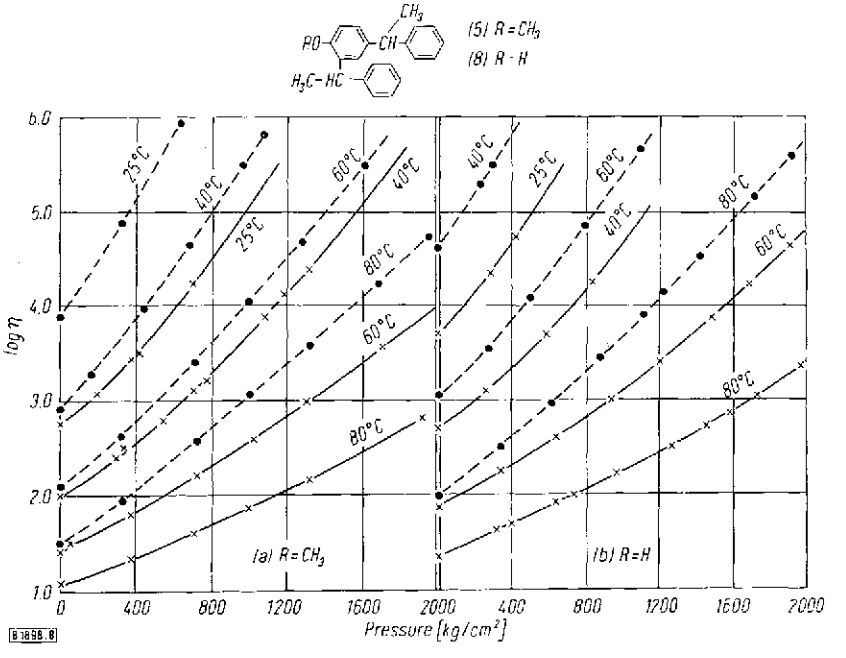


Fig. 7. Viscosity-pressure isotherms of methoxy *(5)* and hydroxy compounds *(8)* containing three rings.
(a): × *(5)*, ● perhydro-*(5)*; (b): × *(8)*, ● perhydro-*(8)*.

3. Compounds with Three Rings

By far the highest pressure coefficients are obtained if another phenylethyl or cyclohexylethyl group is introduced as a side chain. The viscosity-pressure isotherms of 2,4-bis-(1-phenylethyl)anisole and those of the derivatives obtained by hydrogenation, ether cleavage, and ether cleavage + hydrogenation are shown in Fig. 7.

It should also be mentioned that according to Stuart molecular models, 2,4-bis-(1-phenylethyl)anisole *(5)* can exist in a kind of chair form and a kind of boat form (Fig. 8). The model indicates that the interconversion of the two forms is appreciably hindered by the incomplete rotational freedom of the phenylethyl

groups. No evidence for the existence of two forms was, however, found from the viscosity-pressure curve or by infrared spectroscopy.

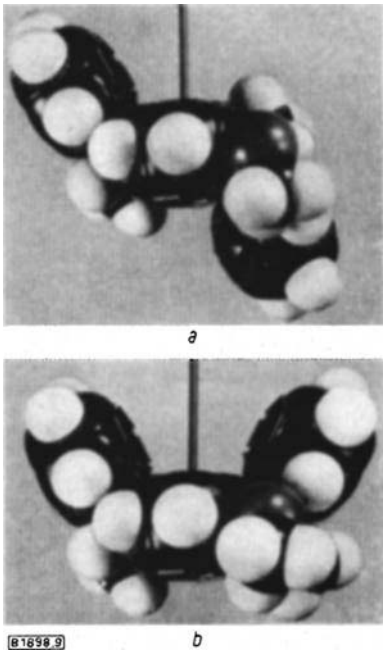


Fig. 8. Stuart models of 2,4-bis-(1-phenylethyl)-anisole *(5)*. *a*: "Chair" form; *b*: "boat" form.

D. Discussion

The data for the methoxy and hydroxy compounds studied are summarized in Table 1. It can be seen that the density decreases on hydrogenation to the extent of 0.10 to 0.12 g/cm³, depending on the number of phenyl groups present. On cleavage of the ether linkage, on the other hand, the density increases, the average increases being 0.084, 0.042, and 0.025 g/cm³ for substances with one, two, and three rings, respectively. The viscosity at atmospheric pressure is increased both by hydrogenation and by cleavage of the ether linkage. The magnitudes of the changes vary by several powers of ten, the strongest effects being observed in the case of compounds with three rings.

Finally, the magnitude of the increase in α on hydrogenation also increases with the number of rings. The conversion of the methoxy group into OH has less effect in substances with three phenyl groups than in substances with one or two rings. The effect of the OH group must obviously be largely screened by the adjacent phenylethyl groups (cf. Fig. 8). According to Table 1, this is also evident to a small extent in the density.

The pressure coefficients of the groups of compounds obtained in this way are much higher than those of mineral oil extracts, which were formerly regarded as very high. Whereas the value of the ratio $\eta_{2000\,atm}/\eta_{1atm}$ in the extreme case is 20000 for oils, factors of up to 8 million are found for the groups of compounds now available. This also shows that the strong pressure-dependence of the viscosities of certain mineral oil extracts is not due to the fact that the oils are mixtures.

Table 1. Densities ρ, viscosities η_i, and pressure coefficients of viscosity α at 40°C for methoxy and hydroxy compounds containing one to three rings.

Compound	ρ_{40} [g/cm³]	η_{40} [cP]	$10^3\,\alpha_{40}$ [atm^{-1}]
Methoxybenzene	0.9757	0.768	0.54
Methoxycyclohexane	0.8479	0.764	0.71
Phenol	1.0586	5.054	(0.81) Solid
Cyclohexanol	0.9339	22.7	1.51
(6)	1.0293	5.86	1.36
Perhydro-*(6)*	0.9191	7.26	2.02
(7)	1.0741	80.0	2.61
Perhydro-*(7)*	0.9583	842	3.56
(8)	1.0441	102.0	3.86
Perhydro-*(5)*	0.9403	859.0	6.09
(5)	1.0719	513	4.15
Perhydro-*(8)*	0.9616	42200	7.95

The values obtained with pure substances raise the question of whether the extremely high pressure coefficients can be explained with the present concepts. To test this question, let us examine the substances containing three cyclohexane rings (Table 1), which have the highest pressure coefficients found so far.

The activation energy for viscous flow E_{visc} is given by the temperature-dependence of the viscosity by

$$E_{visc} = -RT^2 \left(\frac{\partial \ln \eta_i}{\partial T}\right)_{p\,=\,1\ atm}$$

Using the relationships

$$\alpha = \Delta V/RT \quad \text{and} \quad E_{visc} = p_i \Delta V$$

where p_i is the internal pressure of the liquid, we find for the substance with the highest viscosity-pressure coefficient (Table 1) that:

a) the local increase in volume $\Delta V \simeq 0.5$ V.

b) corresponding to the approximations used, the internal pressure of the liquid has a maximum value of $p_i = 6300$ atm.

Both of these values are feasible for an extreme case. The internal pressure p_i is of an order of magnitude that has already been reported [14] for other liquids on the basis of pVT measurements and equations of state. A local volume increase of 50 % during viscous flow is also understandable in view of the molecular structure in question, but this must be regarded as approximately an upper limit.

The results also show a simple relationship between the pressure coefficient α and the molecular structure. In our opinion, however, the extreme pressure-dependence of the viscosity of the compounds studied could also be of interest in technical applications, for the following reasons:

1. In technical processes at low pressures where the influence of the viscosity is not yet known, this could be isolated from other influences by using the substances with high α studied in the present work.

2. The marked changes in viscosity with pressure could be used for control applications.

3. In the lubrication of highly stressed gears, the lubricant can be adapted to special requirements, not only as regards the temperature-dependence of the viscosity, but also as regards its pressure-dependence. In such cases, groups of definite compounds with absolute viscosities and pressure coefficients that cover a wide range would be of value.

E. Summary

Mineral oils and mineral oil extracts differ very markedly from simple substances with low molecular weights in the dependence of their viscosities on pressure. The viscosities of the former group increase by factors of from 30 to 20000 between 1 and 2000 atm, whereas the factors found previously for simple substances are less than 100, and depend on the chain length, intramolecular mobility, the degree of branching, and the presence of functional groups.

In order to find the reasons for this, and with a view to possible technical applications, groups of chemically uniform substances have been made with pressure coefficients of viscosity that cover an extremely wide range. Since substances containing condensed ring systems are solid under normal conditions, the compounds used to obtain the high pressure coefficients were hydrocarbons and ethers in which two to four phenyl groups were linked either by direct C—C bonds, methylene bridges, or $CH(CH_3)$ bridges. The pressure coefficient of viscosity was systematically altered by variation of the number and mutual positions of the rings.

The pressure coefficient could be further increased by hydrogenation of the phenyl groups and by replacement of methoxy groups by hydroxy groups.

The investigations at 25, 40, 60, and 80 °C and at pressures between 1 and 2000 atm were carried out in a high-pressure viscometer with automatic recording of the time of fall. The hydrogenations were carried out at 210 to 240 °C, in an autoclave of our own design, with palladium on barium sulfate as catalyst. The purity of the products was checked by infrared spectroscopy, and in some cases by gas chromatography. The ethers were cleaved by *Prey*'s method. In this way, substances with pressure coefficients up to 8×10^{-3} atm^{-1} were obtained. This corresponds to a viscosity increase of almost 7 powers of ten between 1 and 2000 atm.

Thus by systematic modification of the molecular structure it was possible to find definite groups of chemically uniform substances with pressure coefficients of viscosity that extend far beyond the range covered by mineral oils.

I am grateful to the Chemische Werke Hüls AG. for their generous cooperation, and to the Bergbau-Forschungsgesellschaft GmbH. for some of the samples studied. Thanks are due to Dr. H. Stegemeyer and Dipl.-Chem. P. Pollmann for discussions on chemical questions and in particular for carrying out the preparative work, and to Dr. J. Moos for helpful discussions. I should also like to thank the Hannoversche Hochschulgemeinschaft.

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Translated by Express Translation Service, London

[14] See, *e.g.*, *K. Jellinek*: Lehrbuch der Physikalischen Chemie Vol. I, p. 806, Enke, Stuttgart 1928; *A. Eucken* and *E. Wicke*: Grundriß der physikalischen Chemie, 8th Ed. p. 124, Akad. Verlagsgesellschaft Leipzig 1956; *E. Darmois*: L'Etat liquide de la matière, 2nd Ed., A. Michel, Paris 1943, pp. 141, 221.

COMMUNICATIONS

Synthesis of 5-Aryl-1-methyl-[1,2,4]-triazolo[4,3-d] tetrazoles

By Prof. Dr. F. L. Scott, Dipl.-Chem. R. N. Butler, and Dr. D. A. Cronin

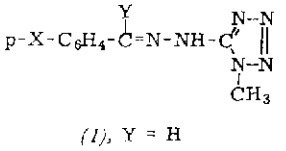
Chemistry Department, University College, Cork (Ireland)

We have prepared methyl derivatives of type *(1)*, hitherto unreported, in two ways.

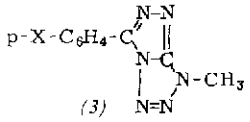
The best method (A) is by the reaction of one equivalent of a benzaldehyde tetrazolylhydrazone [1] in the presence of one equivalent of sodium hydroxide, in 50 % aqueous ethanol solution with 1.2 equivalents of methyl iodide in acetone, the whole mixture being refluxed for 45 minutes. On cooling, the 1-methyl compounds *(1)* precipitate out. A number of other methylated derivatives are formed in small (<10 %) yields in each case.

The second (and unambiguous) method (B) of synthesis involved treating a benzaldehyde 4-methylthiosemicarbazone with lead monoxide and sodium azide in refluxing ethanol under nitrogen [2]. Here, the main products are 1-arylalkylidenecamino-5-methylaminotetrazoles.

When compounds *(1)* were mixed with two equivalents of bromine in glacial acetic acid and the reaction mixtures then stirred for 4 hours at ambient temperatures, careful addition of cold water to the solution precipitated out the bromo derivatives *(2)*. These were dissolved in 50:50 (v/v) dioxane- or acetone-water mixtures with brief heating (10 min at 50 °C) and the resulting solutions were stirred at ambient temperatures for an additional 60–100 minutes. The reaction mixtures were distributed between ether and water. The ethereal layers contained the new 5-aryl-1-methyl-[1,2,4]-triazolo[4,3-*d*]tetrazoles *(3)*. They were dried before removing the ether.



(1), Y = H
(2), Y = Br



(3)

X	*(1)*, Yield [%] A	B	*(1)*, M.p. [°C]	*(2)*, Yield [%]	*(2)*, M.p. [°C]	*(3)*, Yield [%]	*(3)*, M.p. [°C] [a]
H	54	1.2	209	68	147	70.2	157
Cl	41.5	1.9	219–221	75	159	84	173
CH_3	74.5	<0.1	230–232	56	143	82	156–158

[a] These melting points are extremely sensitive to rates of heating. Methyl isocyanide is evolved when the materials melt.

With no alkyl group present at the tetrazole ring in *(2)*, the products are triazolyl azides [3].

Received: July 28th, 1965 [Z 56/881 IE]
German version: Angew. Chem. 77, 963 (1965)

[1] Synthesis: *F. L. Scott, W. N. Morrish,* and *J. Reilly*, J. org. Chemistry *22*, 692 (1957).
[2] *R. Stolle* and *E. Gaertner*, J. prakt. Chem. *132*, 209 (1931).
[3] *F. L. Scott* and *D. A. Cronin*, Tetrahedron Letters *1963*, 715.

Transesterification of Methyl and Ethyl Phosphates, Phosphonates, and Phosphinates in the Presence of Tertiary Phosphines

By Dr. H. G. Henning and G. Busse

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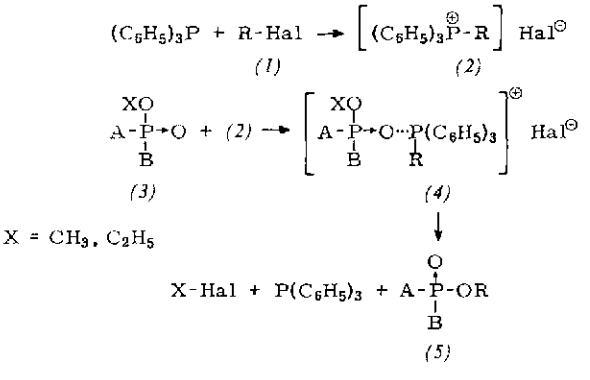
Methyl and ethyl esters *(3)* of phosphoric, phosphonic, or phosphinic acids react surprisingly readily (140–180 °C, 20 to 120 min) with alkyl or aralkyl halides *(1)* in the presence of small amounts (0·01 mole) of triphenylphosphine, yielding the alkyl or aralkyl esters *(5)* and methyl or ethyl halide. The triphenylphosphine, in whose absence the reaction requires appreciably more vigorous conditions (160–210 °C, 10–25 h, bomb tube) [1], may be replaced by other tertiary phosphines, *e.g.* tri-n-butylphosphine, but not by other tervalent phosphorus compounds (phosphonous esters, triphenyl phosphite) or triphenylphosphine oxide. The tertiary phosphine reacts first with the halide *(1)* to give the quaternary phosphonium salt *(2)*, whose adduct *(4)* with the ester *(3)* immediately loses methyl or ethyl halide, regenerating the tertiary phosphine.



The same results are obtained by direct reaction of the pure phosphonium salts *(2)* with the esters *(3)* in the presence or absence of a solvent (xylene, dimethylformamide, *o*-dichlorobenzene).

R	Hal	A	B	*(5)*, Yield [%] [a]	*(5)*, B.p. [°C/mm]
n-C_7H_{15}	Br	C_2H_5O	C_2H_5O	30.0	85/0.08
		C_2H_5O	n-$C_7H_{15}O$	9.1	133/0.003
		n-$C_7H_{15}O$	n-$C_7H_{15}O$	6.2	172/0.0005
Benzyl	Cl	C_2H_5	C_2H_5O	21.7	174/18.5
		C_2H_5	Benzyl-O	10.8	168/0.6
n-C_9H_{19}	Br	n-C_9H_{19}	n-C_9H_{19}	45.6	149/0.002

[a] Molar proportion of *(1)*:*(3)* used = 1:1. Reaction time: 1 h. The esters *(5)* were isolated by distillation. Unsymmetrical diesters are partly rearranged during the reaction to two symmetrical diesters and partly undergo alkene fission. Yields refer to the amount of *(3)* used.

Received: August 9th, 1965 [Z 48/874 IE]
German version: Angew. Chem. 77, 963 (1965)

[1] *A. N. Pudovik, A. A. Muratova, T. J. Konnova, T. Feoktistova,* and *L. N. Levkova*, Zh. obshch. Khim *30*, 2624 (1960); Chem. Abstr. *55*, 15 332 (1961).

Reactions of N,N-Disubstituted Formamides with Alkali Metals

By Prof. Dr. H. Bredereck, Dr. F. Effenberger, and Dr. R. Gleiter

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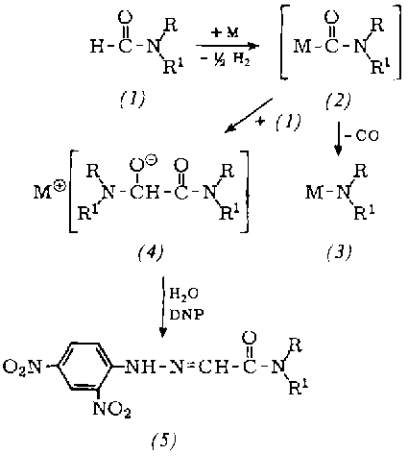
N,N-Disubstituted formamides *(1)* react with alkali metals (Na, K, or Li) in inert solvents with evolution of hydrogen, yielding alkali dialkylamides *(3)* [1] and glyoxylamide derivatives *(4)*. Both products are formed in finely divided condition, and the amides *(4)* are isolated as 2,4-dinitrophenylhydrazones *(5)* after hydrolysis of the whole reaction mixture (25 °C).

The alkali salt *(2)* of the formamide is probably first formed, then partly decomposes into alkali dialkylamide *(3)* and partly forms the alkali salt *(4)* of the substituted glyoxylamide.



Reaction at a higher temperature (*e.g.* in mesitylene at 140 to 150 °C) gives almost exclusively the sodium dialkylamide, which can be used in this form for further reactions (*e.g.* M = Na, R = R^1 = CH_3 or C_2H_5).

R	R^1	Temp. [°C]	Solvent	M	*(5)*, Yield [%]	*(5)*, M.p. [°C]
CH_3	CH_3	35	Ether	Na	31	201
CH_3	CH_3	80	Benzene	Na	37	201
C_2H_5	C_2H_5	80	Benzene	Na	3,4	140–141
C_6H_5	CH_3	80	Benzene	Na	34	217–219
CH_3	CH_3	35	Ether	Li	34	201
CH_3	CH_3	80	Benzene	K	42	201

Received: August 9th, 1965 [Z 52/878 IE]
German version: Angew. Chem. 77, 964 (1965)

[1] *J. C. Powers, R. Seidner,* and *Th. G. Parsons*, Tetrahedron Letters *1965*, 1713, report the formation of sodium dialkylamides from *N,N*-disubstituted formamides and sodium hydride.

Preparation of α-Hydroxy Ketones by Hydrolysis of α-Amino Ketones

By Doz. Dr. E. F. Jenny and Dipl.-Chem. A. Melzer

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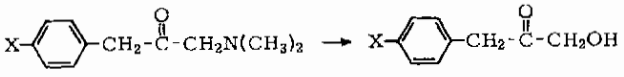
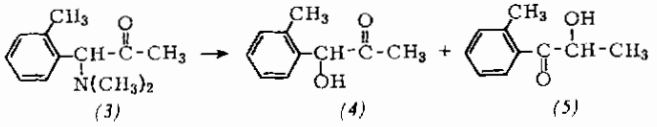
We have found that α-amino ketones, which are stable as free bases, are surprisingly easy to hydrolyse to α-hydroxy ketones. Thus the α-dimethylamino ketones *(1)* and *(3)* yield, respectively, the α-hydroxy ketones *(2)* and *(4)* plus *(5)* when

boiled in pyridine [*(1a)* and *(3)* for 20 h, *(1b)* for 1 h] in presence of HCl (1–3 eq.) and water (5–10 eq.). These α-hydroxy ketones are not very stable under the reaction conditions but can be isolated in 30–50 % yield.



(1), *(a)*: X = H
(b): X = NO_2 *(2)*



(3) *(4)* *(5)*

Hydrolysis of the amino ketones *(1a)* and *(1b)* labeled with ^{14}C in the carbonyl group occurs without positional change of the ^{14}C. Thus the carbon skeleton remains intact during the changes *(1a)* → *(2a)* and *(1b)* → *(2b)*, and there is no migration of the aralkyl group [*]. The reaction seems to be related to the rearrangement of α-anilino ketones [1], with water playing the part of the aniline.

The compound *(1b)* was obtained, with its *o*- and *m*-isomers, by nitration of *(1a)* [2]. Labeled *(1a)* was prepared from $(CH_3)_2NCH_2{}^{14}CN$ and benzylmagnesium chloride [2]; compound *(3)* was prepared by hydration of the Sommelet rearrangement product from benzyldimethylpropargylammonium chloride. We confirmed the structure of *(2b)* by synthesis: *p*-nitrophenylacetyldiazomethane [3] afforded *(2b)* when decomposed with aqueous sulfuric acid. For determination of the position of ^{14}C the hydroxy ketones *(2)* were reduced with $NaBH_4$ and the resulting α-glycols were cleaved by sodium periodate to give formaldehyde (dimedone derivative) and phenyl- or *p*-nitrophenylacetaldehyde (semicarbazone or oxime, respectively). All the new compounds and mixtures of isomers gave the expected analytical values, NMR signals, and infrared and ultraviolet bands.

Received: August 12th, 1965 [Z 49/875 IE]
German version: Angew. Chem. 77, 964 (1965)

[*] Skeletal rearrangements of α-amino ketones were reported by *C. L. Stevens, R. D. Elliott, B. L. Winch,* and *J. L. Klundt*, J. Amer. chem. Soc. *84*, 2272 (1962).

[1] *K. L. Nelson, J. C. Robertson,* and *J. J. Duvall*, J. Amer. chem. Soc. *86*, 684 (1964).

[2] *D. Shapiro*, J. org. Chemistry *15*, 1027 (1950).

[3] *K. Kaji, H. Nagashima, N. Ninoi,* and *T. Hanada*, J. pharmac. Soc. Japan *75*, 438 (1955); Chem. Abstr. *50*, 2548 (1956).

Electrophilic Substitution by α-Azido Ketones [1]

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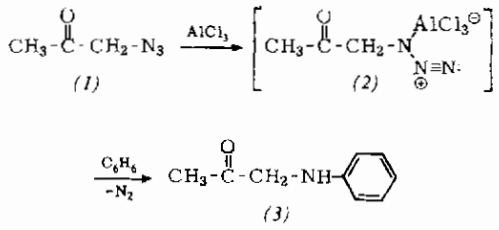
α-Azidoacetone *(1)*, b.p. 53–55 °C/2.5 mm, readily accessible from α-chloroacetone and sodium azide [2], reacts with benzene in the presence of 3 moles of aluminum chloride (5 h at 50 °C) with evolution of nitrogen, yielding α-anilinoacetone *(3)*, m.p. 59–60 °C (hydrochloride, m.p. 140–141 °C), in 35 % yield. α-Azidocyclohexanone, b.p. 70–72 °C/0.3 mm [3], yields α-anilinocyclohexanone, m.p. 84–85 °C (perchlorate, m.p. 190–190.5 °C), analogously in 25 % yield.

Reaction is presumably initiated by electrophilic attack of the aluminum chloride on the N(α) atom of the azide group [4]. The complex *N*-diazonium salt *(2)* assumed as intermediate behaves like a preformed nitrenium ion and on reaction with benzene affords the α-anilino ketone *(3)* with evolution of nitrogen; *i.e.*, *(2)* reacts electrophilically with benzene.



(1) *(2)* *(3)*

In this reaction aliphatic-substituted nitrenium ions have been trapped for the first time with benzene in good yield. These ions are usually stabilized by alkyl or hydrogen migration [5], but these rearrangements are apparently made more difficult in α-azido ketones by the influence of the carbonyl group. Experiments with α-azido carboxylic esters indicate that ester groups have the same effect.

Received: August 16th, 1965 [Z 51/877 IE]
German version: Angew. Chem. 77, 963 (1965)

[1] N_2-Eliminations under the Influence of Lewis Acids, Part III. – Part II: *R. Kreher* and *G. Jäger*, Z. Naturforsch. *20b*, 276 (1965).

[2] *M. O. Forster* and *H. E. Fierz*, J. chem. Soc. (London) *93*, 81 (1908).

[3] *O. E. Edwards* and *K. K. Purushothaman*, Canad. J. Chem. *42*, 712 (1964).

[4] A further mole of aluminum chloride is required by the carbonyl group.

[5] *R. Kreher* and *G. Jäger*, Z. Naturforsch. *19b*, 657 (1964).

Synthesis of Monodisperse Oligoacrylic Acid by Means of a Template Reaction

By Prof. Dr. H. Kämmerer

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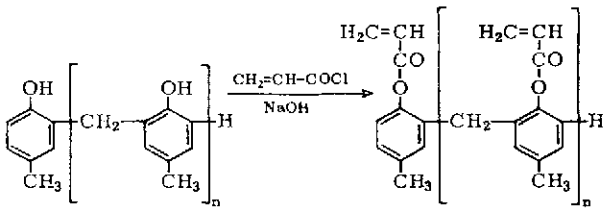
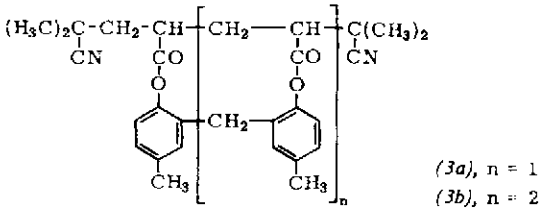
We have synthesised oligoacrylic acid derivatives of type *(4)* by means of a template reaction. The templates used were monodisperse, structurally homogeneous compounds *(1)* that contain *p*-cresol units linked by methylene groups [1]. Treatment of these compounds with acryloyl chloride (molar ratio 1:6 in aqueous NaOH/benzene; addition of the arcyloyl chloride dropwise during 3 h with stirring and cooling in ice) gave the products *(2)* in which the hydroxy groups are quantitatively esterified (yield 95 %; isolated as usual from the benzene layer). Treatment with an excess of azodiisobutyronitrile initiates "polymerization" of compounds *(2)* [about 2.5 mmoles of *(2)* in 200 ml of benzene and 129 mmoles of azodiisobutyronitrile in 200 ml of benzene were added dropwise to 3 l of benzene in 3 h]. Owing to the high dilution, the polymerization proceeds only for as many propagation steps as there are acyl groups in *(2)*. The product, which in accord with experience in cyclopolymerization probably has structure *(3)*, was isolated in 70 % yield by evaporation of the benzene, treatment with petroleum ether, filtration, and washing with petroleum ether. Hydrolysis of *(3a)* with aqueous NaOH/benzene affords the derivative *(4)* of trimeric acrylic acid in 25 % yield; its structure was proved by conversion into the tetramethyl ester with diazomethane and by isolation and identification of the polynuclear phenol formed on hydrolysis.

The oligomeric template has thus predetermined the molecular size of the product. To our kowledge no other reaction is known in polymer chemistry that gives monodisperse products in a single step. The product *(4)* is a mixture of stereoisomers of unknown composition. A stereospecific oligomerization is being attempted.

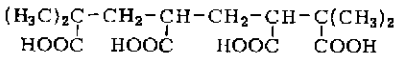
Reactions of the kind described above may perhaps be models for protein synthesis in the living cell.



(1a), n = 1 *(2a)*, n = 1
(1b), n = 2 *(2b)*, n = 2



(3a), n = 1
(3b), n = 2



(4)

Received: August 27th, 1965 [Z 59/886 IE]
German version: Angew. Chem. 77, 965 (1965)

[1] Synthesis: *H. Kämmerer, W. Rausch,* and *H. Schweikert,* Makromolekulare Chem. *56*, 123 (1962).

Di-π-cyclopentadienyltitanium Bis(hydrogen sulfide)

By Dr. H. Köpf and Prof. Dr. Max Schmidt

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der Universität Marburg (Germany)

Di-π-cyclopentadienyltitanium bis(hydrogen sulfide) *(2)* was prepared in almost quantitative yield by the reaction of di-π-cyclopentadienyltitanium dichloride *(1)* [1] with hydrogen sulfide and the stoichiometric amount of triethylamine in anhydrous ether (1 h at 20 °C):

$$\underset{(1)}{(C_5H_5)_2TiCl_2} + 2\ H_2S + 2\ N(C_2H_5)_3 \rightarrow \underset{(2)}{(C_5H_5)_2Ti(SH)_2} + 2\ (C_2H_5)_3N{\cdot}HCl$$

Compound *(2)*, which is surprisingly stable towards oxidation by air and toward hydrolysis, is freed from the accompanying amine hydrochloride by extraction of the mixture with water and is recrystallized from chloroform. The brown-black, malodorous crystals decompose at 150–160 °C. In chloroform solution *(2)* is monomeric [2]. The ^1H-NMR spectrum in $CHCl_3$ [3] contains two sharp signals, at 6.34 (C_5H_5) and at 3.44 (SH) ppm, with an intensity ratio of 5:1. As expected, the proton signal at 3.44 ppm is missing in the spectrum (in $CDCl_3$) of the compound $(C_5H_5)_2Ti(SD)_2$ prepared analogously from D_2S.

The presence of two SH groups was confirmed by iodometric determination of the hydrogen sulfide quantitatively liberated by hydrogen chloride according to

$$(2) + 2\ HCl \rightarrow (1) + 2\ H_2S$$

and by methylation with dimethyl sulfate to di-π-cyclopentydienyltitanium bis(methyl sulfide) [4]. Compound *(2)* does not react with diazomethane. In boiling benzene it slowly eliminates H_2S with the formation of polycrystalline oligomers containing Ti–S–Ti bonds.

Received: September 3rd, 1965 [Z 57/883 IE]
German version: Angew. Chem. 77, 965 (1965)

[1] *G. Wilkinson* and *J. M. Birmingham*, J. Amer. chem. Soc. *76*, 4281 (1954).

[2] By vapor-pressure osmometry (Mechrolab 301 A).

[3] Saturated solution, tetramethylsilane as external standard (Varian A 60).

[4] *S. A. Giddings*, U.S.-Patent 3030395 (April 17th, 1962); Chem. Abstr. *57*, 9881 (1962).

Intermediate Occurrence of 1,2-Dehydrocyclooctatetraene

By Dr. A. Krebs

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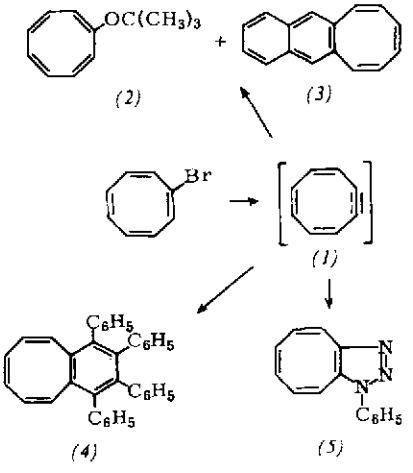
The ring strain and reactivity of 1,2-dehydrocyclooctatetraene *(1)* should lie between those of 1,2-dehydrobenzene, a confirmed but non-isolable intermediate, and of cyclooctyne [1] which can be isolated.

After treatment of bromocyclooctatetraene [2] with an ethereal suspension of potassium t-butoxide and subsequent hydrolysis potassium bromide was found in the aqueous phase in a yield of 95 %. Separation of the reaction mixture gave, apart from a high-melting, brown powder insoluble in ether and benzene, t-butoxycyclooctatetraene *(2)* by distillation, b.p. 37–38 °C/0.05 mm, yield 16 %, and naphtho-2,3-cyclooctatetraene *(3)*, m.p. 113–114 °C, yield 9 %, by chromatography of the distillation residue on silica gel with CCl_4.



The structure *(2)* was proved by elemental analysis, the NMR spectrum, acid hydrolysis to cycloocta-1,3,5-trien-7-one (isolated as the 2,4-dinitrophenylhydrazone [3]), and hydrogenation to t-butoxycyclooctane, which was synthesized independently from cyclooctanol. The structure *(3)* was proved by elementary analysis, spectra (particularly NMR), oxidation (by O_3 and CH_3CO_3H) to 1,2,4,5-benzenetetracarboxylic acid, and independent synthesis of 2,3-cyclooctenonaphthalene, which is obtained on hydrogenation of *(3)*.

The probable intermediacy of 1,2-dehydrocyclooctatriene in this reaction of bromocyclooctatetraene was shown by trapping reactions: if the HBr elimination is carried out *e.g.* in the presence of tetraphenylcyclopentadienone or phenyl azide, the adducts *(4)*, m.p. 241–242 °C, yield 72 %, and *(5)*, m.p. 67.5–68 °C, yield 38 %, respectively, are obtained. The con-

stitutional proof for the compounds *(4)* and *(5)* was obtained from elementary analysis, spectra, and hydrogenation to the corresponding known cyclooctyne adducts [4].

Received: September 6th, 1965 [Z 58/884 IE]
German version: Angew. Chem. 77, 966 (1965)

[1] *A. T. Blomquist* and *L. H. Liu*, J. Amer. chem. Soc. *75*, 2153 (1953).

[2] Preparation: *A. C. Cope* and *M. Burg*, J. Amer. chem. Soc. *74*, 168 (1952); *G. Schröder*, personal communication.

[3] *A. S. Cope, S. F. Schaeren*, and *E. R. Trumbull*, J. Amer. chem. Soc. *76*, 1096 (1954).

[4] *G. Wittig* and *R. Pohlke*, Chem. Ber. *94*, 3276 (1961).

Selective Protolysis of Unsaturated Organoaluminum Compounds

By Dr. B. Bogdanović

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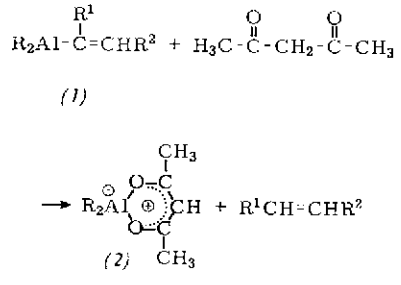
Vinyl groups can be removed preferentially from alkylvinyltin compounds by electrophilic reagents [1]. Similarly vinylboranes are cleaved by acids more easily than alkylboranes [2]. We have found also that organoaluminum compounds of type *(1)*, obtainable by addition of hydridodialkylaluminums to acetylenes, are susceptible to selective protolysis. From compound *(1)* and acetylacetone one obtains exclusively the olefin and acetylacetonatodialkylaluminum *(2)* although Al-alkyl bonds are easily cleaved protolytically.



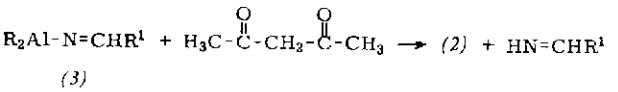
(1)

(2)

R^1 = H, Alkyl
R^2 = Alkyl, Aryl

A solution of acetylacetone in a hydrocarbon, *e.g.* toluene, is dropped slowly at 0° to −30 °C into a solution of the organoaluminum component (molar ratio 1:1). Disappearance of a yellow coloration due to interaction of the compounds *(1)* and *(2)* indicates the end of the reaction. The olefin is separated from the organometallic component by distillation. If this method of cleavage is used in the stereospecific reduction of acetylenes to *cis*-olefins with dialkylaluminum hydrides [2a], the usual hydrolytic cleavage of all metal-carbon bonds can be avoided.

Aluminum imides *(3)*, obtainable by addition of hydridodialkylaluminums to nitriles [3], can also be cleaved selectively at the Al–N linkage by means of acetylacetone, whereby also compound *(2)* and aldimines result. This reaction is significant for the synthesis of aldimines [4], since it can be conducted at very low temperature (−80 °C) where aldimines do not polymerize.



(3)

R^1 = Alkyl

Compounds of the type $R_2Al\text{-}NR_2$ (R = alkyl) are not selectively cleaved at the Al–N linkage, which shows that the H^+ ions attack the π-electron pair of the double bond and not the electron pair of the nitrogen atom. The same is true for compounds *(1)*.

Acetylacetonatodialkylaluminums, which have not been described before [5], are liquids, sensitive to air, monomeric, and almost colorless, and can be distilled in vacuum; their compositions and infrared and H^1–NMR spectra accord with structure *(2)*. Acetylacetonatodiethylaluminum has b.p. 55–56 °C/1–2 mm, and the diisobutyl analogue 40–45 °C/10^{-4} mm.

Received: September 9th, 1965 [Z 67/893 IE]
German version: Angew. Chem. 77, 1010 (1965)

[1] *D. Seyferth*, Progr. inorg. Chem. *3*, 129 (1962).

[2] *H. C. Brown* and *G. Zweifel*, J. Amer. chem. Soc. *81*, 1512 (1959).

[2a] *G. Wilke* and *H. Müller*, Chem. Ber. *89*, 444 (1956); Liebigs Ann. Chem. *618*, 267 (1958); *629*, 222 (1960).

[3] *L. J. Zakharkin* and *J. M. Khorlina*, Proc. Acad. Sci. USSR, chem. Sect. (engl. Transl.) *116*, 422 (1957).

[4] Ketimines can be similarly obtained by addition of Grignard compounds to nitriles, followed by protolysis: *P. L. Pickard* and *T. L. Tolbert*, J. org. Chemistry *26*, 4886 (1961).

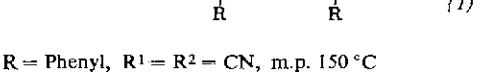
[5] Acetylacetonatodialkylboron compounds have been described recently: *M. F. Hawthorne* and *M. Reintjes*, J. Amer. chem. Soc. *86*, 5016 (1964).

Divinylogous Methylenephosphoranes from Conjugated Diynes, Trialkylphosphines, and Active Methylene Compounds

By Dr. H.-E. Sprenger and Dr. W. Ziegenbein

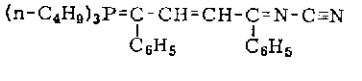
Forschungslaboratorien der Chemischen Werke Hüls AG, Marl (Germany)

Direct preparation of divinylogous methylenephosphoranes can be effected by simultaneous reaction of active methylene compounds and trialkylphosphines with conjugated diynes. For instance, equimolar amounts of diphenyl- or bismorpholinomethyl-1,3-butadiyne with tri-n-butylphosphine and malononitrile, fluorene, or anthrone in ether, tetrahydrofuran, or benzonitrile under reflux afford the methylenephosphoranes *(1a)–(1d)*, which are isolated as follows: After evaporation of the solvent or after mixing the benzonitrile solution with ether [for *(1c)*] the reaction products are washed with ether or quickly recrystallized from methanol, ethanol, dioxane, and benzene [for *(1d)*, *(1a)*, *(1c)*, and *(2)*, respectively].



(1)

(1a), R = Phenyl, $R^1 = R^2 = CN$, m.p. 150 °C
(1b), R = Phenyl, CR^1R^2 = anthromylidene, m.p. 210 °C
(1c), R = Phenyl, CR^1R^2 = fluorenylidene, m.p. 215 °C (decomp.)
(1d), R = Morpholinomethyl, $R^1 = R^2 = CN$, m.p. 200 °C (decomp.)



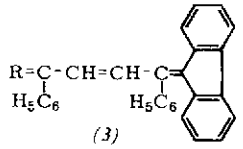
(2), M.p. = 136 °C

With NH-acidic compounds, *e.g.*, cyanamide, products of type *(2)* are formed.

Structures of the products were proved by elemental analysis and by ultraviolet, infrared, and NMR spectroscopy.

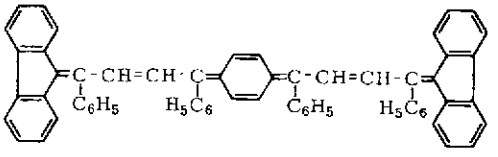
Of the compounds indicated, only *(1c)* reacts with carbonyl compounds and *p*-quinone to give colored, easily crystallizable olefination products of structures *(3)* and *(4)*. Reaction conditions: *(1c)* is heated with exess carbonyl compound or in a solution of an equimolecular amount of carbonyl com-

pound in benzonitrile containing a trace of hydroquinone. Heating is continued until the blue colour of *(1c)* disappears. The products are precipitated with methanol and recrystallized from butanol or tetrahydronaphthalene [preparation of *(4)*].



(3)

R = C_6H_5CH, m.p. 187 °C
R = $C_6H_5CH{=}CH{-}CH$, m.p. 106 °C
R = $C_6H_5{-}C{-}CH_3$, m.p. 146 °C
R = 2-Furylmethylene, m.p. 159 °C
R = Fluorenyliden, m.p. 170 °C
R = *o*-$HO{-}C_6H_5{-}CH$, m.p. 194 °C



(4), M.p. 320° C

Received: September 10th, 1965 [Z 65/891 IE]
German version: Angew. Chem. 77, 1011 (1965)

Synthesis and Reactions of N,N,N′,N′-Tetramethyl-3-methoxy-1-propene-1,3-diamine and N,N,N′,N′,N″,N″-Hexamethyl-2-propene-1,1,3-triamine

By Prof. Dr. H. Bredereck, Dr. F. Effenberger, Dr. R. Gleiter, and cand. chem. K. A. Hirsch

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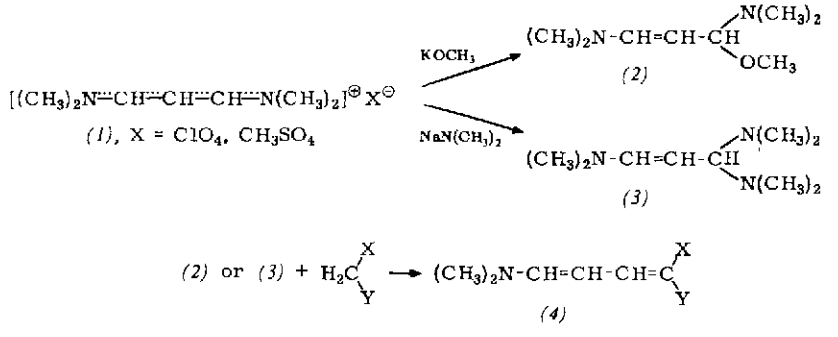
N,N-Dimethyl-3-dimethylaminoprop-1-enylideneammonium perchlorate or methyl sulfate *(1)* [1,2] react with potassium methoxide, giving the vinylogous aminal ester 3-methoxy-*N,N,N′,N′*-tetramethyl-1-propene-1,3-diamine *(2)*, and with sodium dimethylamide, giving the vinylogous trisdimethylamino compound, *N,N,N′,N′,N″,N″*-hexamethyl-3-propene-1,1,3-triamine *(3)*. Both products are even more reactive than the vinylogous amidacetal, *N,N*-dimethyl-3,3-dimethoxypropenylamine described recently [1] and with CH-acidic compounds gives derivatives *(4)* of butadiene.



(1), X = ClO_4, CH_3SO_4

(2) or *(3)* + $H_2C(X)(Y)$ → $(CH_3)_2N{-}CH{=}CH{-}CH{=}C(X)(Y)$ *(4)*

(4)	X	Y	M.p. [°C]	Yield [%]	
(a)	C_6H_5CO	H	117	70	[a]
(b)	C_6H_5	CN	102	74	[a]
(c)	*p*-$NO_2C_6H_4$	H	177	4	[b]
(d)	*p*-$NO_2C_6H_4$	H	177	32	[c]

[a] From *(2)* or *(3)*; [b] from *(2)*; [c] from *(3)*.

Examples:

N,N,N,N′-Tetramethyl-3-methoxy-1-propene-1,3-diamine *(2)*: 19.55 g (0.5 g-atom) of potassium is heated in 200 ml of anhydrous benzene at 75 °C and finely divided with a vibrator. When the suspension has cooled, a solution of 16.01 g (0.5 mole) of anhydrous methanol in 400 ml of anhydrous benzene is added with stirring during 2 h, with heating under reflux for ½ h near the end of the reaction. 113.32 g (0.5 mole) of *N,N*-dimethyl-3-dimethylaminopropenylideneammonium perchlorate is added, and the whole heated for a further 2 h under reflux, allowed to cool, and filtered from the potassium perchlorate that separates. The benzene is distilled off in vacuum and the residue fractionated through a short column. Yield 47.5 g (60 %) of colorless liquid, b.p. 75–76 °C/10 mm.

N,N,N′,N′,N″,N″-Hexamethyl-3-propene-1,1,3-triamine *(3)*: To a suspension of 33.5 g (0.5 mole) of sodium dimethylamide in 500 ml of anhydrous benzene is added 113.32 g (0.5 mole) of the perchlorate *(1)*, and the mixture is heated for 2 h under reflux and processed as described above. Yield 52.5 g (62 %) of colorless liquid, b.p. 75–76 °C/10 mm.

4-Dimethylamino-1-phenyl-1,3-butadienenitrile *(4b)*: 2.34 g (0.02 mole) of benzyl cyanide, 50 ml of anhydrous petroleum ether (b.p. 100–130 °C), and 31.6 g (0.02 mole) of compound *(2)* are heated together at 110 °C for 4 h. The precipitated oil solidifies when kept for a day in a refrigerator. The crystal cake is powdered, filtered off, washed with petroleum ether (b.p. 50–70 °C) (twice with 50 ml), and dried for 24 h in vacuum. The crude product (3.45 g) is recrystallised from *ca.* 300 ml of anhydrous petroleum ether (b.p. 100–130 °C) in presence of basic aluminum oxide and dried for 48 h in vacuum. Yield 2.94 g (74 %) of yellow needles, m.p. 102 °C.

Received: September 10th, 1965 [Z 63/889 IE]
German version: Angew. Chem. 77, 1010 (1965)

[1] *H. Bredereck, F. Effenberger*, and *D. Zeyfang*, Angew. Chem. 77, 219 (1965).

[2] *Z. Arnold* and *J. Zemlicka*, Coll. czechoslov. chem. Commun. 25, 1318 (1960).

Disubstitution in the Vilsmeyer-Haack Aldehyde Synthesis [*]

By Prof. Dr. Ch. Grundmann and Judith M. Dean

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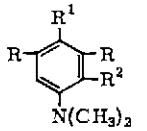
The reaction of an aromatic system with the complex from phosphorus oxychloride and an *N*-formylated secondary amine is known as the Vilsmeyer-Haack aldehyde synthesis. Although it belongs to the most frequently used methods for the preparation of aromatic aldehydes, the introduction of more than one formyl group per aromatic ring has never been achieved [1].

We have, however, found it surprisingly easy to convert *N,N*-dialkylanilines into dialdehydes. Thus from *N,N*-dimethylaniline *(1)* and 2–3 moles of the $POCl_3$-dimethyl-

formamide complex [2], a mixture of 4-dimethylaminobenzaldehyde *(2)* and 4-dimethylaminoisophthaldialdehyde *(3)* is formed from which *(3)* may be isolated with 15–20 % yield. 3,5-Dimethyl-*N*,*N*-dimethylaniline *(4)* is even more easily diformylated. Under conditions which convert *(1)* exclusively to *(2)* [3] a mixture of about equal parts of unchanged *(4)*, 4-dimethylamino-2,6-dimethylbenzaldehyde *(5)*, and 4-dimethylamino-2,6-dimethylisophthaldialdehyde *(6)* is formed. The application of more than two moles of formylating agent results in the exclusive formation of the dialdehyde *(6)* in 60–80 % yield. Monoformylation of *(4)* can only be achieved by adding one mole of the $POCl_3$–DMF complex at 5 °C very slowly to a large excess (5–10 moles) of the amine.



(1), R = R^1 = R^2 = H
(2), R = R^2 = H, R^1 = CHO
(3), R = H, R^1 = R^2 = CHO
(4), R = CH_3, R^1 = R^2 = H
(5), R = CH_3, R^1 = CHO, R^2 = H
(6), R = CH_3, R^1 = R^2 = CHO

The constitution of the aldehydes *(3)*, *(5)*, and *(6)* was ascertained by NMR-spectroscopy: *(5)* displays, beside signals for the *C*-methyl (τ = 7.45) and *N*-methyl (τ = 7.00) groups, only one signal for the two aromatic protons (τ = 3.70) and one signal (unsplit) for the aldehydic proton (τ = −0.08). The dialdehydes *(3)* and *(6)* each give two signals for aldehydic protons (τ = 0.03 and −0.20, resp. τ = 0.10 and −0.28); *(6)* gives furthermore a split signal for the *C*-methyl groups (τ = 7.40 and 7.20). No indication was obtained for the presence of the 2-dimethylaminoisophthaldialdehydes isomeric with *(3)* and *(6)*. The introduction of a third formyl group was not possible even under more rigid conditions.

4-Dimethylaminoisophthaldialdehyde (3) [4]:

N-Dimethylaniline (12.1 g) is added to phosphorus oxychloride (50.0 g) and DMF (81.2 g). The reaction mixture is heated with stirring and exclusion of moisture for 16 hours to 60–65 °C, then poured on ice (600 g), and 33 % NaOH (150 ml) is added at no more than 15 °. After several hours' cooling to 0 °C, the crystalline precipitate, consisting of *(2)* and *(3)*, is filtered off, washed with water and dried in vacuum (11.3 g). Exhaustive ether extraction of the alkaline mother liquor followed by evaporation of the ether yields further 3.5 g. To separate *(3)* from *(2)* the product is distilled with steam until the distillate does not deposit any more crystals of *(2)* on cooling to 0 °C. The crude dialdehyde *(3)* (3.4 g) separates in crystalline form from the aqueous solution (100 ml) remaining in the distillation flask on cooling to 0 °C. After two recrystallizations from ligroine yellowish felted needles of pure *(3)*, m.p. 72 °C, are obtained. Yield: 2.4 g (14 %).

4-Dimethylamino-2,6-dimethylbenzaldehyde (5):

A formylating mixture prepared from phosphorus oxychloride (15.6 g) and dimethylformamide (30.0 g) is added dropwise, with stirring and exclusion of moisture, within 4 hours at 5–10 °C to 3,5-dimethyl-*N*,*N*-dimethylaniline (75.5 g). After keeping the reaction mixture for 16 hours at 25–30 °C, it is decomposed with ice (300 g), made alkaline with 33 % NaOH (75 ml) and extracted with ether. After evaporation of the ether, excess amine *(4)* is distilled off (56.6 g; b.p. 61–62 °C/0.2 mm), and *(5)* is obtained in thick, almost colorless plates (12.5 g, 69 %) from the residue after one recrystallization from ligroine, m.p. 83 °C.

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German version: Angew. Chem. 77, 967 (1965)

[*] This work was supported by Public Health Service Research Grant CA 07272-02 of the National Cancer Institute, Bethesda, Md. (U.S.A.).

[1] The only exception – although with a pseudo-aromatic system – seems to be the preparation of azulene-1,3-dialdehyde from azulene; *K. Hafner* and *C. Bernhard*, Angew. Chem. *69*, 533 (1957); Liebigs Ann. Chem. *625*, 108 (1959).

[2] In principle, these syntheses can be carried out as well with *N*-formyl-*N*-methylaniline; however, the separation of the basic aldehydes from the *N*-methylaniline is more difficult.

[3] Org. Syntheses, Coll. Vol. IV, 331 (1963).

[4] Analogously *(6)*, m.p. 79 °C, is obtained in 81 % yield. Steam distillation of the crude product is unnecessary in this case.

Synthesis of Carboxylic Acids with 1,1-Dichloroethylene

By Dr. K. Bott

Forschungslaboratorien der Chemische Werke Hüls AG., Marl (Germany)

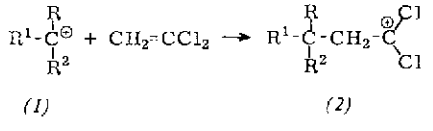
Treatment of carbinols, carbinol esters, or olefins obtainable from carbinols by loss of water with 1,1-dichloroethylene in 80 to 100 % sulfuric acid leads to substituted propionic acids *(3)* (cf. Table). The reaction, which takes place at 0 to 15 °C, is greatly accelerated by boron trifluoride and gives particularly good yields when carbonium ions can easily be formed from the carbinols or olefins used.

Carbinol, ester, or olefin	Product *(3)*	Yield [%] of *(3)*
Norbornene	*exo*-Norbornylacetic acid	72
1-Adamantanol	1-Adamantanylacetic acid [1]	93
1-Bromoadamantane	1-Adamantanylacetic acid	86
α-Methylbenzyl alcohol	3-Phenylbutyric acid; carboxylic acids of higher molecular weight [a]	50 20–25
Benzhydrol	3,3-Diphenylpropionic acid	71
t-Butyl chloride	3,3-Dimethylbutyric acid [b]	78
t-Butyl alcohol	3,3-Dimethylbutyric acid	79
Isobutene	3,3-Dimethylbutyric acid	75

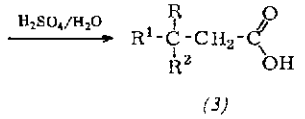
[a] These acids (structure not yet clarified) are probably formed by oligomerization of styrene.

[b] Düsobutene (dimerisation product of isobutene, principally 2,4,4-trimethyl-1- and -2-peotene) and isobutyl alcohol yield only 3,3-dimethylbutyric acid.

The principle of this carboxylic acid synthesis consists in addition of a carbonium ion *(1)* to 1,1-dichloroethylene, giving *(2)*, followed by hydrolysis to the acid *(3)*.



(1) *(2)*



(3)

Received: September 15th, 1965 [Z 61/887 IE]
German version: Angew. Chem. 77, 967 (1965)

[1] *H. Stetter*, *M. Schwarz*, and *A. Hirschhorn*, Chem. Ber. *92*, 1630 (1959).

Formation of Carbonyl Compounds from Azines or Hydrazones with Active Manganese Dioxide

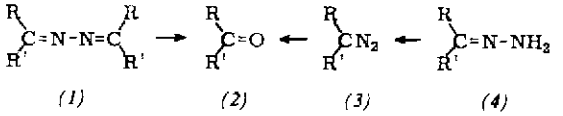
By Priv.-Doz. Dr. G. Maier and cand. chem. U. Heep

Institut für Organische Chemie der Technischen Hochschule Karlsruhe (Germany)

Treatment of 2,5-diphenyl-3,4-diazanorcaradiene with active precipitated manganese dioxide (E. Merck, Darmstadt) gives *cis*-1,2-dibenzoylcyclopropane and nitrogen [1]. We have

tested this reaction for its general applicability and have found that the azines *(1a)* to *(1e)* can be converted smoothly and quantitatively into the carbonyl compounds *(2)* hy stirring them at room temperature with an excess of manganese dioxide in benzene or carhon tetrachloride. We have also studied the hydrazones *(4a)* to *(4d)*. Whereas azines are cleaved relatively slowly (reaction time 2 h to 14 days), hydrazones afford the carbonyl compounds *(2)* more easily (within a few hours), and equally quantitatively, under the same conditions. In the latter case diazo-compounds *(3)* are formed as intermediates, which can be detected spectroscopically. 9-Fluorenone hydrazone is converted analogously into 9-fluorenone by way of 9-diazofluorene.

The carbonyl compounds *(2)* are formed directly from the diazo compounds *(3)* by exchangc of nitrogen for oxygen; thus diphenyldiazomethane gives benzophenone quantitatively. The fact that only acetone arises from acetone



(1) *(2)* *(3)* *(4)*

(a) R = R' = C_6H_5 *(d)* R = R' = CH_3
(b) R = C_6H_5; R' = CH_3 *(e)* R = CH_3; R' = H
(c) R = C_6H_5; R' = H

hydrazone shows that alcohols cannot be intermediates; if they were, isopropyl alcohol would be obtained since it is stable under the reaction conditions.

Benzil dihydrazone gives tolane quantitatively within 30 min, hut no benzil. Moreover, no benzil is obtained from benzil monohydrazone since α-diazo ketones (*e.g.* diazoacetophenone) – and also diazoacetic ester – do not exchange their nitrogen for oxygen. This explains why diazo ketones can be isolated on oxidation of monohydrazones of α,β-dioxo compounds with manganese dioxide [2].

Carboxyhydrazides react with active manganese dioxide with evolution of nitrogen, giving carboxylic acids in quantitative yields.

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German version: Angew. Chem. 77, 967 (1965)

[1] *G. Maier*, Chem. Ber. *98*, 2438 (1965).

[2] *S. Hauptmann, M. Kluge, K.-D. Seidig*, and *H. Wilde*, Angew. Chem. *77*, 678 (1965); Angew. Chem. internat. Edit. *4*, 688 (1965).

Ortho-Rearrangement of Metalated Butynyl Benzyl Ether

By Prof. Dr. U. Schöllkopf and Dr. M. Rizk

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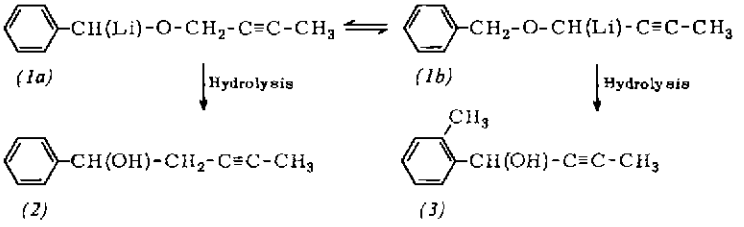
der Universität Göttingen (Germany)

Two types of rearrangement are known [1] to compete in the base-induced rearrangement of trialkylbenzylammonium salts, namely, the Stevens rearrangement (1,2-shift) and the Sommelet rearrangement (*ortho*-rearrangement) in which an alkyl group migrates to the *ortho*-position of the benzyl group. Hitherto only the 1,2-shift has been known for alkyl benzyl ethers, for which it is known as the Wittig rearrangement [1].

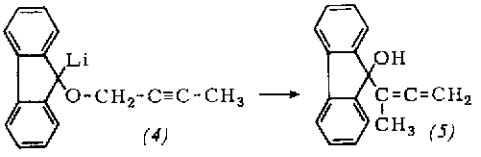
We have now found that an isomerization corresponding to the Sommelet rearrangement is also possible for one of these ethers. For instance, if 2-butynyl lithiobenzyl ether *(1)*, prepared from benzyl 2-butynyl ether and butyl-lithium in tetrahydrofuran at −30 °C, is kept for 14 h in tetrahydrofuran at −60 °C and the mixture is then hydrolysed with CH_3OH/H_2O at 60 °C, 1-(*o*-methylphenyl)-2-butyn-1-ol *(3)* can be isolated in 46 % yield as a result of an *ortho*-rearrangement; 1-phenyl-3-pentyn-1-ol *(2)* is formed also, in 18 % yield, by a Wittig rearrangement [2].

We assume that the rearrangements involve the two metalated ethers *(1a)* and *(1b)*. Whereas the 1,2-shift may occur by a fission-recombination mechanism [3], the course of the *ortho*-rearrangement is unknown.



(1a) *(1b)* *(2)* *(3)*

9-Lithio-9-fluorenyl 2-butynyl ether *(4)*, when similarly treated, yields only 9-(1-methylallenyl)-9-fluorenol *(5)* [4].



(4) *(5)*

Received: September 29th, 1965 [Z 70/899 IE]
German version: Angew. Chem. 77, 1012 (1965)

[1] Cf. *G. Wittig*, Angew. Chem. *63*, 15 (1951); Experientia *14*, 389 (1958); *H. E. Zimmermann* in *P. DeMayo*: Molecular Rearrangements. Interscience, New York/London 1963, Vol. I, p. 372.

[2] Proof of structures by synthesis.

[3] *U. Schöllkopf et al.*, Liebigs Ann. Chem. *642*, 1 (1961); *654*, 27 (1962); *663*, 22 (1963); *H. P. T. Lansbury* and *V. A. Pattison*, J. org. Chemistry *27*, 1933 (1962); J. Amer. chem. Soc. *84*, 4295 (1962).

[4] In cooperation with Dipl.-Chem. *K. Fellenberger*.

Formation of Ylides on Thermal Decomposition of P-(α-Alkoxycarbonylalkyl)triphenylphosphonium Salts

By Prof. Dr. H. J. Bestmann, Dr. H. Hartung, and I. Pils

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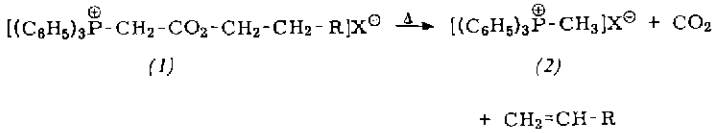
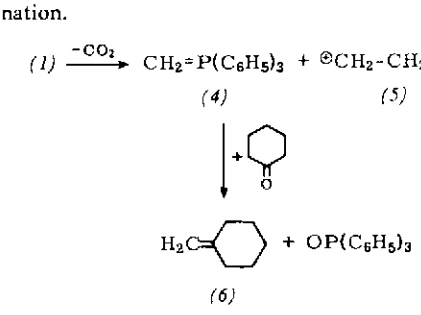
P-(Alkoxycarbonylmethyl)triphenylphosphonium salts *(1)* decompose when heated above the melting point, yielding a methyltriphenylphosphonium salt *(2)*, an olefin *(3)*, and carbon dioxide [1].



(1) *(2)* *(3)*

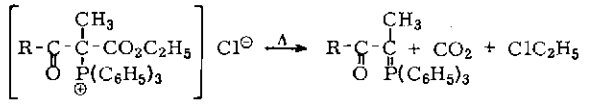
We assume that this reaction begins with the formation of an alkylidenephosphorane *(4)* and a carbonium ion *(5)*, from which the products *(2)* and *(3)* are at once formed by β-elimination.



(1) *(4)* *(5)* *(6)*

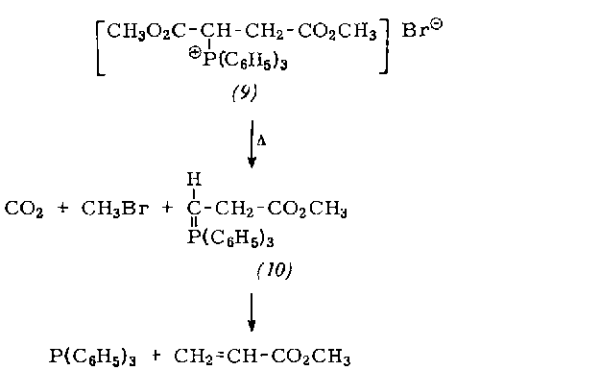
The intermediate occurrence of the phosphorane *(4)* becomes obvious if the decomposition is carried out in boiling cyclohexanone; on subsequent distillation methylenecyclohexanone *(6)* is obtained in 1 % yield.

On thermal decomposition of *P*-(1-acyl-1-ethoxycarbonylethyl)triphenylphosphonium chlorides *(7)* the residues consist of the stable ylides *(8)* (R = C_6H_5, m.p. 172 °C, yield 98 %; R = C_6H_5–CH=CH, m.p. 200 °C, yield 82 %). The compounds *(8)* are weak bases. They attack the carbanions *(5)* (R – H) only slowly, and these ions react preferentially with the chloride ions; one thus obtains ethyl chloride which distils off and can be isolated in a cooled receiver.



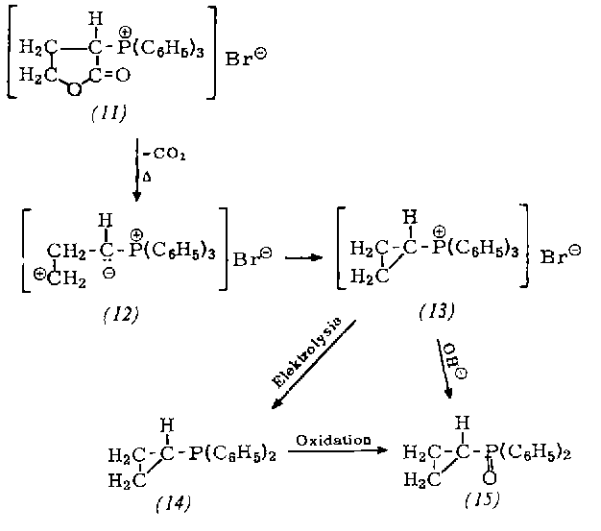
(7) *(8)*

Heating *P*-[1,2-di(methoxycarbonyl)ethyl]triphenylphosphonium bromide *(9)* at 150 °C affords methyl acrylate (75 %) and triphenylphosphine (70 %). We assume that an ylide *(10)* is formed as intermediate in this case also and then decomposes into the products named owing to an intramolecular Hofmann degradation[2]. During the decomposition methyl bromide distils alongside the ester and can be condensed in a cooled receiver.



(9) *(10)*

Carbon dioxide is evolved when the phosphonium salt *(11)* obtained[3] from α-bromo-γ-butyrolactone and triphenylphosphine is heated at 180–190 °C. The carbonium ion *(12)*, assumed to be an intermediate product, passes into cyclopropyltriphenylphosphonium bromide *(13)* by *C*-alkylation of the ylide that is present in the same molecule; this salt *(13)*, which is not otherwise accessible, remains quantitatively as residue in the reaction vessel.



(11) *(12)* *(13)* *(14)* *(15)*

Treating the bromide *(13)* with aqueous sodium hydroxide affords cyclopropyldiphenylphosphine oxide *(15)*, and electrolysis of the aqueous solution[4] affords cyclopropyldiphenylphosphine *(14)* that can be converted into the oxide *(15)* by oxidation. Nuclear magnetic resonance spectra of *(13)*, *(14)*, and *(15)* are in accord with the structures assigned.

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[1] *A. Michaelis* and *H. v. Gimborn*, Ber. dtsch. chem. Ges. *27*, 272 (1894); *D. B. Denney*, *C. J. Rossi* and *J. J. Vill*, J. Amer. chem. Soc. *83*, 3336 (1961); J. org. Chemistry *29*, 1003 (1964).

[2] *H. J. Bestmann*, *H. Häberlein* and *I. Pils*, Tetrahedron *20*, 2079 (1964).

[3] *S. Fliszár*, *R. F. Hudson*, and *G. Salvadori*, Helv. chim. Acta *46*, 1580 (1963).

[4] For the electrolysis of phosphonium salts, see *L. Horner* and *A. Mentrup*, Liebigs Ann. Chem. *646*, 65 (1961).

A New Ring System Containing Boron

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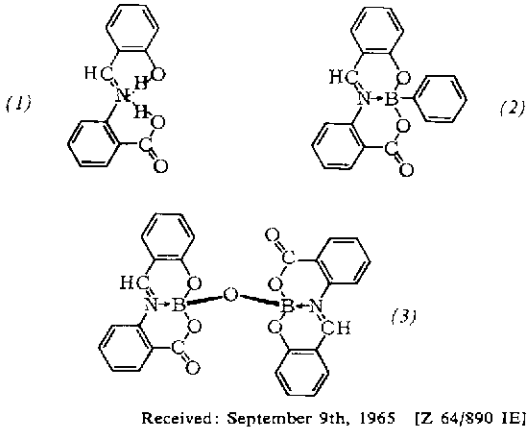
In chelates and chelating agents containing short intramolecular hydrogen bonds (2.4–2.6 Å), boron can be introduced in place of the proton [1, 2]. In *N*-salicylidenanthranilic acid *(1)* there are two possibilities for hydrogen bonds to the same N atom. Thus it should be possible to replace two hydrogen atoms by a single boron atom. In fact, when compound *(1)* reacts with diphenylborinic acid, one phenyl residue is removed from the latter with smooth formation of *B*-phenyl-(*N*-salicylideneanthranilato)-*O,O,N*)-boron *(2)*. Reaction with boric acid affords μ-oxobis-(*N*-salicylideneanthranilato)-*O,O,N*-boron *(3)*. The structures of the products were proved by analysis and infrared spectra. Compounds *(2)* and *(3)* have considerable stability towards acids and alkalis. It is surprising that attempts to prepare chelates of compound *(1)* with the bivalent metals Cu, Zn, and Cd led to chelates of anthranilic acid with fission of the azomethine linking.

Preparative methods

One mole each of compound *(1)* and a compound containing a *B*-phenyl group (phenylboronic or diphenylborinic anbydride, Flavognost®, Kalignost®) for preparation of *(2)*, or boric acid for preparation of *(3)*, are refluxed for about 15 min with about one liter of glacial acetic acid. After cooling, compounds *(2)* or *(3)* slowly crystallize. The products are washed first with glacial acetic acid and then with warm water and alcohol and are dried in a vacuum desiccator over sulfuric acid. They are yellow and fluoresce yellowish-green or green in ultraviolet light.



(1) *(2)* *(3)*

Received: September 9th, 1965 [Z 64/890 IE]
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[1] *F. Umland* and *D. Thierig*, Z. analyt. Chem. *197*, 151 (1963).

[2] *F. Umland* and *C. Schleyerbach*, Angew. Chem. 77, 426 (1965); Angew. Chem. internat. Edit. *4*, 432 (1965).

20th International Congress for Pure and Applied Chemistry, Moscow 1965

Between July 12th and 18th, 1965, more than 4000 scientists gathered in Moscow for the 20th IUPAC Congress. More than 650 plenary and short lectures were delivered, dealing with cosmochemistry, inorganic chemistry, analytical chemistry, radiation chemistry, the physical chemistry of surfaces and of disperse systems, and the fundamentals of chemical technology. An international symposium considered the properties and uses of low-temperature plasmas.

In the following, some of the contributions of interest to chemists are summarized.

Owing to the 3rd International Fluorine Symposium in August, only a few lectures were held on the chemistry of fluorine. *N. Bartlett* (Vancouver, Canada) has shown, by magnetic susceptibility measurements, that "PdF_3" should be written $Pd^{2+}[PdF_6]^{2-}$. The complex anion can be isomorphously replaced by $[GeF_6]^{2-}$, $[SnF_6]^{2-}$, and $[PtF_6]^{2-}$. Progress in the chemistry of the rare gases was reported by *J. G. Malm* (Argonne, Ill., U.S.A.). Solutions of XeF_6 can be oxidized with ozone in an alkaline medium to give perxenates, which contain Xe(VIII), and which are themselves extremely powerful oxidizing agents in acidic solutions. SiF_2, which had previously been known only from transport experiments, was isolated by *M. Schmeisser* (Aachen, Germany) by the thermal decomposition of Si_2F_6 and by the reaction of Si with SiF_4. The compound SiF_2 is monomeric below −80 °C, and readily polymerizes to form a white solid $(SiF_2)_\infty$. *R. Hoppe* (Münster, Germany) obtained very pure ternary fluorides by the fluorination of defined intermetallic compounds; *e.g.*, $NaTlF_4$ was obtained from NaTl.

Many contributions dealt with the synthesis of new inorganic compounds. *M. Dratovsky* (Prague, ČSR) prepared iodates containing I(VI), *e.g.*, Na_2IO_4, by the thermal degradation of periodates. In aqueous solution, IO_4^{2-} disproportionates into IO_3^- and IO_4^-; these iodates (IV) exhibit the expected paramagnetism of 1.7 B.M. in the crystalline state. With the aid of transport experiments in a temperature gradient of from 1200 to 1000 °C, *A. V. Novosselova* (Moscow, USSR) obtained single crystals of Be_2SiO_4; the participation of the gaseous substances $NaBeF_3$, $SiOF_2$, SiF_4, and NaF in the transport was explained on the basis of infrared and mass spectrometry. *A. N. Christiansen* (Aarhus, Denmark) prepared $BaMnO_3$ in a hydrothermal synthesis from freshly precipitated δ-$MnO_{1.8}$ in 0.4 M suspension of $Ba(OH)_2$, the synthesis being carried out under oxygen pressure at 200 to 330 °C in a steel autoclave lined with gold foil. *W. Gerrard* (London, U.K.) reported on the synthesis of inorganic polymers of the type $(-O-PO(OR)-O-SiCl_2-)_n$, which can be prepared from $SiCl_4$ and $OP(OR)_3$ by the elimination of RCl. Using the dilution principle and working in the absence of light, *M. Schmidt* and *E. Wilhelm* (Marburg, Germany) obtained the cyclic sulfur species S_6, S_{10}, and S_{12} from H_2S and S_2Cl_2; the reaction also appears to be suitable for the preparation of S_7, S_9, and S_{11}. *K. Dehnicke* and *J. Strähle* (Stuttgart, Germany) found that the azide chlorides $MoCl_5N_3$ and WCl_5N_3, which are obtained by reaction of $MoCl_5$ and WCl_6 with ClN_3, decompose with loss of N_2 and Cl_2 to form the nitride chlorides $MoNCl_3$ and $WNCl_3$ containing triple bonds between nitrogen and the metal. VCl_4N_3, on the other hand, loses only N_2 to form the readily volatile monomeric $Cl_3V{=}NCl$. According to *P. I. Paetzold* (München, Germany) the thermal decomposition of diaryl borazides at 180 °C leads to the formation of dimeric diarylborazenes $(ArN-BAr)_2$, which are extremely sensitive towards acids, but are thermally stable. The behavior of the BN four-membered ring is similar in many respects to that of the cyclobutadiene ring. A promising method for the preparation of ternary oxides was described by *C. C. Addison* (Nottingham, U.K.), who treated metal oxides such as TiO_2 and MoO_3 with a large excess of elementary sodium at 100 to 600 °C, to obtain *e.g.* Na_2TiO_2 and Na_2MoO_3. The excess of sodium, which acted as the reaction solvent, was distilled off in vacuum after the reaction.

Great interest was shown in the problems of semiconductor chemistry. According to *H. Krebs* (Stuttgart, Germany) a deeper understanding of the properties of semiconductors is offered by two factors: the localization of valence electrons on the atom with the greater effective nuclear charge, and the delocalization as a result of eigenfunctions having maxima in several directions, so permitting the establishment of a continuous bond system in the crystal. *A. A. Vypolin* (Leningrad, USSR) studied the semiconducting properties of compounds of the type $A^{II}B^{IV}C_2^V$, *e.g.* $CdSiP_2$ and $ZnSiAs_2$, in relation to their structure. The ternary compounds Ag_3SBr and Ag_3SI, which crystallize in the antiperovskite structure, were obtained in a solid state reaction by *B. Reuter* and *K. Hardel* (Berlin, Germany). The current is transported almost exclusively by Ag^+ ions, which migrate *via* cationic holes. According to *J. Flahaut* (Paris, France), rare earth sulfides of the type M_5S_7 (M = Dy to Tm) are formed by the thermal degradation of the normal sulfides M_2S_3 in vacuum at 1700 °C. These compounds are monoclinic, isomorphous with one another, and paramagnetic, and they possess semiconductor properties. Ternary sulfides of the type $BaTiS_3$ or $BaZrSe_3$ with semiconductor properties were prepared by *L. A. Aslanov* (USSR). The compounds are isotypic with $LiI{\cdot}3H_2O$.

In connection with the electronic structure and periodic properties of the elements, *N. S. Akhmetov* and *G. S. Vozdvizhensky* (Kasan, USSR) suggested, on theoretical and practical grounds, that the zeroth group of the periodic system should be included with the eighth group, and that the triads of the Fe, Co, and Ni groups should be inserted in gaps between Ar and Kr, between Kr and Xe, and between Xe and Rn, respectively.

Only a few of the lectures dealt with the theory and application of nuclear magnetic resonance spectroscopy. The relationships between chemical shifts and coupling constants on the one hand and properties such as electronegativity, bond energy, electron affinity, ionization potential, *etc.* on the other are not yet accessible to a quantitative theoretical treatment. *G. F. Svatos* (St. Louis, Mo., U.S.A.) attempted to treat the chemical shielding and the spin coupling as functions of the ionic and covalent contributions to the bond energy.

R. J. Chuck (London, U.K.), discussed ion-pair effects in the symmetrical ions $[B(CH_3)_4]^-$, $[Al(CH_3)_4]^-$, $[Al(C_2H_5)_4]^-$, $[Sb(CH_3)_4]^+$, $[Sb(C_2H_5)_4]^+$, and $[P(C_2H_5)_n(CH_3)_{4-n}]^+$. A study of the line-widths revealed a close relationship between ion-ion and ion-solvent interactions.

A new application of NMR spectroscopy has been found in the chemistry of gallium. The ^{71}Ga nucleus has a spin number of 3/2 and a resonance frequency of approximately 20 Mc/s at a field strength of 15400 gauss. *N. N. Greenwood* (Newcastle-upon-Tyne, U.K.) described investigations on complex gallium ions. Since the quadrupole moment is large in comparison with the magnetic moment of the nucleus, only symmetrical ions with no electric field at the position of the nucleus could be studied. The chemical shifts obtained were extremely large (> 1000 ppm). Initial investigations provided proof that gallium(II) halides have the structure $Ga[GaX_4]$. Several new ions were found on hydrolysis of gallium halides.

E. Fluck (Heidelberg, Germany) used ^{31}P resonance spectra to study ligand-exchange reactions in phosphorus halide

pseudo-halide systems such as $PCl_3/P(NCS)_3$, $OPCl_3/OP(NCS)_3$ *etc.* A random exchange of the halogen and pseudo-halogen ligands was observed in most cases.

B. F. Scribner (Washington, D.C., U.S.A.) surveyed recent advances in spectrochemical excitation sources. The properties of chemical flames have been greatly improved by the introduction of new fuel-gas compositions. Notable increases in sensitivity are often obtained by the addition of organic solvents to the specimen solutions. Electrical flames, such as the high-frequency torch and the d.c. plasma jet have considerable advantages over conventional excitation sources, such as high reproducibility and insensitivity to "matrix effects". Vaporization of the material with a laser beam combined with excitation of the metal vapor by a spark discharge has been found suitable for the study of small parts of a sample (*e.g.* inclusions, inhomogeneities). *I. A. Voinovitch* (Paris, France) reported that, in addition to 8-hydroxyquinoline, other quinoline derivatives as well as phenol and acetone eliminate the blocking effect of aluminium on the emission of Ca and Sr in the flame. Aliphatic amines and alcohols have little or no effect.

S. W. Webb (London, U.K.) described the use of a plasma jet in the determination of calcium in the presence of elements (*e.g.* aluminium and phosphorus) which seriously interfere with determinations in conventional flames. This interference, which is due to inhibition of evaporation, does not occur in the plasma jet, the temperature of which is approximately 7500 °K; thus with this excitation source, the calibration curves no longer depend on the other substances present in the solution. The spectroscopic determination of the isotopic composition of various substances was discussed by *A. N. Saidel* (Leningrad, USSR). Emission methods were generally used, and calibration samples with accurately known isotope abundances were not required for the semiquantitative analysis often used in routine work. In precision work in which calibration samples are used, ordinary spectroscopic equipment is generally capable of giving a relative accuracy of 1 %, or even 0.1 % in favorable cases.

Spectroscopic methods for the analysis of strongly radioactive materials were described by *C. Feldman* (Oak Ridge, Tenn., U.S.A.). Owing to the greater ease of calibration, solution methods are generally used. For the investigation of trace constituents, these must be separated from the bulk of the sample. In the case of solutions of nuclear fuels (thorium, uranium, *etc.*), extraction with esters of phosphoric acid or with amines has proved a suitable method of separation, while electrolysis may be useful for solutions of alloys (principal components Fe, Cr, Ni, *etc.*). *C. Cherrier* (Antony, France) has determined trace impurities in mercury by mass spectrometry. The sample was cooled to −140 °C at 2×10^{-7} to 3×10^{-7} mm Hg and vaporized with a high-purity graphite counter-electrode. A sensitivity of 0.5 atom per million was obtained with an exposure time of about 30 min. Other substances, such as very pure acids, can also be analysed in this way.

F. Lux (München, Germany) reported on the determination of small quantities of uranium and technetium in small samples of various matrices by X-ray fluorescence analysis. The sample is preferably used in the form of a thin layer (as in the case of samples for β-radiation measurements), the detection limit for uranium then being 10^{-4} %. Even at higher uranium and technetium contents, however, the layer method has a number of advantages over the usual analysis in solution.

According to *Cagnard* (Paris, France), a laser beam can be used to advantage for the excitation of the Raman spectra of unstable or light-sensitive organic compounds. The He-Ne laser emits a monochromatic beam at 6328 Å, which does not produce the photochemical effects observed with ordinary light, and which gives a spectrum without a continuous background.

In the gas-chromatographic analysis of alloys, *R. W. Moshier* (Wright-Patterson Air Force Base, Ohio, U.S.A.), converted the components of the alloys (*e.g.* Fe, Ti, Nb, Ta, W) into volatile β-diketone complexes, either by treating the anhydrous metal chlorides with 1,1,1,5,5,5-hexafluoropentandione in CCl_4 or by extracting the acetate-buffered solution of the sample with 1,1,1-trifluoropentandione in benzene, CCl_4, or $CHCl_3$. The solutions of the complexes were then introduced directly into the chromatograph.

The concentration of trace impurities in very pure metals by zone melting has been studied by *Sh. I. Peisulayev* (Obninsk, USSR). In adapting this originally preparative method of purification, one must bear in mind that appreciable losses occur as a result of evaporation or scorification of the impurities. The optimum velocity of zone travel and the number of passes required must be calculated separately for each individual case. According to *K. Ueno* (Fukuoka, Japan) it may be advantageous to convert the metal into one of its compounds before zone melting. Suitable compounds include chelates that melt without decomposing, particularly acetylacetonates.

In a plenary lecture on radiation chemistry, *F. S. Dainton* (Leeds, U.K.) spoke on "Important Early Stages in the Radiolysis of Solid and Liquid Systems". High-energy radiation is suitable for the ready production and study of radical-ions, solvated electrons, and free radicals.

M. Magat (Orsay, France), reported on "Radiation-Induced Polymerizations in Solids at Low Temperatures", and *M. Steinberg* (Upton, N.Y., U.S.A.) surveyed "Progress in the Industrial Use of High-Energy Radiation". Outside of the plastics field, only one radiation-induced process is used in industry today, *i.e.* the production of ethyl bromide from ethylene and hydrogen bromide; nevertheless, a number of other processes appear to be suitable. These include the reduction of carbon dioxide, the production of nitrogen oxides from nitrogen and oxygen, and the preparation of hydrazine from ammonia.

Many of the lectures dealt with the radiolysis of aqueous solutions and organic liquids and solids. The discussion was centered on the behavior of the electrons liberated by the ionizing radiation. The existence of solvated electrons in polar solvents is now established. The reactions of the solvated electron have been studied with the aid of electron acceptors, and the rate constants were measured by pulse radiolysis. Reactions with reactive substances have rate constants of up to 10^{10} l/mole sec. However, the reaction of the solvated electron with water is particularly slow. The lowest rate constant found so far for this reaction, according to *E. J. Hart* and *S. Gordon* (Argonne, Ill., U.S.A.), is 16 l mole^{-1} sec^{-1}. According to *A. Kupperman* (Pasadena, Calif., U.S.A.), the existing diffusion model for the radiolysis of water can be checked in the light of more accurate data now available for the reaction rates of electrons. The results show that a large proportion of the "primarily" formed H atoms (H-radical yield) result from a reaction of electrons with protons.

The question of the formation and existence of solvated electrons in non-polar solvents has not yet been settled. *G. Scholes* (Newcastle-upon-Tyne, U.K.), found that the irradiation of hexane in the presence of N_2O yields nitrogen, with a G value greater than two, indicating that electrons also exist in non-polar media. Similar results were obtained by *P. J. Dyne* (Chalk River, Canada) by the low-temperature irradiation of samples consisting of layers of hexane and carbon tetrachloride approximately 100 Å thick. In frozen hexane, the electrons have a range of about 200 Å. Using the same layer technique, *Dyne* also detected the transfer of energy between deuterated and undeuterated hexane.

Opposing views as to the mechanisms leading to the formation of solvated electrons were advanced by *G. R. Freeman* (Edmonton, Canada), and *R. Schiller* (Budapest, Hungary). The question of whether the deciding factor is the static or the dynamic behavior of the material, *i.e.* the static dielectric constant or the relaxation, has not yet been settled.

G. E. Adams (Northwood, Middlesex, U.K.), reported investigations on HO_2, O_2^-, OH, O^-, and O_3^- radicals. The rates of reaction of some of these radicals with organic

substances have been measured as functions of the molecular structure by the pulse radiolysis technique. The same technique has been used to determine the position of the acid-base equilibria of a number of radicals. Thus, according to *J. Rabani* (Jerusalem, Israel), the pK value of the equilibrium $\cdot OH + OH^- \rightleftharpoons O^- + H_2O$ is 11.9, and that of the equilibrium $\cdot HO_2 \rightleftharpoons H^+ + O^-_2$, according to *M. S. Matheson* (Argonne, Ill., U.S.A.) is 4.45.

Ch. S. Bagdassaryan (Moscow, USSR), detected the formation of stable radical-cations by a spectroscopic method, when amines were exposed to γ-rays in organic glasses. The quantum yield for the formation of the radical cation can be as high as 3. Thus in certain cases each primary ionization results in the formation of a radical cation. *G. O. Phillips* (Monmouthshire, U.K.), discussed the energy transfer during irradiation of carbohydrates in the presence of aromatic compounds. It can be shown by ESR spectroscopy and by yield measurements that the decomposition of the carbohydrates decreases in the presence of aromatics. The nature of this protection is not yet clear.

Yu. A. Kolbanovsky (Moscow, USSR), demonstrated the formation of polycarboxylic acids in the polymerization of carbonic acid and ethylene with γ-irradiated catalysts. The products (molecular weight ≈ 3000) contain one carboxyl group per 50 ethylene units, and are soluble in dimethylformamide. *A. J. Swallow* (Manchester, U.K.), in collaboration with *D. Hummel* (Cologne, Germany), reported on the radiation-induced addition of hydrogen chloride to olefins, which may proceed as a chain reaction. *D. Schulte-Frohlinde* and *F. Merger* (Karlsruhe, Germany) studied the mechanism of the radiation-induced hydroxylation of nitrophenol. The first step in this reaction is the extremely selective addition of the hydroxy radical to the benzene nucleus to form a cyclohexadienyl radical.

V. N. Kondratyev (Moscow, USSR), in his lecture on "Problems in the Study of Elementary Processes in Low-Temperature Plasmas", reviewed the present position of the theory and the experimental determination of data for the following processes: the thermal dissociation of diatomic and polyatomic molecules, exchange reactions, the excitation and ionization of atoms by electrons, collision ionization, recombinative ionization, electronic excitation, electronic energy transfer and charge transfer in collisions of atoms and molecules, reactions of ionized molecules, dissociative recombination, and associative ionization. Equilibrium constants cannot yet be determined with sufficient accuracy.

W. Lochte-Holtgreven (Kiel, Germany), in his lecture on "Simple Chemical Reactions in Plasmas", dealt with the formation of negative ions. The ions H^-, C^-, N^-, O^-, Cl^-, Ca^-, and Al^- have been detected by their continuous radiation. The preferred temperature range for the formation of these ions is beetwen 3000 and 8000 °K, *i.e.* higher than flame temperatures and lower than luminous-arc temperatures. This temperature range is reached by supplementary electric heating of flames; a quantity of electrical energy that roughly corresponds to the energy of combustion is supplied to the flame. Reaction products can be isolated from a plasma in various ways: by cooling a streaming plasma, by cooling the anode flame of a luminous arc, or by adiabatic cooling in vacuum. The last method in particular was used by *Lochte-Holtgreven* for the reduction of oxides at a high throughput: castings 15 cm long made of the oxide powder, charcoal, and tar when placed in a carbon tube anode, were reduced within a few seconds. The resulting metal was not pure, however, since the carbon anode partly disintegrated.

M. W. Thring (London, U.K.), in his lecture on "Plasma Engineering", surveyed the possible methods of using a plasma as a "commercial reaction system". He discussed *inter alia* the following endothermic processes which, although unable at present to compete with conventional methods of synthesis, may acquire some importance in the future, *e.g.* the preparation of acetylene in a plasma beam by reactions (a) and (b). The best yields of acetylene are ob-

$$2\,C + H_2 \rightarrow C_2H_2;\ \Delta H = -543\ \text{kcal} \quad \text{(a)}$$

$$2\,CH_4 \rightarrow C_2H_2 + 3\,H_2;\ \Delta H = -86\ \text{kcal} \quad \text{(b)}$$

tained if argon or helium is used as the carrier gas. At a plasma temperature of 12000 °K, 80 % of methane could be converted into acetylene.

Dicyanogen is formed in accordance with Equation (c) in a nitrogen plasma which reacts with the graphite cathode; the

$$2\,C + N_2 \rightarrow (CN)_2;\ \Delta H = -71\ \text{kcal} \quad \text{(c)}$$

yield is 15 %, based on the carbon used. Hydrocyanic acid has been obtained by the reaction of a graphite cathode with a hydrogen-nitrogen plasma. In this reaction (d), 50 % of the

$$2\,C + H_2 + N_2 \rightarrow 2\,HCN;\ \Delta H = -60.2\ \text{kcal} \quad \text{(d)}$$

carbon was converted into hydrocyanic acid and acetylene, which is the most important by-product formed.

Uranium carbide can be prepared from uranium dioxide and carbon at a plasma temperature of from 4000 to 5000 °K

$$UO_2 + 3\,C \rightarrow UC + 2\,CO;\ \Delta H = -179\ \text{kcal} \quad \text{(e)}$$

[Equation (e)]. In this case the uranium dioxide and carbon form the rod anode.

M. J. Joncich and *J. W. Vaughn* (Dekalb, Ill., U.S.A.) have prepared iodides, sulfides, halides, and carbides of magnesium and aluminum, as well as nitrides of magnesium, titanium, zirconium, tantalum, and aluminum, by exploding metal wires in the presence of a non-metal (*e.g.* sulfur, iodine). The yields were from 20 to 60 %. The nitrides of iron, rhodium, platinum, copper, zinc, and cadmium could not be obtained by this method. This synthesis of binary compounds has the following advantages: It permits the preparation of very hygroscopic substances; it can also be used to prepare compounds that are not formed under normal laboratory conditions, since the required activation energy is available only in the case of a wire explosion. The experimental arrangement is simple. The reactions are complete in 100 μsec or less, and the products are very rapidly cooled to the ambient temperature, particularly when the reaction is carried out in a liquefied gas. [VB 955/262 IE]

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International Congress on Fuel Cells

I. Low and Medium Temperature Cells

The Belgian Société d'Etudes, de Recherches et d'Applications pour l'Industrie organized a meeting in Brussels (Belgium) of scientists working on the development of fuel cells. This meeting was the largest on this subject so far to be held on European soil: 60 lectures were delivered to the 380 participants from June 21st to 24th, 1965.

C. Berger, Newport Beach, Calif. (U.S.A.) reported on organic and inorganic ion-exchange membranes. Single-membrane cells are easy to construct and are compact (representative specifications: 0.72 volt, 75 mA/cm², 110 kW/m³, and 80 W/kg). Their disadvantages are the difficulties encountered in controlling the temperature and moisture. Attempts have

been made to avoid these difficulties with double-membrane cells containing mobile electrolyte between two ion-exchange membranes connected to the electrodes, but the power density falls to 46 kW/m³. All organic exchange membranes are prone to decomposition by high temperatures and oxidative attack. The search for an ion-exchange material stable between 25 and 150 °C led to inorganic exchangers, particularly zirconyl phosphates. Membranes were made either from the pure inorganic material or by embedding it in organic supports. Zeolytes can also be incorporated in order to improve the moisture control. The results of prolonged experiments (300 h) at 150 °C are of interest for the direct conversion of hydrocarbons, which is possible only at high temperatures. Current densities of about 10 mA/cm² at a cell potential of 0.4 V were obtained with propane and butane at platinum electrodes using inorganic ion-exchange membranes. These figures are promising. Attempts were made to economise in the platinum consumption by direct impregnation of the membrane surfaces with the platinum catalyst.

K. Schwabe, Dresden (Germany) discussed the use of oxygen electrodes in fuel cells. Reduction of oxygen with high current densities at catalyst-free carbon electrodes can be achieved only in the strongly alkaline region. A platinum coating is required in the acidic range. Reduction of the Pt content from 10–20 mg/cm² to one-tenth these amounts with maintenance of the activity of the electrodes was achieved by a coating of an Al-V spinel. Satisfactory operation in long-term experiments depends largely on the type and amount of agent used for making the electrodes hydrophobic and on the method of impregnation. Application of a 3% solution of polyethylene in toluene proved to be suitable.

O. Vohler and *R. Martina*, Meitingen near Augsburg (Germany) have adopted a new method for making carbon electrodes for fuel cells with a sharp maximum in the pore distribution curve. Extraneous binding agents can be dispensed with by starting out from cellulose of uniform grain size; after coking, samples of satisfactory rigidity are obtained. The integral pore volume and the pore diameter can be influenced by the pressure used and the nature of the hydraulic fluid, *e.g.* H_2O,C_2H_5OH. The hydraulic press can be used simultaneously to introduce a catalyst into the electrode. This method was used to prepare double-layer carbon electrodes with two layers of different pore sizes. Up to 75% of the pore volume of the sintered carbon is accessible to the electrolyte; the specific surface area lies between 5 and 10 m²/g depending on the conditions used for its preparation.

J. M. Auclair, Marcoussis (France) found that sintered Ni/Ag electrodes can be used without activation on both the oxygen and hydrogen sides of hydrogen fuel cells. Industrial gases give current densities of 50 mA/cm² and cell potentials of 0.7 V at 20 °C. The current density rises to 300 mA/cm² on raising the temperature to 80 °C. CO contents of 1–5% in the gas do not interfere with the operation of the element; the current decrease is still reversible at 20–30% CO. In intermittent operation (current drawn for 10% of the time), the life of the cell is 22 months; in continuous operation at 50 mA/cm² it is 6 months.

H. A. Liebhafsky, Schenectady (U.S.A.) dealt with the problem of direct hydrocarbon combustion cells. Anodic oxidation of hydrocarbons occurs in a series of steps: adsorption, cleavage of C–H and C–C bonds, charge transfer, reaction of intermediates with the solvent, and removal of the reaction products. Since C–H bonds are split much easier on the catalyst than C–C bonds, there is a danger that carbon-rich intermediates accumulate and block the reaction. It was therefore surprising that complete oxidation of unbranched saturated hydrocarbons to carbon dioxide and water was observed. A gauze electrode containing platinum black as catalyst was developed as anode in the General Electric Research Laboratory. A thin porous layer of Teflon on the gas side maintains a stationary position of the three-phase boundary within the electrode. The reactivity increases from methane to propane and butane and then falls with increasing chain length. The same electrode can also be used as cathode. Because of the short diffusion path, operation with air instead of oxygen does not involve any significant reduction in output. Current densities of about 20 mA/cm² at 0.5 V were obtained with methane or propane in complete cells containing 85% phosphoric acid as electrolyte at 150 °C. Attempts to replace the acidic electrolytes with another CO_2-repellant but less corrosive electrolyte have so far remained without success. The major task is now to reduce the platinum content of the electrodes, to augment the activity with additives to the platinum, or to replace the expensive noble metal entirely. At present, about 500 g of Pt would be required to achieve an output of 1 kW.

H. Binder, *A. Köhling*, and *G. Sandstede*, Frankfurt/Main (Germany) studied the anodic oxidation of hydrocarbons in acids. In 3 N sulfuric acid, complete direct oxidation of methane, ethane, and propane can be achieved at 90 °C and +0.5 V (*vs.* a reversible hydrogen electrode). Ethylene is only 90% converted to carbon dioxide and water judging from measurements on porous gold electrodes containing 100 mg/cm² of Raney platinum as catalyst. Ethane and propane are the most reactive alkanes. The polarization potentials in 3 N sulfuric acid are lower at 100 °C than at 120 and 155 °C in 26 N phosphoric acid. When the unit is switched off, a small amount of hydrogen and CO_2 is reformed but no methane can be detected. With ethylene, the back reaction leads to CO_2 and ethane. Propane can displace some of the adsorbed hydrogen from the platinum surface judging from the current *vs.* potential curves determined by the potentiostatic potential method. The oxidation of the hydrocarbon occurs on the free surface, *i.e.* in the double-layer portion.

II. High Temperature Cells

G. H. J. Broers and *M. Schenke*, Amsterdam (Holland) dealt with high temperature cells run with paste electrolyte. The life and load capability of such cells have been considerably improved over the past few years but *Broers* maintains that there is still a long way to go before they will be ready for commercial exploitation. Greater demands are placed on the stability of the electrolyte (alkali metal carbonates + magnesium oxide) and electrodes at the high operating temperatures (about 720 °C) than in low temperature cells. Pulse and impedance measurements were made on cells with porous nickel anodes and silver or copper oxide cathodes. The material transport in the film of electrolyte on the electrodes is the rate-determining step. The ohmic potential drop Ri in the cell represents the major proportion of the total polarization. In prolonged experiments iR increases owing to evaporation losses from the carbonate electrolyte but the remaining polarization becomes constant after two months. Small units could be run for 6 months at 100 mA/cm², but the cell potential decreased from 750 to 480 mV during this period. A battery of ten elements in series utilizes 90% of a 1:1 hydrogen/carbon dioxide fuel mixture when the electrodes are worked at 62 mA/cm². The utilization under the same conditions for the gas at the cathode (2.5 parts air + 1 part CO_2) is 94%.

P. Lovy, La Plaine-St. Denis (France) reported that Gaz de France has worked since 1961 on the development of high temperature cells using fused alkali metal carbonates as electrolyte in attempts to use natural gas as an electrochemical fuel. Corrosion of the porous silver cathode used was suppressed by applying a layer 0.1 mm thick of sintered Al_2O_3. However, the electrodes cannot be piled up as in a filter press because they are so fragile. At present, concentric arrangements are being tested. A carbon tube activated with palladium is used as anode; this is covered with the sintered alumina layer containing the electrolyte and then surrounded by the silver electrode. The fuel gas flows through the carbon tube while the air/carbon dioxide mixture flows around the external cathode. Satisfactory mechanical stability is achieved

with this arrangement but its electrochemical properties are poor. At 600 °C and 20 mA/cm², the life of the cell is only a few days.

III. Cells with Solid Electrolyte

D. W. White, Schenectady (U.S.A.) explained that ZrO_2 doped with 7–10 mole-% Y_2O_3 has a higher conductivity at 800–900 °C than ZrO_2 containing 11–14 mole-% CaO. The gradual drop in conductivity can be reversed by brief heating at 1200–1400 °C. A cell with this electrolyte in the form of a crucible containing molten silver as oxygen cathode was run for 5 months using natural gas as fuel. Methane is pyrolysed at the outer wall, and the pyrolytic carbon is oxidized electrochemically to CO. The carbon monoxide and hydrogen pass out of the cell and must be burnt in another cell.

H. H. Möbius and *B. Rohland*, Greifswald (Germany) proposed the use of a bundle of 2500 tubes, each 1 m long, per m² as a suitable construction for a high temperature fuel element which is supplied on the inside with fuel gas and on the outside with air. Large units are expected to work with high efficiency only when the heat dissipated and remaining heat of combustion can be utilized in a coupled power generator. The production of stable electrodes presents some problems. Addition of cerium, uranium, and praseodymium oxides to the surface regions of the ZrO_2 was proposed in order to augment its electronic conductivity. Connection to the ceramic oxide electrodes could then be made through metallic point contacts.

IV. Nonporous Electrodes

M. A. Vertes and *A. J. Hartner*, New York, found that when fuel reformation is allowed to proceed inside the cell in the gas space of a nonporous palladium/silver foil electrode, the "lost heat" developed in the cell can be used for the endothermic reaction in the gas space. Since the foil electrode works satisfactorily at even low hydrogen partial pressures, temperatures of 200–250 °C are high enough in the reforming space. A nickel carrier catalyst is used for hydrocarbon fuels and a zinc/copper oxide catalyst for methanol as fuel. A limiting current density of 85 mA/cm² was found with hexane at 250 °C. Current densities of 100–200 mA/cm² with very little polarization were observed at temperatures as low as 200 °C with methanol/water vapor mixtures. Bacon electrodes were used as oxygen cathodes in complete cells with 85% KOH as electrolyte. With gasoline and oxygen, the cell can be run at 100 mA/cm² and 0.7 V at 250 °C.

S. M. Chodosh and *H. G. Oswin*, New York, investigated the activation of nonporous Pd/Ag electrodes as hydrogen anodes. The entry of the hydrogen into the Pd phase is known to be kinetically inhibited. Various possibilities for activating the foil surface on the gas side, *e.g.* by etching, oxidative or reductive treatment at high temperature, roughening with alumina powder, or the application of pouros layers of Pd or Pt, were discussed. Activating layers of noble metals were applied by galvanic methods or by immersing the palladium foil charged with hydrogen in solutions of the noble metal salts. Foil anodes 40–400 μ thick activated in this way exhibited diffusion-controlled limiting currents which were inversely proportional to the foil thickness. The stability of the activating layer was studied for several hundred hours at a load of 100 mA/cm² at 250 °C.

A. Küssner, Erlangen (Germany) examined irreversible changes in nonporous palladium/silver foil hydrogen electrodes. The diminution in activity and load capacity of hydrogen foil electrodes in long-term experiments led to the discovery of irreversible processes in the foil. The uptake of hydrogen in the palladium/silver alloy is accompanied by a continuous expansion of the lattice. If the foil electrode is now subjected to sporadic changes in load, pressure gradients arise in the proximity of the foil surface and lead to plastic deformations of the foil material. The diffusion of hydrogen is adversely affected by the resultant lattice defects. The alternating expansions and contractions also result is localized separations of the activated material from the base material. It is hoped that hardening of the material will bring improvements.

V. Electrocatalysis

C. E. Heath, Linden, N.J. (U.S.A.) assumed that the oxidation of methanol on platinum catalysts proceeds *via* surface oxides. Since ordinary platinum black does not sufficiently accelerate the reaction in acidic solution, attempts were made to modify the Pt surface by incorporation of other metals, *i.e.* to increase its specific surface area, and to alter its band structure or introduce defects. The experiments did not have the desired results. On the other hand, the introduction of immobile redox couples into the catalyst surface have an activating effect and determine the potential of the electrode. Methanol/air cells with a platinum/ruthenium catalyst were built which could be loaded with 50 mA/cm² at 50–60 °C and a cell potential of 0.5 V. Slightly lower cell potentials were observed in a battery of 16 cells.

F. P. Dousek, Prague (Czechoslovakia) found that the handling of Raney nickel hydrogen electrodes is complicated by the pyrophoric nature of this catalyst. This difficulty can be avoided by expelling most of the adsorbed hydrogen either by anodic polarization or by treatment with organic compounds that can be hydrogenated. However, the catalytic activity is always depleted by this treatment. *Dousek* observed that when Raney nickel is dissolved out of the Al/Ni alloy with 5 N sodium hydroxide and the solution is subsequently brought to pH 6.5 with tartaric acid, hydrogen is released. The desorption proceeds very rapidly when the nickel is heated to 90 °C with distilled water. After this mild treatment, the catalyst is still active but no longer pyrophoric. Electrodes similar to those of the Bacon type were made from this catalyst by sintering at 450 °C in an atmosphere of hydrogen and gave good current *vs.* voltage curves for the oxidation of hydrogen in long-term experiments, where they remained stable for over 10000 h of operation.

R. Jasinski, Waltham, Mass. (U.S.A.) reported that nickel boride of composition Ni_2B is an active catalyst for the hydrogen and hydrazine electrode. Its activity is greater than that of Pd or Pt for the hydrazine electrode.

The nickel borides NiB, Ni_4B_3, Ni_2B, and Ni_3B were studied by *H. Jahnke*, Stuttgart (Germany) by X-ray and metallurgical methods. When embedded in a nickel or gold support, Ni_3B is the best catalyst for the oxidation of hydrogen and methanol. Ternary Ni/B/Al alloys were made by sintering and activated like Raney alloys. The polarization of the methanol electrode with such a catalyst at 80 °C and 50 mA/cm² is 215 mV compared with 330 mV with Ni_3B. Since Raney nickel alone cannot catalyse the oxidation of methanol, the activity was ascribed to the NiB_{12} and B incorporated in the nickel catalyst.

I. Lindholm, Västerås (Sweden) also tested the suitability of catalytically active nickel borides as hydrogen electrodes. Sodium borohydride precipitates a black nickel boride of sum formula $Ni_{2\cdot35}B$ with a high specific surface area (31.7 m²/g) from solutions of $NiCl_2$. Some of the boron can be dissolved out with potassium hydroxide solution with concomitant increase in the specific surface area. This catalyst was dried *in vacuo* at 100 °C, mixed with nickel powder as an embedding medium, and the mixture was sintered. Hydrogen anodes were also obtained by precipitation of NiB_2 in preformed sintered nickel supports. In operation at 80 °C and 150 mA/cm², these had a polarization of 100 mV. In long-

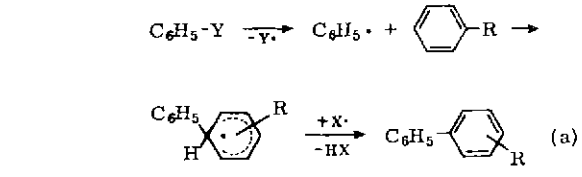
term experiments with single cells, the cell potential fell from 0.9 to 0.8 volt at a load of 50 m/cm² within 4000 h. Replacement of the noble metals in low temperature cells with the activated nickel boride catalyst produced a significant reduction in costs. However, the total cost of a battery cannot yet be given. [VB 952/256 IE]

German version: Angew. Chem. 77, 971 (1965)

Radical Phenylations with Aromatic Diazo Compounds

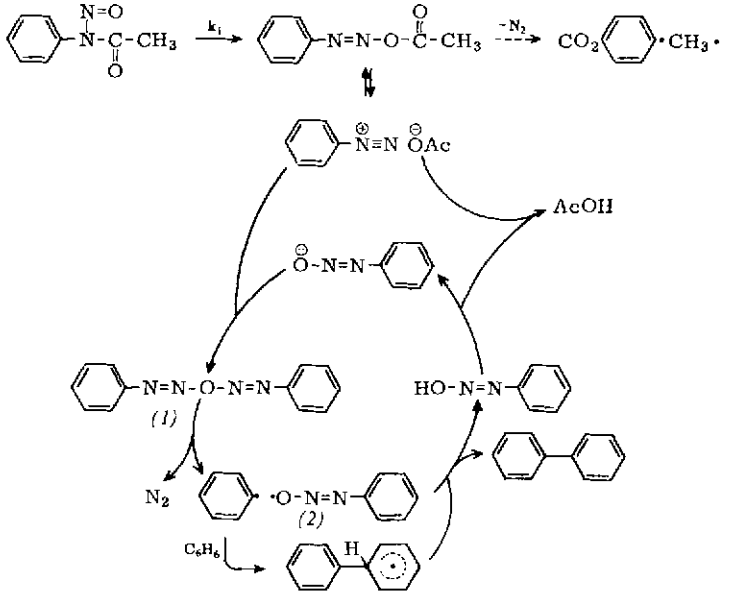
C. Rüchardt, Munich (Germany)

Aromatic radical phenylations occur by the addition-disproportionation mechanism (a). The nature of X· and Y· is essentially clarified for phenylations by dibenzoyl peroxide or

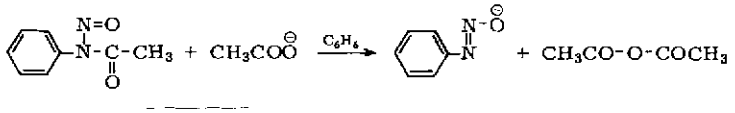


triphenyl(phenylazo)methane, but not for those by aromatic diazo compounds. Assuming that the phenyl radicals are generated from diazohydroxides (Gomberg reaction) or from diazoacetates (thermolysis of *N*-nitrosoacetanilide), or that hydroxyl or acetoxyl radicals constitute X·, contradicts a variety of experimental results [1].

Kinetic investigation of the Gomberg reaction showed that the rate of liberation of nitrogen is proportional to the square of the diazonium salt concentration and is greatest at the pH equal to the pK_a of the diazonium ion-diazotate equilibrium. The results were interpreted as slow formation of diazo anhydrides *(1)* in the aqueous phase and their rapid decomposition in the organic phase. In agreement therewith the formation of biphenyl from benzenediazonium chloride at pH 8.5 is greatly accelerated by addition of *p*-nitrobenzenediazonium chloride, and the yield of 4-nitrobiphenyl under similar conditions increases on addition of benzenediazonium chloride.



Initial reaction



The almost complete absence of evolution of CO_2 on thermolysis of *N*-nitrosoacylanilides, whose acyloxy-radicals must undergo decarboxylation without appreciable activation energy (as, for instance, phenylacetoxyl, phenoxyacetoxyl, or ethoxyoxalyloxy-radicals), is considered a convincing argument against homolytic decomposition of diazo esters formed as intermediates.

Acid anhydrides increase the yield of carbon dioxide from the decomposition of nitrosoacetanilide. The evolution of nitrogen from benzene solutions is first order only in very dilute solutions (0.01 M), and the rate is that of the formation of the diazo ester. The rate of evolution of nitrogen is decreased by the presence of vinylic monomers (acrylonitrile or styrene) and depends greatly on the nature of the solvent. The reaction hardly occurs at all in CCl_4. By reason of these results it was proposed that in the decomposition of diazo esters the formation and decomposition of diazo anhydrides occur in chain reactions. It is known that all steps of this chain reaction proceed rapidly in inert solvents. The diazotate radicals *(2)* were detected and identified by their ESR spectra, which showed them to have a relatively long life, as expected on the basis of chemical results [1].

From 4-chloro-*N*-nitrosobenzanilide in CCl_4 there is formed, besides *p*-chlorobenzoic anhydride and benzenediazonium chloride, a thermolabile compound which, on the basis of its physical and chemical properties, is perhaps the first isolated diazo ester.

[Chemical Colloquium, Universität Heidelberg, June 28th, 1965] [VB 949/258 IE]

German version: Angew. Chem. 77, 974 (1965)

The Acid-Base Catalysis of the Mutarotation of Glucose

Hermann Schmid and *Günther Bauer*, Vienna (Austria)

The negative entropy of activation of the water-catalysed mutarotation of glucose is ascribed to the facts that the activating process is the transfer of a proton from the hydroxyl group on the carbon atom adjacent to the ring oxygen to a water molecule and that the electrical field between the ions formed tends to align the solvent dipole in the activated complex.

$$HG_\alpha + H_2O \xrightarrow{H_2O} \text{activated complex } (G^\ominus \ldots H_2O \ldots H_3O^\oplus)$$

HG_α denotes α-glucose and $G^\ominus$ is the glucose anion in the activated complex.

The activation enthalpy of the catalysis with ammonia is almost 4 kcal/mole lower than that of the catalysis with water because the ammonium ion formed in the reaction of glucose with ammonia has a lower tendency to align the solvent dipole in the activated complex than the hydronium ion formed on activation of the α-glucose with water.

The enthalpy of activation for the catalysis with hydronium ions is identical with that for the catalysis with water, but its entropy of activation is less negative. The catalysis with hydronium ions is in fact water catalysis in which the solvent dipole entering the activated complex is "pre-aligned" by the hydronium ions added as catalyst. The activation enthalpies of the mutarotation of glucose catalysed by anions (formate, acetate, α-glucosate, hydroxyl) also correspond to the activation enthalpy of the catalysis with water. These reactions are also water catalyses in which the first step is a reaction of the hydration shell of the ions with the α-glucose.

The rate of mutarotation of glucose in water was measured with and without addition of finely divided copper powder under otherwise identical conditions. The energies of ac-

[1] *C. Rüchardt, B. Freudenberg*, and *E. Merz*: Organic Reaction Mechanisms. The Chemical Society, Special Publication No. 19, London, 1965, p. 168.

tivation were determined by the Arrhenius method; for pure water the value is 17.8 kcal/mole, for "copper catalysis" it is 19.0 ± 1.5 kcal/mole. This heterogeneous catalysis is also a water catalysis by the water molecules which are oriented on the surface of the copper. The mutarotation of glucose does not proceed *via* the open-chain aldehyde; instead, the activated α-glucosate ion inverts to the β-glucosate ion.

Table 1. Catalysis coefficients for the mutarotation of glucose.

Catalyst	Catalysis coefficients [sec^{-1}]		
	5 °C	15 °C	25 °C
NH_3	–	6.26×10^{-2}	0.142
H_2O	–	1.72×10^{-6}	4.90×10^{-6}
$H_3O^{\oplus}$	–	2.23×10^{-3}	6.67×10^{-3}
$HCOO^{\ominus}$	–	3.06×10^{-4}	8.63×10^{-4}
$CH_3COO^{\ominus}$	1.52×10^{-4}	4.88×10^{-4}	1.48×10^{-3}
$C_6H_{11}O_6^{\ominus}$	0.114	0.336	1.00
$OH^{\ominus}$	9.18	27.8	90.7

Table 2. Activation parameters for the mutarotation of glucose.

Catalyst	ΔG* [kcal/mole]			ΔH*	ΔS*
	5 °C	15 °C	25 °C	[kcal/mole]	[cal mole^{-1} deg^{-1}]
NH_3	–	18.4	18.6	13.3	−17.6
H_2O	–	24.4	24.7	17.2	−24.9
$H_3O^{\oplus}$	–	20.3	20.4	17.2	−10.7
$HCOO^{\ominus}$	–	21.5	21.6	17.1	−15.2
$CH_3COO^{\ominus}$	21.1	21.2	21.3	18.2	−10.4
$C_6H_{11}O_6^{\ominus}$	17.4	17.4	17.4	17.3	− 0.4
$OH^{\ominus}$	15.0	14.9	14.8	18.3	+11.8

[Fritz-Haber-Institut, Berlin-Dahlem (Germany), June 29th, 1965] [VB 942/248 IE]

German version: Angew. Chem. 77, 973 (1965)

Some Reactions of Hydroximic Chlorides

A. Dornow, Hannover (Germany) [1]

Hydroximic chlorides were treated with compounds containing amino groups. The amidoxime derivatives formed react with thionyl chloride to give oxathiadiazole *S*-oxides which on being heated decompose to yield carbodiimides with release of SO_2 [2]. There is an analogy here to the Lossen degradation of hydroxamic acids with thionyl chloride. It also proved possible to cyclize substituted amidoximes with phenylboric anhydride to form oxadiazaboroles.

Ethyl glycinate reacts with ethyl chloroacetohydroxyimate to give ethyl (ethoxycarbonylmethylamino)acetohydroxyimate; with ethyl anthranilate a quinazoline derivative is formed. – *Musante* [3] obtained 1,2,4-oxadiazoles from hydroximic chlorides and amidines. 2-Aminopyridine is similar to the amidines; however, its reaction with the above hydroximic chloride affords a bicyclic compound, a purine analogue, and in contrast to the experiments of *Musante*, here all the nitrogen atoms of the starting components recur in the product.

The reaction of hydroximic hydrazides with carbon disulfide leads by elimination of hydroxylamine to thiadiazoline derivatives, probably *via* the stage of a derivative of hydrazinodithioformic acid. However, when hydroximic chlorides were treated with *S*-methyl hydrazinodithioformate, the cyclization with elimination of hydroxylamine expected did not occur; instead, an amino-1,3,4-thiadiazole was formed. The course of this reaction was clarified by using non-basic components containing the grouping S=C–NH– ⇌ HS–C=N–. The basic hydrazino group is not essential for the reaction to occur, for the initial step is a substitution at the tautomeric mercapto group. This is followed by an intramolecular addition of the oxime group onto the C=N double bond and the intermediate formation of a 1,4,2-oxathiazole. The latter decomposes thermally into the oxygen analogue of the starting material and isothiocyanate, which can react further with basic components. In this way the aminothiadiazole derivative is formed, either unchanged dithio ester or its O-analogue reacting with the isothiocyanate.

[GDCh-Ortsverband Hannover (Germany), July 1st, 1965] [VB 941/246 IE]

German version: Angew. Chem. 77, 975 (1965)

[1] *A. Dornow*, Chem. Ber., in the press.

[2] *P. Rajagopalan* and *H. U. Daeniker*, Angew. Chem. 75, 91 (1963); Angew. Chem. internat. Edit. 2, 46 (1963).

[3] *C. Musante*, Gaz. chim. ital. 68, 331 (1938).

The Role of the Nitrosyl Ion in the Dissolution of Metals in Nitric Acid

G. Schmid, Köln (Germany)

There is much controversy about the reactions involved in the dissolution of relatively noble metals such as Ag, Hg, Cu, Bi in nitric acid. The experimental results are contradictory. The autocatalytic effect of nitrous acid is generally acknowledged but is interpreted in various ways.

We examined the reduction of nitrous acid at platinum electrodes in the presence of strong acids (H_2SO_4, $HClO_4$, and H_3PO_4) but in the absence or with stepwise addition of only minute amounts of nitric acid. Measurements of potentiostatic current-time curves [1] and of the stationary current *vs.* potential curves at a rotating disc cathode [2] were made. The results showed that the first step is the discharge of nitrosyl ions to give nitric oxide.

When metals dissolve in nitrous acid, the $NO/NO^{\oplus}$ electrode (standard potential = 1.46 volt [3]) apparently plays the same part as the $H_2/H^{\oplus}$ electrode in the dissolution of ordinary metals in hydrochloric or sulfuric acid. In the latter case, H_2 is formed first, in the former NO is the primary product. In the presence of nitric acid, NO is reoxidized in a homogeneous secondary reaction to nitrous acid, more HNO_2 being formed in this way than is consumed in the primary reaction. Thus the amount of autocatalytic HNO_2 present progressively increases.

The dissolution of a metal in nitric acid (with Ag as an example) can be represented by a scheme proposed by *Abel* [4] (see Scheme 1).

III	II	I		
1	3	2	$Ag \rightarrow Ag^{\ominus} + e^{\ominus}$ (a)	primary reaction of
1	3	2	$NO^{\oplus} + e^{\ominus} \rightarrow NO$ (b)	the corrosion current
2	4	3	$HNO_2 + H^{\oplus} \rightleftharpoons NO^{\oplus} + H_2O$ (c)	Nitrosyl equilibrium
1	2	2	$NO + NO_2 + H_2O \rightleftharpoons 2\,HNO_2$ (d)	Secondary regeneration
1	1	1	$NO^{\oplus} + NO_3^{\ominus} \rightarrow N_2O_4 \rightleftharpoons 2\,NO_2$ (e)	of HNO_2
			$2\,Ag + NO_3^{\ominus} + 3\,H^{\oplus} \rightarrow 2\,Ag^{\oplus} + HNO_2 + H_2O$	I (overall)
			$3\,Ag + NO_3^{\ominus} + 4\,H^{\oplus} \rightarrow 3\,Ag^{\oplus} + NO + 2\,H_2O$	II (overall)
			$Ag + NO_3^{\ominus} + 2\,H^{\oplus} \rightarrow Ag^{\oplus} + NO_2 + H_2O$	III (overall)

Scheme 1. Processes occurring during the dissolution of noble metals in nitric acid.

Initially HNO_2 begins to accumulate according to Equation I (partial reactions multiplied by factors in column I). However, on account of the equilibrium (d), the HNO_2 concen-

[1] *G. Schmid* and *G. Krichel*, Ber. Bunsenges. physikal. Chem. 68, 677 (1964).

[2] *M. A. Lobeck*, Doctorate Thesis, Universität Köln 1965.

[3] *U. Neumann*, Diploma Thesis, Universität Köln, 1961.

[4] *E. Abel*, Z. anorg. allg. Chem. 271, 76 (1953).

tration reaches a limiting value, whereupon the reactions proceed according to Equation II. When the HNO_3 or $NO^{\oplus}$ and $NO_3^{\ominus}$ concentrations are very high, Reaction (e) becomes important and the dissolution proceeds according to the overall Equation III. At the highest HNO_3 concentrations, direct discharge of the $NO_2^{\oplus}$ ion is probably also an important factor in the reaction.

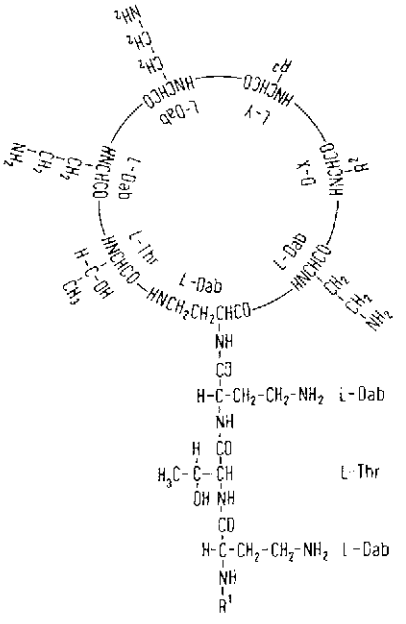
[GDCh-Ortsverband Aachen (Germany), July 16th, 1965] [VB 944/251 IE]

German version: Angew. Chem. 77, 975 (1965)

The Chemistry of Polymyxins

K. Vogler, Basel (Switzerland)

The chemistry of polymyxins, a class of basic polypeptide antibiotics, began in 1954 when polymyxin B_1 was first purified by countercurrent distribution *(L. C. Craig)*. Partial hydrolysis with mineral acid led to the conclusion that this was a cyclohepta- or cyclooctapeptide with side-chains containing α,γ-diaminobutyric acid (Dab) *(W. Haussmann)*. An amide linkage of the side chain with a fatty acid – (+)-6-methyloctanoic acid (MOA) or 6-methylheptanoic acid (IOA) – confers the properties of an invert soap on these antibiotics. They are particularly active against Gram-negative bacteria. Difficulties were encountered in elucidating the point of attachment of the side chain and in finding an answer to the question whether the rest of the molecule also contained a D-α,γ-diaminobutyric acid residue. Syntheses with D-Dab led to highly active products which were not however identical with natural polymyxin B_1. Degradation experiments with nagarase *(T. Suzuki)*, which specifically degrades the side chain, revealed that the polymyxins are cycloheptapeptides with α-linked side chains and with a D-amino acid in the ring *(1)*. The α,γ-diaminobutyric acid groupings all have the L-configuration. Structure *(1)* has now been proved by synthesis of polymyxin B_1 and colistin



	R¹	R²	R³	X	Y
Polymyxin B_1	MOA	$-CH_2-C_6H_5$	$-CH_2-CH(CH_3)_2$	Phe	Leu
Polymyxin B_2	IOA	$-CH_2-C_6H_5$	$-CH_2-CH(CH_3)_2$	Phe	Leu
Colistin A (=Polymyxin E_1)	MOA	$-CH_2-CH(CH_3)_2$	$-CH_2-CH(CH_3)_2$	Leu	Leu
Colistin B (=Polymyxin E_2)	IOA	$-CH_2-CH(CH_3)_2$	$-CH_2-CH(CH_3)_2$	Leu	Leu
Circulin A	MOA	$-CH_2-CH(CH_3)_2$	$-CH(CH_3)-C_2H_5$	Leu	Ileu

A, which is identical with polymyxin E_1. Circulin A, which was previously thought to be a cyclodecapeptide, is also a cycloheptapeptide according to the results of new analytical and synthetic experiments.

[GDCh-Ortsverband Aachen (Germany), July 30th, 1965] [VB 951/259 IE]

German version: Angew. Chem. 77, 974 (1965)

General Meeting 1965 of the German Chemical Society and Kekulé Celebration

This year's general meeting of the German Chemical Society in conjunction with the Kekulé Celebration commemorating the 100th anniversary of the benzene formula took place in Bonn (Germany) from 13th to 18th September. The following report contains abstracts of the discussion papers, but is confined to those papers which have not yet been published. Abstracts are arranged alphabetically according to the names of the authors. For a subject index, see page 1003 of this issue.

1

Reactions of "Hot" Carbon Atoms in Nitrogen/Alkane Systems

H. J. Ache and *P. Wolf*, Upton, L.I., New York (U.S.A.)

Reactions of "hot" carbon atoms [generated by $^{14}N(p,\alpha)^{11}C$, $^{12}C(p,pn)^{11}C$, or by $^{11}B(p,n)^{11}C$ processes] in nitrogen/alkane mixtures give rise to ^{11}C-labelled hydrocarbons (*e.g.* acetylene), and $H^{11}CN$ as the only compound containing nitrogen. The reaction of an energetic carbon atom with a nitrogen molecule presumably leads to an $^{11}CN\cdot$ radical, which is stabilized to $H^{11}CN$ in a second rapid step by abstraction of hydrogen from a hydrocarbon molecule.

Further insight into the formation of the second main product, *viz.* [^{11}C]acetylene, was obtained on mixtures of protonated and deuterated hydrocarhons by the "double tracer" technique. The fact that more than 90 % of the [^{11}C]acetylene in 1:1 mixtures of protonated and perdeuterated hydrocarbons is found as $H^{11}C{\equiv}CH$ or $D^{11}C{=}CD$ shows that it is formed by an intramolecular process in which the first step is the insertion of an energy-rich carbon atom into a C–H bond. The highly exited complex formed can decompose to acetylene and other by-products.

In the reaction of hot ^{11}C-atoms with hydrocarbon molecules containing both primary and secondary C–H bonds (*e.g.* propane), preferential formation of [^{11}C]acetylene by C-insertion into C–H bonds of *methyl* groups is observed in the ratio of about 1.3:1.

In mixtures of protonated and perdeuterated hydrocarbons, the acetylene formation shows isotope effects ranging from C_2H_2/C_2D_2 = 1.08 for alicyclic compounds to 1.28 for methane.

2

Radiometric Determination of the Self-Diffusion Coefficient of the Pertechnetate Ion in Aqueous Solutions

L. Astheimer and *K. Schwochau*, Köln (Germany)

In the polarographic determination of electron transfer by the Ilkovič equation, ionic diffusion coefficients calculated from the limiting equivalent conductivity of the ion are generally used. This method assumes the absence of added foreign electrolytes, in disagreement with the conditions used in polarography. Thus at the usual depolarizer concentrations, the self-diffusion coefficient should be used[1]. We determined the self-diffusion coefficient D of the TcO_4^- ion by the capillary method. The long-lived, β^--active ^{99g}Tc was labelled with ^{95m}Tc, which is formed on bombardment of natural molybdenum with deuterons. The equation

$$D = (4l^2/\pi^2 t)\ln[(8/\pi^2)\, A_0/A_t]$$

was used to obtain D from the fraction A_t/A_0 of the activity remaining in the capillary after a time t, where l is the length of the capillary. At 10^{-3} M TcO_4^- in 1 M aqueous NaOH, $D = 1.27\times10^{-5}$ cm²/sec, in 1 M LiCl: 1.24×10^{-5} cm²/sec. In the absence of supporting electrolyte, $D = 1.49\times10^{-5}$ cm²/sec, which almost coincides with the value $D = 1.47\times10^{-5}$ cm²/sec obtained from the limiting ionic conductance. Although the supporting electrolytes noticeably affect the self-diffusion of TcO_4^-, the consequent effects on rate of electron transfer can be neglected. The self-diffusion coefficient of 10^{-3} M perrhenate was also determined in 1 M NaOH and found to be 1.27×10^{-5} cm²/sec, *i.e.* the same as that of TcO_4^- under the same conditions.

[1] *R. J. Bearman*, J. physic. Chem. *66*, 2072 (1962).

3

Effects in Polarography Attributable to the Specific Adsorption of Reactants

G. C. Barker and *J. A. Bolzan*, Harwell, Berks. (England)

Maxima in d.c. polarography are known to be caused by tangential motion of the surface of the mercury drop and the accompanying streaming of solution near the drop. It has been believed that this tangential motion is due to surface tension gradients connected solely with non-uniformity in the interfacial potential arising from the finite electrical conducitivity of the solution and the non-spherical flow of diffusion current through the solution surrounding the shielded drop. An explanation based on this non-uniformity of potential, however, cannot account for sharp maxima, neither is it consistent with the tendency in many cases for the maximum to increase as the supporting electrolyte concentration is raised. The latter facts become understandable when regard is given to the effect of specific adsorption of a reactant on the electrocapillary curve. If either the oxidized or the reduced form of the depolarizer is strongly adsorbed at the electrode-solution interface, there is a sharp break in the electrocapillary curve at the half-wave potential which greatly affects the rate of change of surface tension with potential in the neighbourhood of this potential. Streaming then tends to be most pronounced close to the half-wave potential and hence a sharp maximum is observed. The height of the maximum may increase along with the supporting electrolyte concentration as the integral adsorption coefficient may be proportional to a power of the anion concentration greater than unity. Although non-uniformity of interfacial potential often plays some part in causing maxima in the presence of specific adsorption, sharp maxima may still occur with solutions of very high conductivity as surface tension gradients may persist due to reactant concentration gradients at the drop surface arising from lack of spherical symmetry in the diffusion systems for the oxidized and reduced forms of the depolarizer.

Specific adsorption of inorganic depolarizers is largely confined to ions of the heavy metals and is most pronounced with halide supporting electrolytes. Approximate values of the adsorption coefficient at potentials close to the half-wave potential can be deduced from changes in wave shape and height produced by specific adsorption in a.c. and pulse polarography. But the most powerful technique for studying specific adsorption of inorganic depolarizers is R.F. polarography as measurements can be made with low depolarizer concentration and with solutions containing insufficient of the adsorption-promoting anion to affect the half-wave potential. Such measurements suggest that lead is adsorbed from perchloric acid solutions containing small amounts of bromide ion in the forms $PbBr^+$ and $PbBr_2$.

4

New Compounds of Lithium Oxide with Europium Oxide

H. Bärnighausen, Freiburg (Germany)

The compound $LiEu_3O_4$ was intensively studied. It is readily prepared by reduction of Eu_3O_4Br with LiH or by treatment of Eu_2O_3 with LiH in a LiCl melt. In the latter procedure evaporation of the LiCl in a high vacuum (600 °C) affords single crystals, examination of which by means of Weissenberg and precession diagrams leads to the following crystal data:

Orthorhombic; a = 11·565 Å, b = 11·535 Å, c = 3·480 Å;
space group Pbnm; Z = 4; ρ_R = 7·539 g/cm³.

According to the formula $LiEu_3O_4$ found analytically, the formula unit must contain two Eu^{2+} ions and this is indirectly confirmed by formation of the isotypic compound $LiSr_2EuO_4$ from the stoichiometric amounts of $LiEuO_2$ and SrO at 700 °C (lattice constants: a = 11·611 Å, b = 11·540 Å, c = 3·4846 Å).

Heating of $LiEu_3O_4$ in air affords the compound $LiEuO_2$, as well as Eu_2O_3 (C form). The new substance occurs in two modifications, which are each obtained in pure form when Eu_2O_3 is treated with Li_2O on slight modification of the reaction conditions. The crystal data of the orthorhombic modification have been reported previously[1]. Crystals of the monoclinic modification belong to space group $P2_1/c$, with lattice constants a = 5·6815 Å, b = 5·9885 Å, c = 5·6211 Å, β = 103·17 ° (Z = 4, ρ_R = 6·807 g/cm³).

[1] *H. Bärnighausen*, Acta crystallogr. *16*, 1073 (1963).

5

Ternary Compounds and Solid Solutions in the System Calcium Oxide/Phosphorus(V) Oxide/Boron(III) Oxide

Helmut Bauer, Karlsruhe (Germany)

The ternary system $CaO/P_2O_5/B_2O_3$ has previously been investigated only with regard to the formation and properties of glasses. Investigations confined mainly to the CaO corner show the existence of two compounds with incongruent melting points having the formulae $15CaO\cdot2P_2O_5\cdot3B_2O_3$[1] and $2CaO\cdot P_2O_5\cdot B_2O_3$[2]. The former compound is stable only

between about 1300 and 1400 °C, but can be obtained in a metastable state by rapid quenching. The structure of the compound is not yet known; powder diagrams, however, indicate wide occurrence of the structure type. Thus isostructural phases of wider stability range and a certain range of compositions are found in the systems $SrO/P_2O_5/B_2O_3$ and $BaO/P_2O_5/B_2O_3$, and compounds of the type $6MO \cdot P_2O_5 \cdot B_2O_3$ (M = Mg, Zn, Cd, Cr, Mn, Co, Ni) show similar powder diagrams. $2CaO \cdot P_2O_5 \cdot B_2O_3$ crystallizes in the hexagonal system and is a member of an isotypical series $2MO \cdot X_2O_5 \cdot B_2O_3$, of which the compounds with M = Ca, Sr, Ba, and X = P, As have been prepared.

Besides the ternary compounds, two ranges of solid solutions were found in the system $CaO/P_2O_5/B_2O_3$. These can be assigned structures of the apatite type[1] and the β-tricalcium phosphate type[3]. The solid solutions of apatite structure are based on a combination of substitution (of BO_4^{5-} for PO_4^{3-} groups) and addition (insertion of B^{3+} in interstitial sites and of O^{2-} on the two-fold positions of the apatite lattice); those with the β-tricalcium phosphate structure are formed by pure addition. Both types of solid solutions are also found in other systems $MO/X_2O_5/B_2O_3$: the apatite type in systems with M = Ca, Sr, Ba, and X = P, As, as well as M = Ca, X = V; the β-tricalcium phosphate type in the system $CaO/As_2O_5/B_2O_3$.

[1] *H. Bauer*, Habilitation Thesis, Technische Hochschule Karlsruhe, 1963.

[2] *H. Bauer*, Z. anorg. allg. Chem. *337*, 183 (1965).

[3] *H. Bauer*, Neues Jb. Mineralog., Abh. *102*, 68 (1964).

6

Optical Investigations of the Surface Chemistry of Germanium and Silicon

K. H. Beckmann, Hamburg (Germany)

The state of polarization of polarized light reflected from a solid having a thin surface coating depends on the refractive index and the thickness of the film, and can therefore be used to determine these parameters. Thickness measurements on very thin layers (d < 100 Å) can be made with particular accuracy. This method was used to follow the growth of a copper layer on a germanium surface formed by electrode position. It was further shown that during the anodic dissolution of p-germanium in a weakly alkaline electrolyte solution, thin layers of presumably GeO_2 are reversibly formed at certain potentials.

In chemical reactions between a semiconductor surface and the surrounding medium, some of the reaction products often remain on the surface in the form of very thin films. *Harrick*[1] has described a method of determining the infrared spectrum, and thus the composition, of such films in which the radiation is made to traverse the layer 100 times or more by total internal reflections. The infrared spectrum of 15 Å layers of GeO_2 on Ge and the constitution of layers which form on the surface of germanium in various etching solutions were determined by this method.

If in this arrangement the sample in an electrolyte is irradiated with continuous light and an alternating potential is applied between sample and counter electrode at 13 c/s (the modulation frequency of the infrared spectrometer), only the change in the infrared absorption due to the alternating electrochemical polarization is recorded. Such a change occurs, *e.g.*, when the number of absorbing particles changes with the electrochemical polarization. By this means the infrared spectra of free electrons and defect electrons in the space charge zone immediately beneath the semiconductor surface were measured and used to calculate the concentration changes of these charge carriers due to the electrochemical polarization.

[1] *N. J. Harrick*, Physic. Rev. *125*, 1165 (1962).

7

The Mode of Action of the Antibiotic Chromomycin

W. Behr, K. Koschel, and *G. Hartmann*, Würzburg (Germany)

The antibiotic chromomycin is a very effective inhibitor of DNA-dependent nucleic acid synthesis[1]. Comparative experiments showed that it inhibits the DNA-dependent RNA synthesis as strongly as does actinomycin. The glycosidically bound chromose groups in the chromomycin molecule are essential for this activity. On stepwise cleavage of the sugar residues, a considerable decrease of inhibition efficiency is observed. The sugar-free rest has no effect on RNA synthesis under the conditions used.

As in the case of actinomycin, the reaction of chromomycin with DNA is accompanied by a change in absorption spectrum (red-shift of the maximum in the visible region by about 25 mμ). This indicates that this antibiotic also blocks the DNA. The association indicated by the spectral displacement is, however, significantly slower than that with actinomycin. The apparent enthalpy of activation is about 7 kcal/mole. In the presence of an excess of chromomycin, on the average 29 nucleotides of the DNA bind one molecule of the antibiotic. For actinomycin this ratio is 11:1.

In contrast to actinomycin[2], chromomycin associates not only with DNA and apyrimidinic acid, but also with apurinic acid and transfer-RNA (t-RNA). The spectrum of these associates differs from that of the complex with DNA. With an excess of chromomycin, three t-RNA nucleotides suffice to bind one chromomycin molecule. The antibiotic has no effect on the enzymatic aminoacylation of t-RNA with arginine. Free nucleosides and nucleotides of comparable concentration do not alter the spectrum of chromomycin.

[1] *G. Hartmann, H. Goller, K. Koschel, W. Kersten*, and *H. Kersten*, Biochem. Z. *341*, 126 (1964).

[2] *M. Liersch* and *G. Hartmann*, Angew. Chem. *77*, 731 (1965); Angew. Chem. internat. Edit. *4*, 707 (1965).

8

Experiments in Chemical Documentation

G. Bergerhoff, Bonn (Germany)

On the bibliography of a very specialized field as an example it is shown that the requirement of completeness increases considerably the number of journals to be scanned. The information material must therefore be condensed. Resolution of publications into words screened with respect to import and redundance can be accomplished by data processing equipment, which can also answer requests for information by logical combination of the stored concepts. The enquirer is led to the original reference without noticing the condensed nature of the stored information.

A randomly selected set of information comprising about 10000 words in 36 publications was processed with a programme of the Deutsches Rechenzentrum. With the aid of a cumulative thesaurus synonyms, foreign words, chemical formulae, and conjugated and declined words can be related to their basic forms, superfluous words can be eliminated, and a reduction to about 10 % is possible. The relatively frequent homonyms are included with all their meanings.

The "ballast" in answers to detailed questions is slight, for general questions stimulating. A logically constructed notation taking into account the expressive power of words would help to reduce ballast and to obtain relations which are not evident in the formalism based on the usual language.

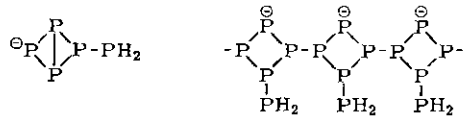
9

Reactions with Potassium Dihydrogen Phosphide

G. Bergerhoff and *F. Knoll*, Bonn (Germany)

Although alkali diorganyl phosphides have become extremely versatile reagents, little is known of the chemistry of the parent compound KPH_2. In oxidation experiments and re-

actions with halides, secondary reactions at the P–H bond always occur. Pure addition reactions can so far be obtained only on elementary phosphorus in dimethylformamide. These can be regarded as nucleophilic cleavage of the P_4 molecule. By following this reaction conductometrically, several intermediate stages were observed, of which the red-brown, amorphous product KP_5H_2 was precipitated with benzene. Attempts to obtain phosphanes by reactions with alkyl halides always resulted in polymers formed by cleavage of P–H bonds as shown by the formation of triphenylmethane from KPH_2 and chlorotriphenylmethane.



(1) *(2)*

Whereas solutions of KPH_2 in dimethylformamide show well-defined ^{31}P- and ^1H-NMR spectra with chemical shifts δ_P = 255.3 ppm (*vs.* 85 % H_3PO_4) and δ_H = 1.12 ppm (*vs.* tetramethylsilane) and coupling constants J_{PH} of 139 and 136.8 cps, the complicated KP_5H_2 gives no ^1H-NMR spectrum and only a poor ^{31}P-NMR spectrum. From the course of the reaction the structure of a monomeric pentaphosphide ion *(1)* or of a polyphosphide ion *(2)* is proposed. The structure *(1)* is supported by molecular-weight determinations. A route to defined polyphosphanes *via* degradation is thus indicated.

10

Reactions at the N=N Double Bond of Azodiphosphoric Acid Derivatives

H. Bock and *E. Kinzel*, München (Germany)

The energy levels of orange azodicarboxylic acid derivatives differ from the corresponding levels of violet azodiphosphoric acid derivatives[1] by up to 20 kcal/mole. Comparison of the reactivity of the two types of compounds was therefore of interest.

Reactions of $Ph_2OP–N=N–POPh_2$ include Diels-Alder cycloadditions, metalation, electrophilic substitution, and addition of proton-active compounds, *i.e.* the same broad reactivity spectrum as the azodicarboxylic ester.

Whereas azodicarboxylic esters oxidize hydroquinones smoothly and without detectable intermediates to quinones the reactions with azobis(diphenylphosphinic acid) gave rise to new 1:1 adducts.

[1] *H. Bock, G. Rudolph, E. Baltin*, and *J. Kroner*, Angew. Chem. *77*, 469 (1965); Angew. Chem. internat. Edit. *4*, 457 (1965).

11

Initiation of Polymerization by Radical Ions and by Dianions

D. Braun and *W. Neumann*, Darmstadt (Germany)

Mono- and disodium adducts of 1,1-diphenylethylene, *trans*-stilbene, and tetraphenylethylene in tetrahydrofuran initiate polymerization of styrene, methyl methacrylate, and acrylonitrile. The corresponding derivatives of benzophenone, *p*-biphenylyl phenyl ketone, bis(*p*-biphenylyl) ketone, and benzophenone anil are initiators for methyl methacrylate and acrylonitrile, but styrene is only initiated by the disodium derivatives. The monosodium adducts of azobenzene, *p*-dimethylaminoazobenzene, azoxybenzene, and nitrosobenzene initiate the polymerization of acrylonitrile; the disodium adducts polymerize acrylonitrile and methyl methacrylate, whereas styrene is not affected. Both the radical ions and the dianions give rise to an anionic polymerization mechanism.

The polymerization of styrene by alkali metal ketyls of benzophenone described by *Smith*[1] is actually initiated by the disodium derivative formed by the addition of two sodium atoms to benzophenone and is not stereospecific, in contrast to earlier reports[1].

Polymers obtained by free-radical polymerization and copolymerization of *p*-vinylbenzophenone, *p*-vinylbenzophenone anil, and *p*-vinyl-1,1-diphenylethylene can be converted into the corresponding poly-radical ions and polydianions; they are suitable for ionic graft polymerization.

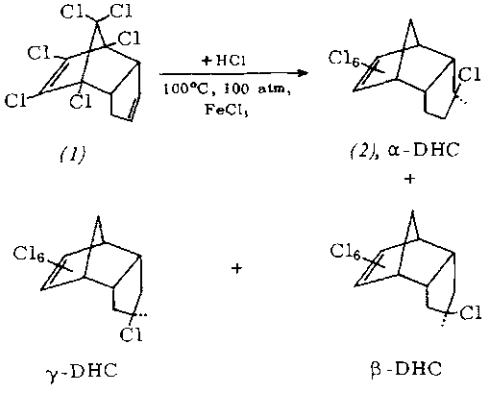
[1] *S. Smith*, J. Polymer Sci. *38*, 259 (1965).

12

Synthesis and Structure of Insecticidal Polychlorotetrahydromethanoindanes

K. H. Büchel, Birlinghoven (Germany)

Little has hitherto been known about the numerous possible stereoisomers in the cyclodiene series of insecticides of the type of heptachlor [1,4,5,6,7,8,8-heptachloro-3a,4,7,7a-tetrahydro-4,7-methanoindene]. The isomeric dihydro-compounds *(2)* of heptachlor seem to be of particular interest because after removal of the double bond from the five-membered ring its biological epoxidation to toxic products cannot come into effect.



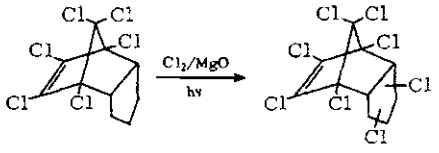
(1) *(2)*, α-DHC + γ-DHC + β-DHC

Addition of HCl under pressure and in presence of a Lewis acid catalyst to the unsaturated hexachloro-analogue *(1)* affords α-, β-, and γ-dihydroheptachlor (DHC)[1], whose configuration has been proved by independent syntheses and ^1H-NMR spectra. The addition is an equilibrium reaction. The relative amounts of the isomers produced can be influenced by varying the conditions (solvent, pressure, temperature), so that the synthesis can be caused to yield, for instance, almost homogenous β-isomer. α- and γ-DHC can be isomerised to β-DHC under the conditions of the addition. β-Dihydroheptachlor[1] is an insecticide whose spectrum of activity is comparable with that of chlordane or DDT and which has a very low toxicity to warm-blooded animals (LD_{50} > 9000 mg/kg mouse). Moreover, it has given no sign of possessing chronic toxicity[2].

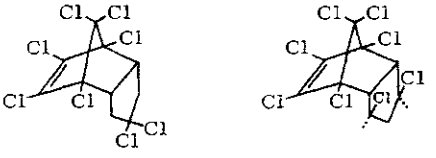
In the octachlorotetrahydromethanoindane (chlordanes) series *(5)*, *(6)*, the number of possible isomers is still larger. On chlorination of hexachlorotetrahydromethanoindane *(3)* one obtains a crystalline product *(4)* from which, by chromatography on silica gel (n-hexane), have been isolated β-DHC and β-chlordane, the new isomers γ-, δ-, and ε-chlor-

[1] *K. H. Büchel, A. E. Ginsberg, R. Fischer*, and *F. Korte*, Tetrahedron Letters *1964*, 2267.

[2] *P. L. Chamber, C. G. Hunter, J. Robinson*, and *D. E. Stevenson*, Med. Pharmacol. exp. *12*, 289 (1965).



(3) (4)



(5), γ-Chlordane (6), δ-Chlordane

dane, and a nonachloro-derivative. The symmetrical γ- and δ-chlordane have the best insecticidal properties. The structures of all the known chlordane isomers have been confirmed by independent syntheses and ^{1}H-NMR spectra.

13

Automatic Determination of Molecular Weights by Light Scattering

H.-J. Cantow, Freiburg (Germany)

The reciprocal absolute scattering intensity (Rayleigh ratio) R multiplied by the concentration C and the characteristic optical constant K of a dissolved substance can be recorded simultaneously with the measurements versus the angle function $\sin^2\vartheta/2$ + const·C by a combination of analogue computing elements.

The reciprocal Rayleigh ratio is formed by a servo-controlled potentiometer. The geometrical correction factor $\sin\vartheta$ is introduced and the scattering angle is converted to $\sin^2\vartheta/2$ by function potentiometers coupled to the rotating optical system. The solvent scattering is eliminated by an opposing potential.

The weight-average molecular weight $\overline{M}_w$ and the dimensions of the dissolved macromolecules as well as the thermodynamic solution paramters can then be obtained in the usual way from the resulting Zimm diagram. The angular range of 30°–150° can be scanned in 12 sec for each concentration. The recorded curves have the further advantage that errors made in point-by-point measurements are smoothed out.

A system is proposed which instantaneously indicates the molecular weight (at a single concentration in a theta-solvent where the effects of solute-solvent interactions are cancelled) by sacrificing information about the molecular dimensions. The method consists in determining the Rayleigh ratio R_0 at zero angle, which is independent of shape and dimensions of the molecule, by measuring the intensity scattered at two angles in alternation with a rotating-sector system. For monodisperse and polydisperse randomly coiled molecules, angles of 45° and 70° are suitable. The signals are combined so that the alternating component of the resulting signal is $2R_{45}-R_{70}$, which practically equals R_0. Such measurements at fixed angles are possible with an average accuracy (independent of the molecular dimensions) of ±2 % in R_0 or $\overline{M}_w$.

A gas laser with $\lambda = 6328$ Å is a suitable light source. The refractive index increment can be measured simultaneously with the same light source. A simple circuit then allows the direct recording of R_0/CK, which in theta-solvents is equal to $\overline{M}_w$.

It thus appears possible to follow rapid processes as well as continuous fractionations, *e.g.* those using Baker-Williams columns. The method should also be suitable for rapid routine determinations of $\overline{M}_w$.

14

Formation of Ferrocene

H. Cordes, Ludwigshafen (Germany)

The four processes in the formation of dicyclopentadienyliron (ferrocene) from ferrous chloride and cyclopentadiene in presence of alkali alkoxide, *i.e.* the preparation of $FeCl_2$, the reaction with alkoxide, the reaction with monomeric cyclopentadiene, and the isolation of the ferrocene, were investigated.

Anhydrous $FeCl_2$ is formed rapidly and quantitatively by reduction of sublimed $FeCl_3$ in organic solvents, such as alcohols, in which both chlorides are sufficiently soluble, with metals such as Fe, Zn, or Al in the presence of acid, which is essential for the process. Acid is often autogenically produced by partial hydrolysis of the very hygroscopic $FeCl_3$; small amounts of water are removed *via* the insoluble oxide hydrates.

On the addition of methoxide, the remaining acid is neutralized and white to light grey Fe(II) methoxide is then precipitated. An excess of at least 100 % of methoxide should be added to obtain good yields of ferrocene. At 40–50 °C, addition of monomeric cyclopentadiene gives ferrocene in yields of over 80 % within a few minutes. Derivatives such as methylcyclopentadienyl react more slowly.

When a water-soluble solvent is used, hydrolysis of the reaction mixture gives crude ferrocene in better than 95 % purity, particularly if an excess of Fe(II) methoxide is used, since all components except ferrocene are soluble in weakly acidified water. Analytically pure ferrocene is obtained by recrystallization, sublimation, or steam distillation.

The main side reaction is the hydrolysis of the iron salts to oxide hydrates, which, presumably owing to their extreme insolubility (even when freshly precipitated), do not react with cyclopentadiene. Therefore the presence of more than traces of water decreases the ferrocene yield considerably, and even anhydrous alkali hydroxides are not suitable as bases in place of alkali alkoxides.

15

Interpretation of the Spectra of Monoamino-p-benzoquinones

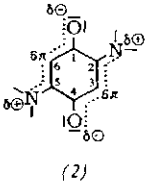
S. Dähne, D. Leupold, H. Paul, and *J. Ranft*, Berlin and Leipzig (Germany)

The spectra of many disubstituted quinone dyes can, like those of indigo dyes, be explained by the assumption that two polymethine elements of the structure *(1)* are coupled within one molecule[1]:

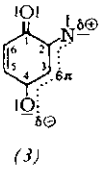
$$\begin{matrix} .....(n+3)\pi..... \\ X\text{-}(CR)_n\text{-}X' \end{matrix} \qquad (1)$$

X,X' = Elements of group IV, V, or VI;
R = any substituents; n = 1,3,5. . . .

For example, 2,5-diamino-*p*-benzoquinones *(2)* can be regarded as coupling products of two trimethinemerocyanines *(1)*, X = NR_2, X' = O, n = 3.



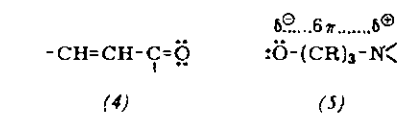
(2)



(3)

[1] *S. Dähne, D. Leupold, H. Paul*, and *J. Ranft*, Mber. dtsch. Akad. Wiss. *7*, 25 (1965); *D. Leupold* and *S. Dähne*, Theoret. chim. Acta *3*, 1 (1965).

Analogously the properties of monosubstituted quinone dyes, *e.g.* 2-amino-*p*-benzoquinone *(3)*, are ascribed to a polyene-polymethine coupling. The term schemes, calculated by a supplemented LCAO–MO method, of the uncoupled polyene *(4)* and the uncoupled polymethine *(5)* can be combined to that of the monoaminoquinone *(3)* by a stepwise approach of the separate molecules, *i.e.* by stepwise increase of the resonance integral of the coupling bonds C(1)–C(2) and C(4)–C(5).



(4) *(5)*

These ideas were confirmed by measurements of infrared and NMR spectra. The C=O stretching frequency of the polyene part of the molecule is higher than that of the polymethine part. The chemical shifts of the protons in *(3)* after correction for the ring current are essentially the same as in the separate polyene and polymethine.

Because of the asymmetry of the polyene-polymethine coupling, the $\pi \rightarrow \pi^*$ transition of longest wavelength of the monosubstituted benzoquinones is allowed. They therefore absorb considerably more strongly in the visible than the centrosymmetric compounds of type *(2)*, in which this symmetry-forbidden transition is only slightly allowed by a Herzberg-Teller mixture [2].

[2] *S. Dähne* and *D. Leupold*, Z. Naturforsch. *20b*, 76 (1965); *D. Leupold* and *S. Dähne*, J. molecular Spectroscopy, in press.

16

Specificity and Mode of Action of Pepsin in the Condensation of Oligopeptides

H. Determann, Frankfurt/Main (Germany)

In the pepsin-catalysed plastein reaction, the terminal amino acids of the peptides play a decisive part. The specificity of pepsin is more marked in condensation than in hydrolysis reactions. Thus pentapeptides with C-terminal L-Leucine, L-phenylalanine, and L-tyrosine can be condensed, whereas those with L-valine, L-isoleucine, and D-phenylalanine are no substrate of the enzyme. The amino-end appears to be less important to the reactivity. Here L-tyrosin can be replaced by L-alanine; the reaction does not take place with D-phenylalanine on either end. A D-amino acid in the peptide interior does not affect the reactivity (experiments with *J. Heuer* and *D. Jaworek*).

The mechanism of pepsin-catalysed peptide hydrolysis is still unknown. The specificity shown by pepsin in our condensation experiments suggests that the carboxy group is activated. Attempts to capture a reactive intermediate by the addition of various acceptors were, however, not successful. Neither inhibition of the plastein reaction, nor inclusion of the additives into the polypeptide, were observed when various amounts of aniline, phenylacetic acid, alanine amide, or acetyltyrosin where present in the reaction mixture.

17

Chelation of Neptunium, Plutonium, and Americium by Derivatives of 8-Hydroxyquinoline

S. H. Eberle and *C. Keller*, Karlsruhe (Germany)

Ter- and quadrivalent ions of the transuranium elements form compounds ML_3 and ML_4 (HL = ligand) with 8-hydroxyquinoline (Hox) and its 5,7-dihalo derivatives. Only basic substances are obtained from aqueous solutions with 2-methyloxine; the neutral neptunium compound is formed in the melt under water. Similarly to $Ce(ox)_3$, $Pu(ox)_3$ is very sensitive to oxidation and is only obtainable under strict exclusion of oxygen. Neptunium(V) forms the neutral chelate $NpO_2(ox)\cdot(H_2O)_2$, difficultly soluble in water and organic solvents, and a water-soluble anion $[NpO_2(ox)_2\cdot aq]^-$. Plutonium(V) gives only chelates of the type $PuO_2(L)(HL)_2\cdot aq$. Both ions give compounds of composition $MO_2(Mox)(Hmox)\cdot aq$ with 2-methyloxine (Hmox). No chelation was observed with 6-valent actinides, since they are reduced by all the ligands used.

The extraction behavior and the stability constants are very similar to those of complexes of the rare earths, thorium, and uranium(IV); the stabilities of the actinide chelates are however always higher than those of the analogous elements. The 5-valent ions stepwise form 1:1 and 1:2 complexes with 8-hydroxyquinolinesulfonic acids, which for neptunium and plutonium have the same stability constants. The measurements show that the tendency to form chelates with oxine derivatives decreases in the sequence M(IV) > M(III) > M(V).

18

Transport and Phase-Boundary Reactions of Defect Electrons in Silver Bromide

E. Eisenmann and *W. Jaenicke*, Erlangen (Germany)

The mobilities of defect electrons as determined by diffusion and Hall-effect measurements, respectively, differ by a factor of about 10^4 at room temperature. To determine whether this discrepancy is caused by reactions at the phase boundary, trapping reactions inside the crystal, or space-charge limited transport, an electrochemical cell with an AgBr single crystal as diaphragm between a bromine and a bromide solution was polarized. The mobility was determined by the rate of migration of the resulting boundary. Current-potential measurements in both directions of polarization allowed the study of rate determining phase-boundary reactions. The mobility from the moving-boundary method agrees with that obtained by diffusion.

Between 0 and 150 °C the mobility has an activation energy of 0.71 eV. At 175 °C it passes through a maximum and maintains a negative temperature coefficient to higher temperatures (measurements to 250 °C). This part of the curve agrees with the curve obtained by extrapolation of the Hall-effect data (measurements to 140 °C). A trapping mechanism is proposed to explain the results.

19

Effect of Ultraviolet Radiation and of Carcinogenic Nitrosamines on Constituents of Nucleic Acids [1]

E. Fahr, *R. Kleber*, and *E. Boebinger*, Würzburg (Germany)

The carcinogenic activity of nitrosamines [2] has been ascribed [3] to a conversion into diazoalkanes. This explanation is supported by the fact that di-t-butylnitrosamine and diphenylnitrosamine, which can give no diazoalkanes, are not carcinogenic.

From the relatively high reactivity of the N–NO group in nitrosamines it may be expected that these can also effect directly chemical reactions in living organisms. We found that in aqueous solution (pH 4.2 and 3.0 at 30 °C, nitrosamine:

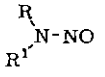
[1] For the part of this lecture dealing with the effects of UV-irradiation, cf. Naturwissenschaften *52*, 513 (1965).

[2] *H. Druckrey*, *R. Preussmann*, *G. Blum*, *S. Ivankovic*, and *J. Afkham*, Naturwissenschaften *50*, 100 (1963).

[3] *D. F. Heath*, Nature (London) *192*, 170 (1961); *P. N. Magee* and *E. Farber*, Biochem. J. *83*, 114 (1962); *H. Druckrey*, *R. Preussmann*, *D. Schmähl*, and *M. Müller*, Naturwissenschaften *48*, 134 (1961).

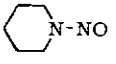
pyrimidine = 200:1) dimethylnitrosamine reacts with cytosine, cytidine, and cytidylic acid, but not with adenosine and guanosine. The reaction is first order with respect to the pyrimidine with half-lives at pH 4.2 of 13000 min (cytosine), 18800 (cytidine), and 6800 (cytidylic acid). The obvious assumption that the reaction is a deamination is incorrect, since the expected products uridine and uridylic acid could not be detected.

Model experiments with the nitrosamines *(1a)–(1e)* and *(2)* showed that the carcinogenic nitrosamines *(1a)*, *(1b)*, and *(2)* react with urea and cytidine, whereas the non-carcinogenic compounds *(1c)–(1e)* do not. These results show that the dialkane hypothesis is not necessary to explain the different behavior of the nitrosamines.



(1)

a: $R = R^1 = CH_3$ d: $R = CH_3$; $R^1 = (CH_3)_3C$
b: $R = R^1 = C_2H_5$ e: $R = R^1 = (p)CH_3\text{-}C_6H_4$
c: $R = CH_3$; $R^1 = C_6H_5$



(2)

20

The Electronic Structure of Metal Tri(cyclopentadienyl) Complexes

R. D. Fischer, München (Germany)

The bonding in lanthanide and actinide complexes containing three equivalent, centrally attached C_5H_5 ligands was investigated with a simple LCAO–MO method. The qualitative one-electron approximation already shows that each complex $(C_5H_5)_3M$ has one unoccupied, non-bonding molecular orbital of rotational symmetry along the molecular axis.

This essentially covalent model explains the unexpectedly strong Lewis acidity of most tri(cyclopentadienyl)-lanthanide complexes and the ready formation of many surprisingly stable adducts[1]:

$$(C_5H_5)_3M + :B \rightarrow (C_5H_5)_3MB$$

A satisfactory explanation can also be given for the low magnetic moment and the relatively high dipole moment of $(C_5H_5)_3U$[2]. The MO treatment further enables the U···BH_4 linkage in $(C_5H_5)_3UBH_4$[2] to be understood, as well as the green colour of $(C_5H_5)_3Yb$, which is unusual for Yb(III) complexes.

[1] *E. O. Fischer* and *H. Fischer*, Angew. Chem. *77*, 261 (1965); Angew. Chem. internat. Edit. *4*, 246 (1965).

[2] *Y. Hristidu*, Dissertation, Universität München, *1962*.

21

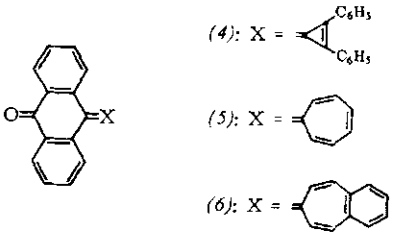
Cyclopropenylium and Tropylium Systems

B. Föhlisch, *P. Bürgle*, and *D. Krockenberger*, Stuttgart (Germany)

The strongly polarized ketones diphenylcyclopropenone, tropone, and 4,5-benzotropone react already at 0–20 °C with phosgene almost quantitatively to 3,3-dichloro-1,2-diphenylcyclopropene *(1)*, 7,7-dichlorocyclohepta-1,3,5-triene *(2)*, and 7,7-dichloro-3,4-benzocyclohepta-1,3,5-triene *(3)*, respectively. ^{1}H-NMR studies show that *(2)* and *(3)* ionize in liquid sulfur dioxide to chlorotropylium chloride and 1-chloro-4,5-benzotropylium chloride, respectively. With $SbCl_5$, *(1)–(3)* form the hexachloroantimonates.

With phenols, *(1)* gives hydroxyarylcyclopropenylium salts[1]. The cyclopropenylium salt formed from *(1)* and anthrone can be deprotonated with triethylamine to the methylenecyclopropene derivative *(4)*. Contrary to previous assumptions[2], the reaction of diphenylcyclopropenylium perchlorate with anthrone in glacial acetic acid/pyridine leads not to *(4)*, but to 10-(2,3-diphenylallylidene)anthrone.

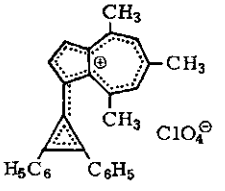
4,6,8-Trimethylazulene is also electrophilically substituted by *(1)*; the isolatable perchlorate *(7)* reacts with ethanol in the presence of bases to 1-(1-ethoxy-2,3-diphenylcyclopropenyl)-4,6,8-trimethylazulene.



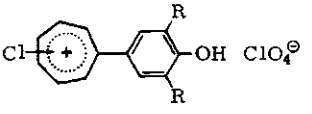
(4): X =

(5): X =

(6): X =



(7)



(8)

Anthrone with *(2)* and *(3)* gives the heptafulvene derivatives *(5)* and *(6)*, respectively, corresponding to *(4)*. With phenol, 2,6-dimethylphenol, and 2,6-diethylphenol, *(2)* reacts in fair yields to x-chloro-(*p*-hydroxyphenyl)tropylium salts *(8)*. Comparison of the $\nu_{C=O}$ frequencies and the dipole moments of *(4)–(6)* [*(4)*: 1630 cm^{-1}, 9.4 D; *(5)*: 1655 cm^{-1}, 3.8 D; *(6)*: 1655 cm^{-1}, 3.7 D] shows that the methylenecyclopropene system is a stronger electron donor than the heptafulvene system.

[1] *B. Föhlisch* and *P. Bürgle*, Tetrahedron Letters *1965*, 2661.

[2] *B. Föhlisch* and *P. Bürgle*, Angew. Chem. *76*, 784 (1964); Angew. Chem. internat. Edit. *3*, 699 (1964).

22

The Influence of the Crystal Field on the Acidity of Protons in the Crystal and on the Surface

F. Freund, Göttingen (Germany)

In hydroxides the proton is situated within the electron cloud of the oxygen ion. When optical excitation is excluded, it vibrates in the zeroth energy level of a potential energy well, the form, position, and connection to neighboring potential wells of which is determined by the gradient of the electric field and the electron density "ρ(H)" at the proton position.

The proton in the electron cloud of the oxygen ion and the cations partly bound covalently to the OH^- group perturb the charge distribution of the oxygen ion: the more covalent the cation-oxygen bond, the weaker the oxygen-proton bond, *i.e.* ρ(H) is decreased and the proton becomes more acidic. The component of the coulomb field of the cation along the O–H direction causes an additional loosening of the O–H bond.

If O^{2-} ions are present as ligands in addition to OH^- groups (as in many oxide hydroxides), the cation is polarized preferably towards the more electronegative O^{2-} ligands, so that

the cation-hydroxyl bond is weakened. This releases electron density from the oxygen ion of the hydroxyl group, which becomes available for firmer binding of the proton: ρ(H) is increased, the proton acidity decreased. The magnitude of this effect increases with increasing polarization of the cations by O^{2-} compared to OH^-.

23

The Interaction of Pigments and Binders in Solid Paint Films

W. Funke, Stuttgart (Germany)

From the dependence of water absorption and water permeability of paint films on the volume concentration of pigment, the behavior of the pigment/binder interface in the presence of water can be determined. If the adhesion of the binder to the pigment is maintained on uptake of water, the water uptake is, relative to the amount of binder, independent of pigment volume concentration, whereas the water permeability decreases with increasing pigment volume concentration. If the adhesion is lost on water uptake, this uptake increases with pigment volume concentration corresponding to the expansion (swelling) of the binder. Since in this case the water vapor need not diffuse through the binder, but can make its way through the crevices on the surface of the pigment particles, the vapor permeability increases with increasing pigment volume concentration.

When soluble substances are present on the pigments or at the interfaces, osmotic processes can lead to increased water absorption if the permeation of these soluble substances through the binder is retarded. As soon as the pigment volume concentration becomes sufficiently large, the binder becomes permeable and the water uptake decreases again.

Electron-microscopic investigations showed that in solid paint films relations exist between both water uptake and permeability to water vapor and the state of agglomeration.

24

Enzymatic Reactions of Isonicotinic Hydrazide

H. W. Goedde, W. Schloot, and *A. Valesky*, Freiburg (Germany)

The tuberculostaticum isonicotinic hydrazide (INH) is converted mainly into acetyl-INH in animals and excreted as such in the urine. Enzyme preparations were made from liver homogenates of *Cercopithecideae* (*C. aethiops sabaeus*). By the use of ^{14}C-labelled acetyl-coenzyme A it was shown according to the reaction

$$\text{INH} + [^{14}\text{C}]\text{-acetyl-S-CoA} \xrightarrow{\text{Acetylase}} [^{14}\text{C}]\text{-acetyl-INH} + \text{CoA-SH}$$

that acetyl-coenzyme A is the acetyl-group donator in this reaction.

The acetylation of INH with acetyl-coenzyme A and with the model substance *N,S*-diacetylcysteamine can be followed spectrophotometrically at 303 mμ and pH 9.0.

The activity of acetylase preparations from liver homogenates of *Macaca mulatta rhesus* can be increased twenty-fold by precipitation with acid and acetone. At 50 °C the enzyme is largely deactivated.

The substrate specificities towards INH, *p*-nitroaniline, *p*-aminosalicyclic acid, and sulfanilamide were studied as a function of acetyl-coenzyme A or *N,S*-diacetylcysteamine concentration, and the inhibition by Hg(II)Cl-benzoate and *N*-ethylmaleinimide were tested.

Further studies with the acetylases of *Macaca mulatta rhesus* and *Cercopithecus aethiops sabaeus* showed a close correlation of the INH concentration in the plasma after injection of INH with the specific activity of the enzyme proteins determined spectrophotometrically in the acetylation reaction, where INH is determined colorimetrically as the coupling product with vanillin.

Differences in the specific activity indicate enzyme variants of INH-acetylase and genetically determined polymorphism for the INH-acetylation in these species similar to that observed in man.

25

Infrared-Spectroscopic Investigation of Barbiturates

S. Goenechea, Bonn (Germany)

The following characteristic absorption bands were found in the infrared spectra of 21 barbiturates:

The N–H stretching vibrations give rise to two strong bands at 3220–3200 and 3100–3080 cm^{-1}. Some of the compounds show a third band in this region; only for Luminal does this band appear at 3310 cm^{-1}.

In all spectra three carbonyl bands are observed: at 1750, 1730, and 1690 cm^{-1} (amide I-band). The derivatives which are not N-methylated show an additional absorption between 1540 and 1515 cm^{-1} (amide II-band). This band is absent from the spectra of N-methylated barbiturates, whereby they can be distinguished.

Substituents at C-5 have the following effects: The asymmetric CH_3 stretching vibration of alkyl groups gives rise to definite absorption at 2975–2960 cm^{-1}. If the substituent is small (*e.g.* ethyl, isopropyl, or n-propyl), then, depending on the nature of a second substituent, additional bands can appear at 2990–2980 cm^{-1} and 2960–2950 cm^{-1}. This splitting occurs when the second substituent is ethyl, allyl, bromoallyl, phenyl, or cycloalkenyl. The symmetric CH_3 stretching vibrations are assigned the absorption at 2875 ± 10 cm^{-1}. The asymmetric CH_2 stretching frequencies (2950–2930 cm^{-1}) become noticeable only when many CH_2 groups are present. The absorptions due to the symmetric CH_2 stretching vibration are generally very weak.

Allyl groups absorb at 1640–1637 cm^{-1}; the bromoallene residue absorbs at 1620 cm^{-1} and can readily be recognized in the presence of the allyl group. Vinyl substituents give a band at 1630–1628 cm^{-1}. Δ^1-Cycloolefins as substituents on C-5, on the other hand, do not absorb between 1680 and 1600 cm^{-1}. In allylcyclopentenylbarbituric acid the allyl absorption also is missing.

Alcoholic OH groups on C-5 give a strong absorption band around 3470 cm^{-1}. Phenyl substitutents can best be recognized by the three sharp bands at 1590, 1575, and 1490 cm^{-1}. In the spectrum of Luminal the band at 1590 cm^{-1} occurs only as an uncharacteristic shoulder.

26

The Charge Distribution in Phosphazines

H. Goetz, Berlin (Germany)

The controversial problem of possible $d_\pi - p_\pi$ conjugation was studied on phosphazines of the type

$$(p\text{-X-C}_6\text{H}_4)(\text{C}_6\text{H}_5)_2\text{P=N-N=(9-fluorenyl)} \qquad (1)$$

with X = H, Cl, Br, OCH_3, and $N(CH_3)_2$, and the corresponding alkyldiphenyl and trialkyl compounds, and on phosphazines of the type

$$(p\text{-X-C}_6\text{H}_4)(\text{C}_6\text{H}_5)_2\text{P=N-N=C}(p\text{-Y-C}_6\text{H}_4)(p\text{-Z-C}_6\text{H}_4) \qquad (2)$$

with Y = Z, Cl, and Y = H, Z = NO_2 by measurements of dipole moments and ultraviolet absorption spectra.

The dipole moments vary between 5 and 10 D, depending on the substituent. This indicates the resonance

$$\geq P{=}N{-}N{=}C\leq \longleftrightarrow \geq \overset{\oplus}{P}{-}N{=}N{-}\overset{\ominus}{C}\leq$$

for the ground state, with high participation of the ionic form, for which in type *(2)* there is a stronger dependence on the substitutents Y and Z than on X. The influence of X cannot be explained purely on the basis of its inductive effect.

The ultraviolet spectra of all the compounds show a $\pi \rightarrow \pi^*$ transition at long wavelengths, which can be assigned to the P=N–N=C chromophore. Solvatochromic effects indicate an isoenergetic point[*], confirming the results of the dipole moment studies. No $n \rightarrow \pi^*$ transitions can be recognized. The $\pi \rightarrow \pi^*$ band is considerably shifted towards the blue with respect to that in symmetrical and asymmetrical diketazines $> C{=}N{-}N{=}C <$. This is however not due to conjugation across the phosphorus, but to a strong decrease of the excitation energy by the resonance of the ground state. The substituents X in type *(2)* have less influence on the position of this $\pi \rightarrow \pi^*$ transition than the substituents Y and Z. The phosphorus atom terminates the conjugation. Further, in the ground state (π) there is an interaction (in the sense of a qualitative LCAO–MO model) of the p_z orbitals of the *p*-phenyl substituents with the d_{xz} or the d_{yz} orbital of the phosphorus atom. No such interactions can be detected in the excited states (π^*).

[*] At the isoenergetic point the participation of the two resonance forms is equal.

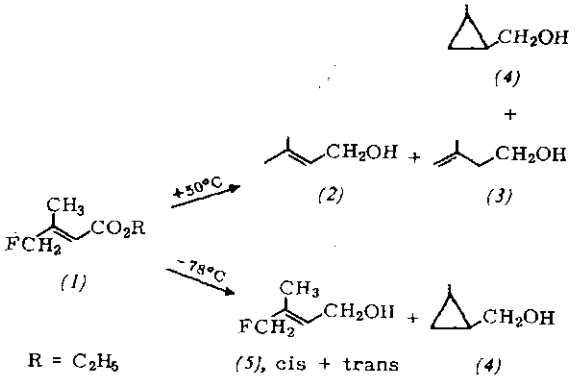
27

Fluoroisoprenols

W. Grell, H. Machleidt, J. Piek, and *H. Schumacher*, Bonn (Germany)

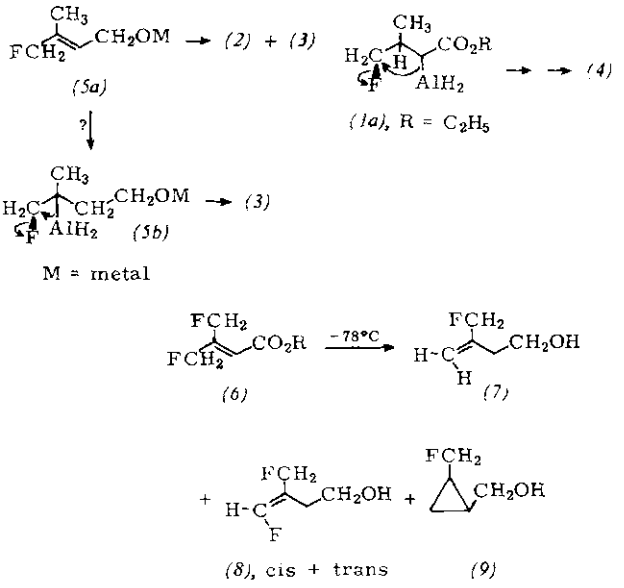
Fluoroisoprenols and their pyrophosphates deserve interest as antimetabolites of squalene and steroid biosynthesis.

$LiAlH_4$ reduces ethyl (3-fluoromethyl)crotonate *(1)* at +50 °C to a mixture of 60–70 % of *(2)*, 20–10 % of *(3)*, and 20 % of *(4)*; at −78 °C to 86 % of *cis/trans*-3-fluoromethyl-2-butenol *(5)*, 14 % of *(4)*, and a trace of *(2)*.

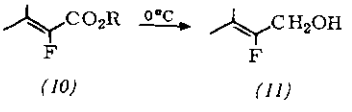


The cyclopropane derivative *(4)* is formed, essentially independently of temperature, *via* the adduct *(1a)* by S_Ni substitution. Compounds *(2)* and *(3)* are probably formed by S_Ni and/or S_N2 reactions from *(5a)*, and *(3)* possibly also *via* the adduct *(5b)*.

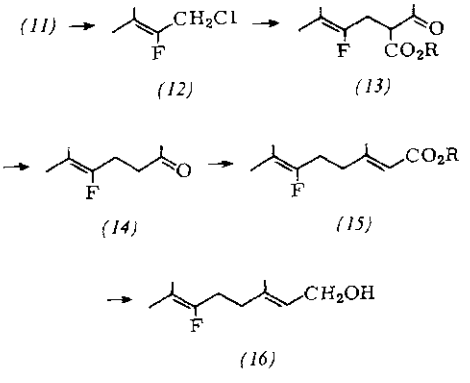
Ethyl 4-fluoro-3-fluoromethylcrotonate *(6)* is reduced by $LiAlH_4$ at −78 °C to 3-fluoromethyl-3-butenol *(7)*, a little *cis/trans-(8)*, and a trace of *(9)*.



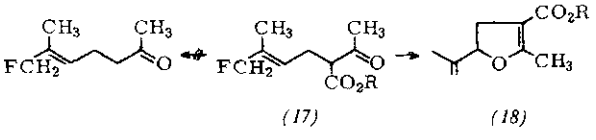
Esters containing olefinic fluorine *(10)* can be reduced without elimination of fluorine[1].



6-Fluorogeraniol *(16)* can be obtained in five stages from *(11)*



In contrast to *(13)*, the acetylacetic ester *(17)* is unstable. It rearranges to the dihydrofuran derivative *(18)* under elimination of HF.



[1] *H. Machleidt* and *R. Wessendorf*, Liebigs Ann. Chem. *674*, 1 (1964).

28

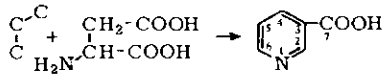
The Biosynthesis of Nicotinic Acid by Mycobacterium tuberculosis

D. Groß, Halle/Saale (Germany)

Nicotinic acid is formed in some fungi and in mammals as a product of tryptophan degradation. This degradation does, however, not occur in most bacteria and in higher plants. In

Mycobacterium tuberculosis (BCG strain), tryptophan is also not a precursor of nicotinic acid. However, here ^{14}C-labelled aspartic acid is incorporated into the nicotinic acid molecule. After application of [4-^{14}C]-aspartic acid, the radioactivity occurs only in the carboxy group of nicotinic acid, whereas on application of [u-^{14}C]-aspartic acid, ^{14}C-activity is found in the ring carbon atoms, too. By application of [1-^{14}C,4-^{15}N]-aspartic acid it was shown that the carboxy group C-1 of aspartic acid is eliminated in the biosynthesis of nicotinic acid, that the carboxy group C-4 of aspartic acid supplies the carboxy group of nicotinic acid, and that the carbon atoms 2,3 and 7 as well as the nitrogen atom of the nicotinic acid are derived from aspartic acid.

After application of ^{14}C-labelled C_3-compounds such as [2-^{14}C]-glycerol, [1,3-$^{14}C_2$]-glycerol, [1-^{14}C]-glyceraldehyde, [1-^{14}C]-glycerate, and [3-^{14}C]-pyruvate, the radioactivity recurs in the pyridine ring of nicotinic acid. [2-^{14}C]-Glycerol and [1,3-^{14}C]-glycerol are preferably incorporated into C-4, C-5, and C-6 of nicotinic acid. These results show the following biosynthesis route for nicotinic acid in *M. tuberculosis*:



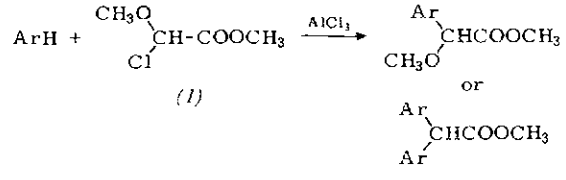
The pyridine ring apparently is synthesized in the same way in higher plants and in other bacteria.

29

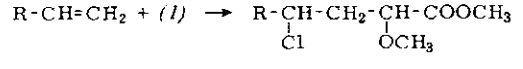
Syntheses with Methyl Methoxychloroacetate

H. Groß and *J. Freiberg*, Berlin-Adlershof (Germany)

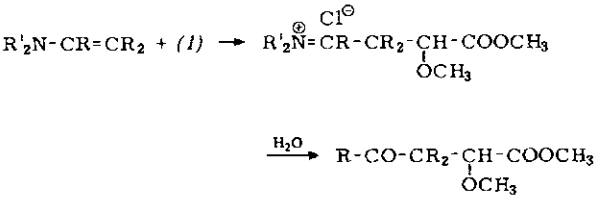
With aromatic compounds in the presence of Friedel-Crafts catalysts, methyl methoxychloroacetate *(1)* gives either methyl methoxyarylacetate or methyl diarylacetate:



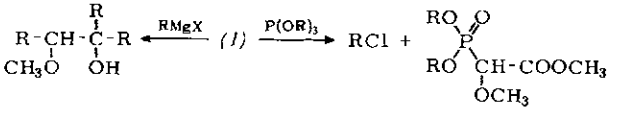
Compound *(1)* adds to unsaturated compounds to give methyl α-methoxycarboxylates:



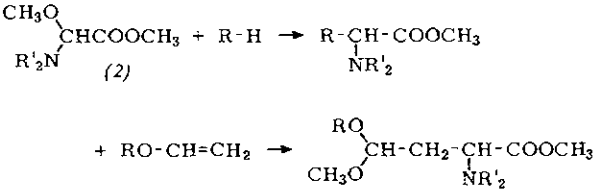
From enamines and *(1)*, methyl α-methoxy-γ-ketocarboxylates are obtained after hydrolysis:



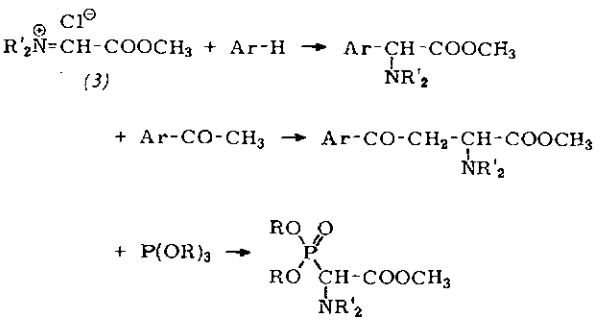
With an excess of Grignard reagents, *(1)* reacts to glycol monomethyl ethers; with trialkyl phosphite *(1)* eliminates alkyl chloride and rearranges to the corresponding dialkyl phosphonate:



Secondary amines or diacylimides react with *(1)* to give *ON*-acetals of type *(2)*, which can be condensed with CH-acidic compounds or added to vinyl ethers.



From *(2)* and acetyl chloride or thionyl chloride, immonium salts of type *(3)* are formed, which give the substituted glycine



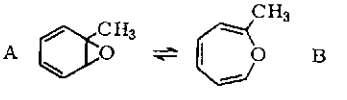
derivatives with aromatic or heterocyclic compounds, and aroylalamine derivatives with ketones. Aliphatic diazo compounds add to *(3)*; trialkyl phosphites react by rearrangement to phosphonic esters as with *(1)*.

30

NMR-Spectroscopic Studies of the Equilibrium and Kinetics of Benzene Oxide — Oxepin Conversions

H. Günther, Köln (Germany)

The hypothesis that substituted oxepins are in equilibrium with the isomeric benzene oxides was confirmed[1] on α-methyloxepin synthesized by *Vogel* and *Schubarth*.



In the NMR spectrum of this compound in CF_3Br solution at about −110 °C, the methyl signal is split into a doublet with chemical shifts τ_A 8.45 and τ_B 8.09. The equilibrium constant K (= γ_B/γ_A) is 4.0 at −90 °C. The temperature-dependence of K between −74 and −123 °C yields the enthalpy difference $\Delta H^\circ = H_B^\circ - H_A^\circ \simeq 0.4$ kcal/mole. The activation energies (9.3 ± 1.0 kcal/mole) of the forward and reverse reaction are the same within the limits of error. The introduction of the methyl group thus lowers the enthalpy difference between monocyclic and bicyclic isomers relative to the unsubstituted compound. The position of the equilibrium at higher temperatures is determined essentially by the entropy term, as in the oxepin case.

[1] In collaboration with *H. Friebolin*, Freiburg.

31

Free-Radical Reactions on Thermolysis of Methyl Oleate in the Absence of Oxygen

A. K. Sen Gupta, Hamburg (Germany)

When methyl oleate is heated to 280 ± 5 °C in an atmosphere of argon, homolytic cleavage of the C–C single bonds adjacent to the double bond occurs as well as dimerization. The

free radicals are stabilized by recombination, hydrogen abstraction, or addition to the chain end of another molecule. The main products isolated were 9-octadecene, 9,17-hexacosadiene, methyl decanoate, methyl 9,17-hexacosadienoate, dimethyl 9-octadecene-1,18-dioate, and dimethyl 9,17-hexacosadien-1,26-dioate.

32

Biochemical Difference Between Fresh and Frozen Meat

R. Hamm and *L. Körmendy*, Kulmbach (Germany)

It could previously not be decided with certainty whether a sample of meat is fresh or had been frozen and thawed. Since there is no reliable histological test, a biochemical method was sought. Previous work[1,2] had shown that two isozymes of glutamate-oxalacetate transaminase occur in the skeletal muscle of beef and pig. One of these (GOT_M) is localized in muscle mitochondria; the other (GOT_S) occurs in the sarcoplasm. The isozymes can be separated by high-voltage electrophoresis on cellulose acetate membranes and determined[2] by spraying the strip with α-ketoglutarate/malate dehydrogenase/NADH/pyridoxal phosphate[3]. The centrifuged juice of fresh meat shows the GOT_S band only. After freezing (−10 to −40 °C) and thawing, however, GOT_M enters the sarcoplasm, evidently because of damage to the mitochondrial structure. A strong GOT_M band is then found in electrophoresis together with the GOTs band. The method is not affected by the duration of the cold storage nor by the normal time of aging of the meat.

[1] *G. Gantner* and *R. Hamm*, Z. Lebensmittel-Unters. u. Forsch. *126*, 1 (1964).

[2] *L. Körmendy*, *G. Gantner*, and *R. Hamm*, Biochem. Z. 342, 31 (1965).

[3] Commercially available as "GOT-Test-Kombination" from C. F. Boehringer & Söhne GmbH., Mannheim (Germany).

33

Rearrangements of Homoallylic Carbonium Salts

M. Hanack and *H. J. Schneider*, Tübingen (Germany)

From 1-bromo-3-butene and 1-bromo-3-pentene in nitromethane or dichloromethane, the corresponding tetrafluoroborates were prepared with silver tetrafluoroborate, and the rearrangements of the carbonium ions were studied as a function of reaction time and temperature. To this end the solutions were hydrolysed rapidly with an excess of sodium hydrogen carbonate solution, and the alcohols formed were analysed.

Cyclopropylcarbinols, cyclobutanols, homoallylic alcohols, and allyl alcohols were found, the proportions of which depended on the rearrangement time and temperature. The roughly equimolar mixture initially formed from the butenyl tetrafluoroborate of about equal amounts of cyclopropylcarbinyl and cyclobutyl cations first alters its composition in favor of the cyclobutyl cation, which then is converted into the allyl cation. In the rearrangement of the pentenyl system, the cyclopropylcarbinyl cation is found to be the more stable. From this it is concluded that the rearrangements proceed *via* different ionic intermediates. The results give indications of the stabiltities and rearrangement rates of the ions involved.

34

Hydrocyanic Acid in Some Prunoideae Seeds and in their Products such as Marzipan and Marzipan Substitutes

E. Hanssen and *W. Sturm*, Hannover (Germany)

The hydrocyanic acid contents of bitter almonds and of apricot and peach kernels are often higher than has been assumed. On processing of these *prunoideae* seeds to persipan, especially on soaking in water and by the dehydrating process, a stepwise decrease of the HCN content takes place, so that the amounts remaining in the final product are slight and toxicologically insignificant.

When bitter almonds are baked the hydrocyanic acid is only expelled in part (depending on the conditions of baking), and on cooking as well as on burning of bitter almonds practically no HCN is set free. This is because the emulsin required for the liberation of HCN is inactivated by heat.

At the optimum pH-value (4–6) the hydrocyanic acid can be quantitatively liberated at room temperature in 3 hours if it is distilled directly and titrated. It is warned against acid hydrolysis (pH < 3) as well as against acid addition before distillation because the amount of HCN liberated is reduced by lowering pH. – This method of determination also can be used to estimate the amount of bitter almonds mixed with sweet almonds.

35

Non-stationary Processes in the Reduction of Zinc Oxide with Hydrogen

W. Hirschwald, Berlin (Germany)

The kinetics of the reduction of zinc oxide with hydrogen:

$$ZnO(s) + H_2(g) \longrightarrow Zn(g) + H_2O(g)$$

was studied between 280 and 500 °C at hydrogen partial pressures of 0.1–0.01 mm. The rate-determining step then becomes the reaction at the phase boundary instead of diffusion in the gas phase.

On sintered samples of almost the theoretical density, a lag period was observed during which the phase boundary reaction increased to a stationary value. From the temperature dependence, a change in activation energy is found in the non-stationary initial phase of the reaction.

The following relations were obtained for the rate constants k_i and k_{st} of the reduction of fresh samples and those in the stationary period, respectively:

$$k_i = 1 \times 10^6 \, e^{-19500/RT} \text{ [cm/sec]}$$
$$k_{st} = 5 \times 10^4 \, e^{-13900/RT} \text{ [cm/sec]}$$

Although under the conditions used solid zinc is not thermodynamically stable, zinc can remain interstitially in the solid oxide phase and considerably alter the degree of lattice disorder near the surface. Simultaneous measurement of electrical conductivity showed a proportionality of the latter to the reaction rate. On the basis of this result, chemisorption of hydrogen as rate-determining step is excluded by the boundary-layer theory.

The results are interpreted with the assumption of catalytic activity of the interstitial zinc. Pretreatment of the samples in air and with oxygen ions causes an "extraction" of interstitial zinc; this supports the assumption made.

36

Determination of Pilocarpine in the Aqueous Humor of the Eye by Polarographic Adsorption Analysis

O. Hockwin, Bonn (Germany)

Pilocarpine, $C_{11}H_{16}N_2O_2$, an alkaloid occurring in jaborandi leaves (*Pilocarpus pennatifolius*), is used in ophthalmology to decrease the pressure within the eye.

In a study of the influence of pilocarpine on the metabolism of the eye lens, a decrease of oxygen uptake was observed. At a pilocarpine concentration of 10^{-3} M in the nutrient medium of the lens, O_2-uptake was completely inhibited.

The usual methods of determining pilocarpine fail in the study of the aqueous humor because of the small volume (0.1 to

0.15 ml) of the sample. In polarographic adsorption analysis, the diminution or suppression of maxima by surface-active substances is measured. *Von Stackelberg* and *Schütz* measured instead the displacement of the break-off potential, which is directly proportional to the concentration of surface-active agent. This method is suitable for the determination of pilocarpine.

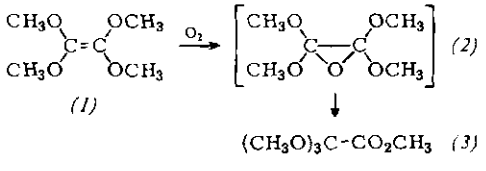
Studies of the aqueous humor of human and rabbits' eyes showed that 20 min after the administration of pilocarpine, $^1/_5$ to $^1/_{10}$ of the amount taken occurs in the aqueous humor. The resulting concentration of pilocarpine is sufficient to completely suppress oxygen uptake by the eye lens.

37

Reactions of Tetramethoxyethylene

R. W. Hoffmann, Heidelberg (Germany)

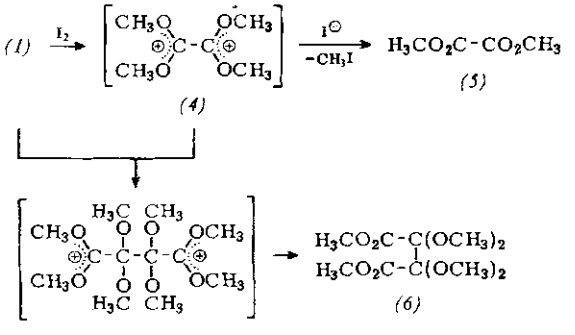
As a particularly electron-rich olefin, tetramethoxyethylene *(1)* is very sensitive to oxidation. With oxygen it gives methyl trimethoxyacetate *(3)* (39 %), as well as dimethyl carbonate (51 %), probably by way of the epoxide *(2)*. Oxidation with iodine affords dimethyl oxalate *(5)* (61 %)



(1) *(2)*

$(CH_3O)_3C\text{-}CO_2CH_3$ *(3)*

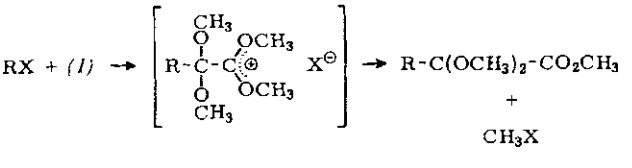
and a small amount of dimethyl tetramethoxysuccinate *(6)*. Occurrence of a radical cation cannot be excluded, but formation of *(5)* and *(6)* is most simply formulated as involving the tetramethoxyethylene dication *(4)*. Attack of iodide on *(4)* gives *(5)*, and attack of *(4)* on *(1)* gives *(6)*. In conformity therewith, oxidation by iodine in the



(4) *(5)* *(6)*

presence of $AgBF_4$, which removes all the iodide as it is formed, leads to a preponderating amount of *(6)*; this compound is also obtained from *(1)* by means of $AgBF_4$ or $HgCl_2$ at a higher temperature.

Compound *(6)* is obtained on alkylation of *(1)* by *(4)*; similar alkylations are readily effected by other cations, *e.g.*, those from tropylium bromide (62 %), benzenediazonium



chloride (88 %), triphenylmethyl chloride (30 %). The larger the partial positive charge on the alkyl group, the easier is alkylation of *(1)*, whereas with, *e.g.*, n-butyl iodide there is no reaction. This shows that *(1)* is readily attacked in an S_N1 reaction but does not function as a nucleophile in S_N2 reactions.

38

Relations between Rotational Isomerism, Hydrogen Bonding, and Substituent Effects

H. Hoyer and *M. Chua*, Bonn (Germany)

Intramolecular hydrogen bonds to rotatable carbonyl groups are supposedly strenthened by the presence of methyl or methylene groups ortho to the carbonyl group by bond deformation [1]. This hypothesis can be tested by measurement of the infrared spectra of solutions (in CCl_4) of compounds in which an OH group is offered a second proton acceptor besides the carbonyl group for the formation of intramolecular hydrogen bonds.

The spectrum of methyl 5,6,7,8-tetrahydro-2-hydroxy-3-nitro-1-naphtoate shows that here the postulated strengthening does not occur, but that the ester group is turned out of the plane of the aromatic system.

In compounds like *N*-(4-methylphenyl)-2-hydroxy-3-methoxycarbonyl-5,6,7,8-tetrahydronaphylideneimine or *N*-(4-methylphenyl)-2-hydroxy-3-methoxycarbonyl-5,6-dimethylbenzylideneimine, however, the hydrogen bond to the azomethine group is favored by the ortho methylene or methyl group. These groups hinder the rotation of the azomethine group and thereby reduce the energy difference between the conformation required for hydrogen bonding and a conformation which is more stable but unfavorable for hydrogen bonding.

The same explanation is given for the facilitation of hydrogen bonding to the aldehyde group in 2-hydroxy-3-nitro-5,6,7,8-tetrahydro-1-naphthaldehyde. The infrared spectrum in CCl_4 shows two carbonyl bands. Their intensities indicate that hydrogen bonding to the aldehyde group is less unfavorable than in the simpler 3-nitrosalicylaldehyde.

[1] *I. M. Hunsberger, H. S. Gutowsky, W. Powell, L. Morin*, and *V. Bandurco*, J. Amer. chem. Soc. *80*, 3294 (1958); *idem* in *D. Hadzi*: Hydrogen Bonding. Pergamon Press, London 1959, pp. 461–474.

39

Preparation of Cyanosilanes

J. Hundeck, München (Germany)

In the presence of chlorotrimethylsilane the yield of cyanotrimethylsilane in the reaction of bis(trimethylsilyl)amine and hydrocyanic acid [1] is approximately doubled.

$$[(H_3C)_3Si]_2NH + (H_3C)_3SiCl + 3\ HCN \rightarrow 3\ (H_3C)_3SiCN + NH_4Cl \quad (a)$$

Adducts of iodosilane with tertiary amines react even at −20 to −70 °C with hydrocyanic acid or cyanogen iodide with the formation of cyanosilanes, possibly according to Eq. (b).

$$R_3SiI\cdot NR_3' + HCN(ICN) \rightarrow R_3SiCN + NR_3'\cdot HI\ (NR_3'\cdot I_2) \quad (b)$$

The action of cyanogen iodide on methyldialkylaminosilanes in bulk or in ether solution at 0 to −20 °C gives methyldialkylaminocyanosilanes according to Eq. (c) (R=CH_3,C_2H_5).

$$(H_3C)_nSi(NR_2)_{4-n} + ICN \rightarrow (H_3C)_nSi(NR_2)_{3-n}CN + [NR_2I] \quad (c)$$

Diethylaminodimethylcyanosilane was also prepared from diethylaminoiododimethylsilane and cyanogen iodide in 28 % yield:

$$(H_3C)_2Si[N(C_2H_5)_2]I + ICN \rightarrow (H_3C)_2Si[N(C_2H_5)_2]CN + I_2 \quad (d)$$

[1] *T. A. Bither, W. H. Knoth, R. V. Lindsey Jr.*, and *W. H. Sharkey*, J. Amer. chem. Soc. *80*, 4151 (1958).

Reaction of organylsilylamines with hydrocyanic acid and cyanogen halide also gives organylcyanosilanes [Eq. (e)]. When organylsilyldialkylamines are used, dialkylcyanamides and organylsilylcarbodiimides are formed as by-products [Eq. (f)].

$$2\ (H_3C)_3Si{-}NR_2 + XCN + 2\ HCN \rightarrow 2\ (H_3C)_3Si{-}CN + NR_2(CN) + NR_2H{\cdot}HX \quad (e)$$

$$2\ [(H_3C)_3Si]_3N + XCN + 4\ HCN \rightarrow 4\ (H_3C)_3Si{-}CN + (H_3C)_3Si{-}N{=}C{=}N{-}Si(CH_3)_3 + NH_3{\cdot}HX \quad (f)$$

Trialkylcyanosilanes $R_3Si{-}CN$ ($R{=}CH_3, C_2H_5$) can further be detected in the reaction of cyanogen with trialkylmethylaminosilanes alongside cyanoformamidine derivatives.

40

Isotope Effects in the Separation of Rare Earths on Ion-Exchangers

H. Ihle, Bonn (Germany)

Equilibria for chemical exchange of isotopes have hitherto been measured mainly for light elements (H, Li, B, C, N, O), where the equilibrium constants are considerably greater or less than unity.

For elements of medium to high mass number the equilibrium constants K for isotope exchange approximate to unity. Values of 10^{-3} to 10^{-4} can be estimated for $\varepsilon = K - 1$.

We have measured the quotients of the distribution coefficients of samarium isotopes between a cation-exchanger and two complex-forming aqueous phases. Because of the high selectivity of the ion-exchange chromatography, microcolumns (length 80 mm, inner diameter 2 mm) suffice in band-elution experiments to give enrichments that are measurable by mass spectrometry. Values of ε have been calculated from the measured relative isotope abundances in the eluted fractions[1]. For two neighboring samarium isotopes, with mass numbers M and M + 1, the following values of ε were obtained at 20 °C:

$$\varepsilon_1 = K_1 - 1 = \frac{[M]_r[M+1]_{w1}}{[M]_{w1}[M+1]_r} - 1 = 3.4\times10^{-5} \pm 10\%$$

$$\varepsilon_2 = K_2 - 1 = \frac{[M]_r[M+1]_{w2}}{[M]_{w2}[M+1]_r} - 1 = 2.4\times10^{-5} \pm 10\%$$

where r denotes cation-exchanger Dowex 50 W X 4, w1 denotes aqueous 0.4 M α-hydroxyisobutyric acid of pH 3.45, and w2 denotes aqueous 0.43 M tartronic acid of pH 2.00.

The results are lower than those estimated from current theory. The discrepancy probably arises because the theory requires a series of simplifying assumptions that cannot be verified experimentally.

[1] E. Glueckauf, Trans. Faraday Soc. *54*, 1203 (1958).

41

Alteration of the Barrier-Layer Properties of Oxide-Protected pn-Junctions in Silicon

D. Jahn, Baden (Switzerland)

The rectifying properties of pn-junctions in silicon can be stabilized by covering the crystal surface with an insulating protective coating, particularly at the intersection of the junctions with the surface. If SiO_2 is used as insulator, which can he applied to silicon in thicknesses of several μ by oxydation at high temperatures, this oxidation process often has unfavorable effects on the rectifying properties, *i.e.* redistribution of doping agents at the phase boundary Si/SiO_2 in accord with the distribution coefficients, rapid diffusion of impurities with high temperature coefficients of solubility into the crystal and formation of inclusions on cooling, and formation of inversion layers in the silicon owing to space charges in the SiO_2 layer.

The blocking action of silicon samples with npn structure (P-diffusion in p-Si of 10^3 ohm·cm) and mechanically and chemically exposed pn junctions having a hard characteristic and high blocking voltage (> 1000 volts) was lost on oxidation in dry O_2 at 1000 °C (SiO_2 film thickness 0.1 μ). This change is due partly to a surface effect. When the oxidized samples were polarized for several minutes at 50–200 volts *versus* a platinum cathode in an electrolyte (*e.g.* glycol with 2 % of H_2O and 0.4 % of KNO_3), high blocking voltages were again obtained, although the characteristic remained soft (which indicates defects in the bulk of the material). The same changes are observed when the oxide layer is removed with HF or when the sample is etched with HF/HNO_3. The possibility of changing the effect of the thermally produced SiO_2 layer on the semiconductor by electrolysis supports the assumption[1] that near the Si/SiO_2 interface there are oxygen vacancies in the SiO_2, which represent a strong positive space charge. In the high field prevailing during the electrolysis, migration of ions is evidently possible already at room temperature, which leads to elimination of the space charge.

[1] *J. E. Thomas* and *D. R. Young*, IBM Journal *8*, 368 (1964); *M. Croset*, Onde Electrique *45*, 499 (1965).

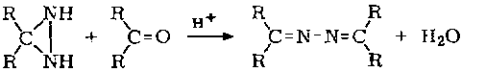
42

Conversion of Diaziridines into Azines

A. Jankowski, Essen (Germany)

Diaziridines *(1)* are isomeric with hydrazones. Like hydrazones they are hydrolysed by acids to a hydrazinium salt and a ketone. In contrast to hydrazones they cannot be hydrolysed in neutral or alkaline media, which limits their applicability in hydrazine synthesis *via* diaziridines.

Diaziridines can be converted into azines *(2)* with a new reaction: Treatment of diaziridines with catalytic amounts of acids, aqueous solutions of acid salts (*e.g.* hydrazine sulfate), or acidic agents (ion exchange resins), in the presence of a carbonyl compound and with the medium kept acidic, opens the ring and an exothermic reaction with the carbonyl compound takes place which yields the azine.



(1) *(2)*

The rate of conversion is strongly temperature-dependent. At 50 °C, *C*-methyl-*C*-ethyldiaziridine is completely transformed after 30 min, whereas at 25 °C the reaction takes 9 h. The reaction rate is also influenced by the substituents R. It increases in the sequence *C,C*-dimethyl- < *C*-methyl-*C*-ethyl- < *C,C*-diethyl-diaziridine.

The optimum pH is 2.5. Below this, the azine is partially cleaved to a hydrazine salt and a ketone; above it an as yet unexplained side reaction occurs with the formation of ammonia and nitrogen, which lowers the azine yields. If instead of acid an aqueous solution of a hydrazine salt is used and the solution is maintained at pH 2.0–2.5, hydrolysis of the azine is prevented and it is obtained in 95 % yield.

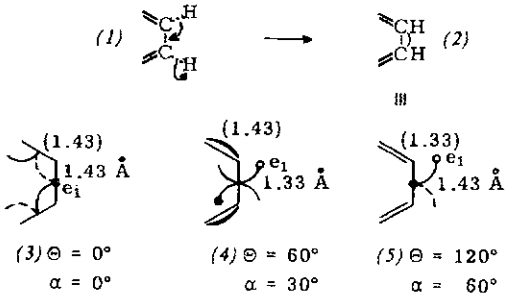
The formation of azines is industrially interesting, since they can be easily hydrolysed to hydrazine hydrate and can be used as starting materials in syntheses.

42a

An Accurate and Simple Calculation of the C-C Distance in Benzene

J. J. Jennen, Mortsel (Belgium)

There is a discrepancy between the observed C–C distance in benzene (1.397 Å [1]) and the average value of C–C single and double bond distances: (1.53 + 1.33)/2 = 1.43 Å. According to *Rogowski* [2] this discrepancy can be attributed to a shortening of the C–C single bond. According to the author a σ-delocalization, due to an electron releasing effect from the three C–H bonds in *m*-position toward the aromatic ring, is responsible for said shortening. Consequently, the Kekulé structure *(1)* changes into a Thiele structure *(2)* with saturated partial valencies. For structure *(2)*, wherein σ-electrons also are involved, the author introduces a segment



notation [3] [see *(3)* to *(5)*]; the segment radius for single and double bonds remains unaltered. In order to describe the bond configurations a segment must rotate around the z-axis of the carbon atom considered (angle Θ) and simultaneously around the segment axis (center of the circle – middle of the arc) (angle α = Θ/2). In this way only three structures result: one Kauffmann *(3)* and two Thiele structures *(4)* and *(5)*; from this it follows that the mean bond length in benzene is (1.33 + 1.43 + 1.43)/3 = 1.397 Å, in agreement with the observed value

[1] *A. Almenningen, O. Bastiansen*, and *L. Fernholt*, Kgl. norske Vidensk. Selsk., Skr. Nr. 3 (1958); *A. Langseth* and *B. P. Stoicheff*, Canad. J. Physics *34*, 350 (1956).

[2] *F. Rogowski*, Fortschr. chem. Forsch. *4*, 44 (1962).

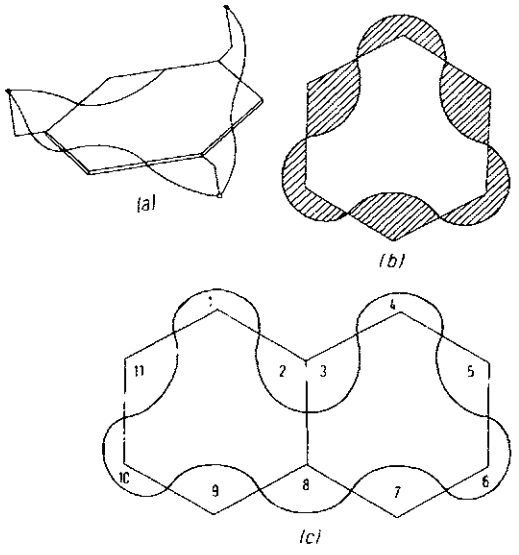
[3] *J. J. Jennen*, J. prakt. Chem. [2] *25*, 188 (1964).

42b

A New Semiquantitative Calculation of the Delocalisation Energy in Benzene and in the Acenes

J. J. Jennen, Mortsel (Belgium)

The ring currents generated by the mobile electrons (six π-electrons and six σ-electrons) in benzene are represented graphically using the segment method [1]. In this way Fig. (a) is obtained, wherein for a mobile electron half of the entire path is represented (the other half is enantiomorphic to the plane of the benzene nucleus). By the segment spin and the exchange in the Kauffmann structure the mobile electrons travel alternatively above and below the ring plane. By projection of the path shown in Fig. (a) the equivalent surfaces of Fig. (b), which are a measure for the delocalisation energies [2], are obtained. With the aid of the segment method delocalisation energies are calculated for the acenes, which agree with those obtained with the MO-method. Fig. (c)



illustrates the situation for naphthalene [surfaces 2, 3 and 8 are equivalent since the segments of the central bond are spinless (α = 0).].

Acene	Delocalisation energies in β: segment method	MO-method
Benzene	6 × 1/3 = 2	2.00
Naphthalene	11 × 1/3 = 3.67	3.68 [3]
Biphenyl	13 × 1/3 = 4.33	4.38 [3]
Anthracene	16 × 1/3 = 5.33	5.32 [3]
Tetracene	21 × 1/3 = 7	6.93 [4]

[1] Graphical representation with six π-electrons alone: *J. J. Jennen*, Meded. vlaamse chem. Veren. *26*, 208 (1964) [Kekulé issue].

[2] For this concept cf. also *A. J. Stavermann*, Chem. Weekbl. *39*, 344 (1942), Chem. Zbl. *1942*, II 2466.

[3] *H. A. Staab:* Einführung in die theoretische organische Chemie. Verlag Chemie, Weinheim/Bergstr. 1959, p. 121.

[4] *A. Streitwieser jr.*: Molecular Orbital Theory for Organic Chemists. Wiley, New York, 1961, p. 241.

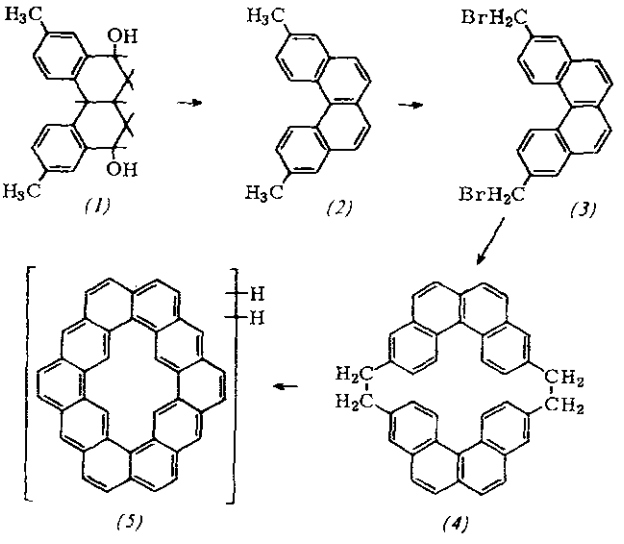
43

Coronaphenes, a New Group of Cyclic Hydrocarbons

W. Jenny and *R. Peter*, Basel (Switzerland)

The influence of ring fusion on the absorption spectra and reactivity of ortho-fused benzenoid hydrocarbons has repeatedly been studied in the acene and phene series. The empirical rules obtained can be extended only with reserve to angularly fused phenes which are combined in a larger polycyclic ring system. A number of new hydrocarbons was synthesized with the aim of studying these relations. The new polycyclic compounds are related to the circo-hydrocarbons, but in contrast to these they have an "empty" interior. The name coronaphene is proposed for these compounds, with a numerical prefix indicating the number of benzene rings fused in the molecule. All coronaphenes formally contain two concentric annulene systems and are therefore also of theoretical interest.

A synthesis leading to the skeleton of a [10]-coronaphene is described. Starting from 1,1-di-*p*-tolyl-2,2-ethoxycarbonylethane, the diol *(1)* was obtained after several steps. By dehydration and dehydrogenation, this was converted into 3,10-dimethylbenzo[c]phenanthrene *(2)* in 50 % yield. The action of phenyl-lithium on the dibromomethyl derivative *(3)* gave di(benzo[c]phenanthren-3,10-dimethylene) *(4)*, the structure of which was confirmed by NMR and mass spectra. Extensive dehydrogenation of *(4)* was achieved by treatment with $AlCl_3/CS_2$ and subsequent heating in the presence of Pd/C



(1) (2) (3) (5) (4)

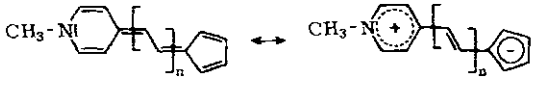
to 320–340 °C in a current of CO_2. A greenish-yellow dihydro derivative *(5)* was isolated by repeated column chromatography.

44

Studies on Azalogous Sesquifulvapolyenes

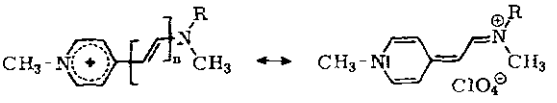
Ch. Jutz, R. Kirchlechner, and *W. Müller*,
München (Germany)

Vinylogous azalogues of sesquifulvalene (with the pyridine or quinoline system instead of the cycloheptatrienylidene group in sesquifulvalene) were previously unknown. For an investigation of bathochromic shifts of the principal absorption when the polyene chain is extended, the set of compounds *(1b)–(1d)* was built up by reaction of the vinylogous 1-methyl-4-aminopyridines *(2a)–(2c)* with cyclopentadienylsodium in tetrahydrofuran.



(1a): n = 0 [1] *(1c)*: n = 2
(1b): n = 1 *(1d)*: n = 3

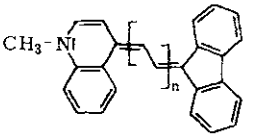
[λ_{max} (log ε) in acetonitrile: *(1a)*, 438 mμ (4.57); *(1b)* 542, 515 mμ (4.69; 4.71); *(1c)* 584 mμ (4.8); *(1d)* 602 mμ].



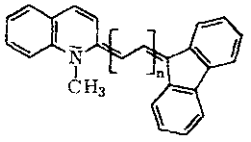
(2a): n = 1, R = CH_3
(2b): n = 2, R = C_6H_5
(2c): n = 3, R = C_6H_5

[λ_{max} (log ε) in acetonitrile: *(2a)* 399.5 mμ (4,96) *(2b)* 483 mμ (4.93); *(2c)* 575 mμ (4.96)].

Compound *(2)* was obtained from *N*-methylpicolinium perchlorate by reaction with dimethylformamide dimethylacetal, *(2a)* and *(2b)* by reaction of 3-(*N*-methylanilino)prop-1-enylidenemethylanilinium and 3-(*N*-methylanilino)penta-1,3-dienylidenemethylanilinium perchlorates, respectively, and sodium methoxide. The betaine-like basic compounds *(1)*, which are poorly soluble in non-polar solvents, are unstable and decompose below their melting points. Only *(1b)* and *(1c)* could be obtained pure; *(1d)* was obtained only in solution. By contrast, the fluorenylidenedihydroquinolines *(3a)–(3d)* and *(4a)–(4d)* are stable, deeply colored compounds of low polarity and basicity.



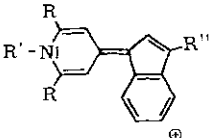
(3a): n = 0 *(3c)*: n = 2
(3b): n = 1 *(3d)*: n = 3



(4a): n = 0 *(4c)*: n = 2
(4b): n = 1 *(4d)*: n = 3

[λ_{max} (log ε) in acetonitrile: *(3a)* (m.p. 220 °C), 541 mμ (4.30); *(3b)* (m.p. 215 °C), 547 mμ (4.60); *(3c)* (decomp. at 229 °C), 562 mμ (4.68); *(3d)* 574 mμ (4.84); *(4a)* (m.p. 181 °C), 523 mμ (4.34); *(4b)* (m.p. 212 °C), 503.5 mμ (4.65); *(4c)* (m.p. 215 °C), 539 mμ (4.79); *(4d)* (decomp. at 214 °C), 552 mμ (4.84)].

Compounds *(3a)*, *(3b)*, *(4a)*, and *(4b)* were obtained by reaction of 4-methoxy- or 2-methoxy-*N*-methylquinolinium perchlorate with fluorene or 9-ethylidenefluorene, respectively, and sodium methoxide; *(3c)*, *(3d)*, *(4c)*, and *(4d)* were prepared from vinylogous *N*-methyl-4- or *N*-methyl-2-aminoquinolines. Electrophilic substitution on the 4-(1-indenylidene)-1,4-dihydropyridine system, *(5)*, R = H, leads to derivatives substituted in the 5-membered ring: The action of dimethylformamide/$POCl_3$ leads *via* the immonium perchlorate *(5a)* (λ_{max} = 475 mμ, log ε = 4.64) to the aldehyde *(5b)* (λ_{max} = 475 mμ, log ε = 4.97); *(5)* with *p*-dimethylaminobenzaldehyde and perchloric acid gives the dye salt *(5c)* (λ_{max} = 515 mμ, log ε = 4.67; methylation of *(5)*, R = H, with dimethyl sulfate gives *(5d)*; coupling of *(5)* with diazonium salts leads *via* a cation to the azo compounds *(5e)* (λ_{max} = 639 mμ, log ε = 4.9).



(5a): R = R' = CH_3; R'' = $-CH=\overset{\oplus}{N}(CH_3)_2ClO_4^{\ominus}$
(5b): R = R' = CH_3; R'' = $-CH=O$
(5c): R = R' = CH_3; R'' = $-CH=p-C_6H_4=\overset{\oplus}{N}(CH_3)_2ClO_4^{\ominus}$
(5d): R = R' = R'' = CH_3
(5e): R = H; R' = n-C_4H_9; R'' = $-N=N-C_6H_5$
(5f): R = H; R' = n-C_4H_9; R'' = $-N=N-p-C_6H_4-NO_2$

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Ternary Oxides of Seven- and Four-Valent Technetium

C. Keller, B. Kanellakopulos, and *M. Wassilopulos*,
Karlsruhe (Germany)

Tc(VII) and Re(VII) are closely related crystallochemically. Thus the alkali pertechnetates $MTcO_4$ (M = Li to Cs), M_3TcO_5 (M = Na, K), and M_5TcO_6 (M = Li, Na), the alkaline earth pertechnetates $M^{II}(TcO_4)_2$ (M = Ca to Ba), $M_3^{II}(TcO_5)_2$ (M = Ba, Sr), and $M_5^{II}(TcO_6)_2$ (M = Ca to Ba), and the quaternary oxides $M^{II}(M^{I}_{0.5}, Tc^{VII}_{0.5})O_3$ (M^{II} = Ba, Sr; M^{I} = Li, Na) with ordered perovskite structure, largely correspond to the analogous perrhenates. When $Sr(TcO_4)_2$ and $Ca(TcO_4)_2$ are prepared by the evaporation of aqueous solutions, the dihydrates are obtained, which at 90 °C (Sr) and 100 °C (Ca) are transformed to the monohydrates, which are dehydrated at 210 °C (Sr) and 155 °C (Ca), respectively, to the anhydrous compounds. The pertechnetates are generally less stable than the perrhenates. Any

[1] *J. A. Berson* and *E. M. Evleth*, Chem. and Ind. *1961*, 1962; *J. A. Berson, E. M. Evleth, Z. Hamlet*, and *L. Manatt*, J. Amer. chem. Soc. *87*, 2887 (1965).

phase transition temperatures are always lower in the Tc compounds, *e.g.* the transformations of orthorhombic $CsXO_4$ and $TlXO_4$ to the tetragonal Scheelite structure occur at 95 °C ($TlTcO_4$) and 136 °C ($CsReO_4$), respectively. In the compounds of the six-valent elements, the differences in transition temperatures are considerably larger, *e,g.* α-Li_6XO_6 → β-Li_6XO_6 at 310 °C and 620 °C for X = Tc and Re, respectively.

In its solid-state chemistry, TcO_2 shows no similarity to ReO_2. Whereas only one ternary oxide, *viz.* Na_2ReO_3, has so far been prepared with Re(IV) [in most cases disproportionation of Re(IV) occurs in the reaction of ReO_2 with M_2O or MO], TcO_2 reacts to give defined compounds of Tc(IV), *e.g.* Li_2TcO_3(Li_2TiO_3 structure), Na_2TcO_3, Na_4TcO_4, $MTcO_3$ (M = Ba, Sr, Ca; perovskite structure), and M_2TcO_4 (M = Ba, Sr; K_2NiF_4-structure). $BaTcO_3$ was obtained in two modifications: in the direct reaction BaO + TcO_2, $BaTcO_3$ is formed in the $BaTiO_3$-structure (a = 5.763 Å, c = 14.05 Å); in the symproportionation from BaO + Tc + $Ba(TcO_4)_2$, cubic $BaTcO_3$ (a = 8.140 Å) is obtained. Tc(IV) thus is similar to Mn(IV) in its solid-state chemistry.

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Attempted Preparation of Carbenes, Nitrenes, and Sulfenes

D. Klamann and *K. Ulm*, Hamburg-Harburg (Germany)

Although trihalomethanes and chloromethyl phenyl sulfide form carbenes with ethylene oxide in the presence of tetraalkylammonium halides, alkyl, allyl, and benzyl halides and *p*-toluenesulfonates, as well as halogen compounds activated by neighboring groups, give the corresponding alkyl 2-substituted ethyl ethers smoothly under the same conditions. In these reactions the reactivity, but also the concurrent β-elimination of HX, increases along the series chlorine to iodine and with increasing substitution of the alkyl residue. Dihalomethanes afford bis-(2-halogenoethyl)formals.

On treatment of *N*-halo compounds such as *N*-chloroamines and *N*-haloamides and -urethanes under the same conditions, the nitrene intermediates could not be isolated. Chlorination of the reactant (especially ethylene oxide) and polar addition of the *N*-halo compound to the acceptor double bond occur. On treatment of methane- or benzenesulfonyl chloride with ethylene oxide in the presence of tetraalkylammonium halides and addition to substituted butenynes or butadienes, ethylene oxide is inserted into the SO_2Cl group, yielding 2-halogenated sulfonic esters. This reaction is general for sulfonyl chlorides and epoxides.

47

Preparation and Reactions of Dihalocyclopropanes

D. Klamann and *P. Weyerstahl*, Hamburg-Harburg (Germany)

Dihalocarbenes are formed when trihalomethanes are heated with ethylene oxide in presence of tetraalkylammonium salts at 120–170 °C. By reaction of open-chain and cyclic mono- and di-olefins numerous, mostly new, 1,1-dichloro-, 1,1-difluoro-, and 1-chloro-1-fluorocyclopropanes have been prepared. Diolefins afford various amounts of bis-adducts.

Reaction of chloroform and ethylene oxide with tetrasubstituted ethylenes does not afford the primary product, but the 2-chlorodiene was obtained as a result of elimination of hydrogen chloride and isomerization. One or the other product can be obtained from trisubstituted olefins, depending on the reaction temperature.

1,1-Disubstituted olefins cannot be converted directly into 2-chlorodienes by reaction with chloroform and ethylene oxide, but the resulting dichlorocyclopropanes are smoothly cleaved to the 2-chlorodiene and hydrogen chloride by quinoline at 200 °C or by pyrolysis at about 400 °C.

48

Synthesis of Aliphatic Amines from Carbon Monoxide, Steam, and Ammonia

H. Kölbel and *J. Trapper*, Berlin (Germany)

At 200 to about 270 °C, the equilibrium

$$3n\ CO + n\ H_2O + NH_3 \rightleftharpoons C_nH_{2n+1}NH_2 + 2n\ CO_2$$

favors the products, in which amines with many carbon atoms predominate over those with few. The reaction is exothermic and was studied at 11 atm total pressure of a gas consisting of, *e.g.*, 56 % of CO, 21 % of H_2O, 11 % of NH_3, and 22 % of an inert gas. An iron catalyst containing small amounts of copper and potassium carbonate was used. In continuous operation (for several weeks), a single passage of the gas through the reactor gives conversions of 80 % for CO and 30 % for NH_3 at a gas velocity of 50–60 liters per liter of catalyst per hour.

The liquid products contain, apart from hydrocarbons, up to 23 % of nitrogen-containing compounds, mainly 1-aminoalkanes from methylamine to n-dodecylamine. About 50 % of the non-gaseous products are liquids; the rest have the consistency of soft to hard paraffin waxes. The nitrogen content of the hard paraffin (up to 1.35 %) suggests that more than 50 % of the constituent molecules contain nitrogen. Oxygen compounds are also formed, *e.g.* alcohols, carbonyl compounds, and fatty acids. It is therefore probable that amino acids are also formed, but significant amounts were not found. Since the melting points of the amino acids expected lie in the range of the synthesis temperatures, they probably decompose during the process.

If the yields can be increased, this reaction should be suitable for the technical production of the aliphatic amines mentioned.

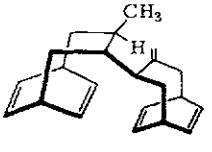
49

A New Photochemical Reaction of Benzene and Some of Its Homologues

G. Koltzenburg and *K. Kraft*, Mülheim/Ruhr (Germany)

Under direct photochemical excitation at 254 mμ, benzene reacts in even dilute solutions (in ether, n-pentane, *etc.*) with isoprene to give at least ten products. The two chief products, a 2:2 adduct (46 %, based on benzene consumed) and a 1:1 adduct (23%), were isolated.

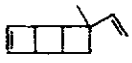
The 2:2 adduct, $C_{22}H_{28}$, forms colorless crystals melting at 164–168 °C. It contains five non-conjugated double bonds; four *cis*-substituted double bonds come from benzene and one *exo*-methylene group from isoprene (shown by comparison of the NMR spectra of $C_{22}H_{28}$ and the analogous adduct of C_6D_6 and isoprene, $C_{22}D_{12}H_{16}$). One of the two methyl groups of the isoprene molecules is retained; it is found on a tertiary carbon atom. The compound can be hydrogenated under pressure. After hydrogenation of the four *cis* double bonds, the *exo*-methylene group is saturated only at 100 atm of H_2.



$C_{22}H_{28}$

The 2:2 adduct isomerizes at 130 °C to a colorless, lower-melting compound (m.p. 82–85 °C) containing a 1,3-cyclohexadiene partial structure (λ_{max} = 38400 cm^{-1}, ε = 3400 in cyclohexane).

The 1:1 adduct, a colorless oil of b.p. 55 °C/6 mm, is probably a mixture of stereoisomers *(1)*.



(1)

Crystalline 2:2 adducts were obtained from toluene (m.p. 132–138 °C), *p*-xylene (m.p. 170–196 °C), *o*-xylene (m.p. 150–170 °C), hexafluorobenzene (m.p. 238–271 °C), and 1,2,4,5-tetrafluorobenzene (m.p. 230–241 °C). Benzene and butadiene also form a 2:2 crystalline adduct which sublimes at 195 °C.

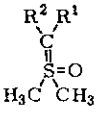
In the presence of sensitizers such as benzophenone and benzil, no crystalline adducts were obtained. Irradiation with electrons or with γ-rays from ^{60}Co also failed to produce adducts.

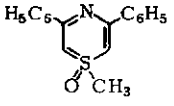
50

Reactions with Sulfur Ylides

H. König, Ludwigshafen (Germany)

Dimethyloxosulfonium methylide *(1)* was acylated in usually very good yield to the crystalline mono- and diacyl derivatives *(2)* and *(3)*.



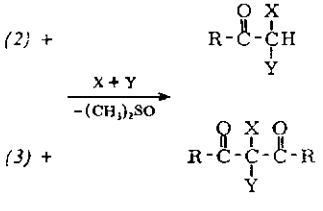


(4)

(1) $R^1 = R^2 = H$
(2) $R^1 = H$; $R^2 = CO\text{-}R$
(3) $R^1 = CO\text{-}R^1$; $R^2 = CO\text{-}R$

The structure elucidation of the new class of compounds is based *inter alia* on the strong displacement of the carbonyl band to longer wavelengths ($\lambda \simeq 6.4\mu$), on the ultraviolet and particularly on the NMR spectrum, which shows a characteristic 6-proton singlet due to the methyl groups on the sulfur atom.

The reaction of excess of benzonitrile with *(1)* gives *inter alia* a crystalline heteroaromatic ylide *(4)*.



Compounds *(2)* and *(3)* react in 40–99 % yield with simultaneous addition of an electrophilic particle X and a nucleophilic partner Y, and elimination of dimethyl sulfoxide, to carbonyl and 1,3-dicarbonyl compounds. Suitable combinations XY are, *e.g.*, formally the ions $X = H^+, CH_3^+, Br^+$, and $Y = Cl^-, Br^-, H^-, C_6H_5S^-, C_6H_5NH^-$.

51

New Syntheses and Reactions of Isoindoles

R. Kreher and *J. Seubert*, Darmstadt (Germany)

Isoindole is formed from 2-benzyloxyisoindoline by base-catalysed elimination; however, it can be recognized only as its adduct with maleic anhydride or *N*-phenylmaleimide[1].

[1] *R. Kreher* and *J. Seubert*, Z. Naturforsch. *20b*, 75 (1965).

2-Alkyl- and 2-Arylisoindoles are obtained from 2-alkyl- or 2-arylisoindoline-2-oxides in the presence of acetic anhydride and triethylamine, even at 0 °C, and can be isolated in pure form by distillation or crystallization[2]. 2-Arylisoindoles can also be obtained from 1,2-dibromobenzocyclobutene and primary aromatic amines.

1-Arylisoindoles are formed on reductive cyclization of 2-cyanobenzophenones with hydrogen and Raney nickel; 1,1'-diaryl-3,3'-dehydrobiisoindoles are by-products which can be regarded as diazafulvalene derivatives.

The substituted isoindoles react like isoindole itself with philodienes as in the Diels-Alder reaction or Michael addition. According to the substituents on the nitrogen, 1:1 or 1:2 adducts are formed; their constitution and configuration have been elucidated in several cases.

[2] *R. Kreher* and *J. Seubert*, Angew. Chem. *76*, 682 (1964); Angew. Chem. internat. Edit. *3*, 639 (1964).

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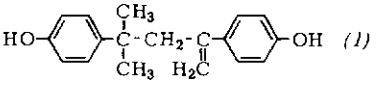
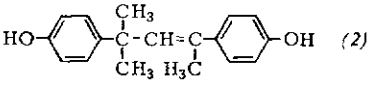
Reactions of p-Isopropenylphenol

H. Krimm, Krefeld-Uerdingen (Germany)

p-Isopropenylphenol dimerizes readily to *(1)*, less easily to *(2)*.

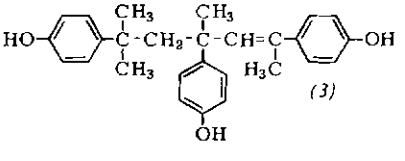


(1)

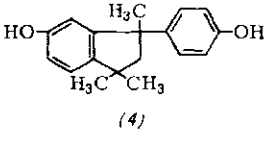


(2)

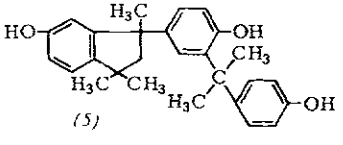
The trimer *(3)* occurs in two geometrically isomeric forms. Two further, saturated oligomers *(4)* and *(5)* have indane structures.



(3)

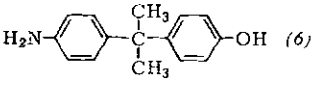


(4)



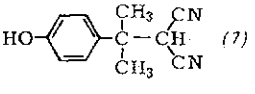
(5)

The reactions of *p*-isopropenylphenol with phenol to 2,2-bis-(*p*-hydroxyphenyl)propane and with aniline to 2,2-(*p*-amino-*p*-hydroxydiphenyl)propane *(6)* are reversible. In *(6)* the hydroxyphenyl and aminophenyl groups are interchangeable. This leads to 2,2-bis-(*p*-hydroxyphenyl)propane and 2,2-bis-(*p*-aminophenyl)propane in good yields.



(6)

CH-active compounds add to *p*-isopropenylphenol; *e.g.*, malonodinitrile gives *(7)*.



(7)

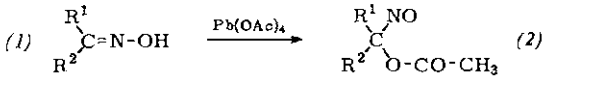
p-Isopropenylphenol can be copolymerized ionically or free-radically with vinyl monomers. Polyfunctional esters of *p*-isopropenylphenol are particularly suitable for radical copolymerization.

53

Geminal Nitrosoacyloxyalkanes and their Dimers

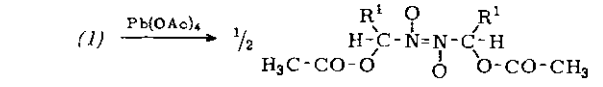
H. Kropf, Hamburg (Germany)

Aliphatic ketoximes *(1a)* to *(1i)* are converted into *gem*-nitrosoacetoxyalkanes *(2)* by lead tetraacetate[1]. Some of the products can be isolated in the monomeric form as deep blue oils (λ_{max} = 660–690 mμ). From aliphatic aldoximes *(1k)* to *(1n)* the nitroso-bridged dimers *(3)* are obtained.



(1) $\xrightarrow{Pb(OAc)_4}$ *(2)*

(a) $R^1 = R^2 = CH_3$ *(d)* $R^1 = CH_3$; $R^2 = C(CH_3)_3$
(b) $R^1 = CH_3$; $R^2 = C_2H_5$ *(e)* $R^1 = CH_3$; $R^2 = CH_2{-}C_6H_5$
(c) $R^1 = R^2 = n\text{-}C_3H_7$ *(f)-(i)* $R^1R^2 = (CH_2)_n$, n = 4,5,6,7

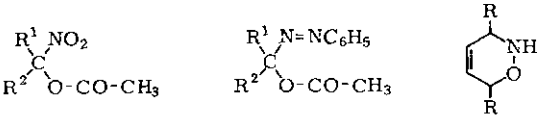


(1) $\xrightarrow{Pb(OAc)_4}$ $\frac{1}{2}$ *(3)*

(k) $R^1 = n\text{-}C_3H_7$ *(m)* $R^1 = n\text{-}C_7H_{15}$
(l) $R^1 = n\text{-}C_5H_{11}$ *(n)* $R^1 = CH_2{-}C_6H_5$

Infrared spectra of *(2)* in tetrachloroethylene: C–O: 1215 to 1240 cm^{-1}; CH_3–(CO): 1360–1370 cm^{-1}; N=O: 1550 to 1570 cm^{-1}; C=O: 1735–1750 cm^{-1}. Infrared spectra of *(3)* in KBr: *trans*-NO–NO: 1185–1200 cm^{-1}; C–O: 1205 to 1220 cm^{-1}; CH_3–(CO): 1360–1375 cm^{-1}; C=O: 1730 to 1750 cm^{-1}.

The structures were confirmed by NMR and mass spectra. The *gem*-nitrosoacetoxyalkanes *(2)* are oxidized to the nitro compounds *(4)* by $H_2O_2/NaNO_2$[1]. Condensation of *(2)* with aniline leads to α-phenylazo-α-acetoxyalkanes *(5)*, Diels-Alder reaction with compounds R–CH=CH–CH=CH–R leads (analogously to the reaction of *gem*-nitrosochloroalkanes[2]) to 3,6-dihydro-1,2-oxazines *(6)*, whereby alcoholysis of the alkyl group takes place.



(4) *(5)* *(6)*

[1] Cf. *D. C. Iffland* and *G. X. Criner*, Chem. and Ind. *1956*, 176.
[2] *O. Wichterle*, Collect. czechoslov. chem. Commun. *16*, 33 (1951).

54

Sodium Acetonitriles, Preparation and Reactions

C. Krüger, Mülheim/Ruhr (Germany)

Monosodium acetonitrile *(1)* can be isolated as an insoluble salt, sensitive to air and moisture, by treating sodium bis(trimethylsilyl)amide[1] with acetonitrile in ether at −60 °C.

$$CH_3CN + NaN[Si(CH_3)_3]_2 \rightarrow \underset{(1)}{NaCH_2CN} + HN[Si(CH_3)_3]_2$$

^{1}H-NMR and infrared spectra show all three tautomers

$$NaCH_2CN \quad CH_2{=}C{=}N{-}Na \quad CH{\equiv}C{-}NH{-}Na$$

to be present as a mixture in which the first form predominates. The compound forms a crystalline but unstable adduct with pyridine. It adds to carbonyl compounds according to

$$R_2C{=}O + NaCH_2CN \rightarrow R_2C(ONa){-}CH_2CN$$

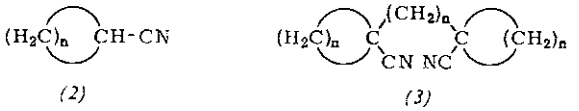
or to nitriles according to

$$R{-}C{\equiv}N + NaCH_2CN \rightarrow R{-}C(NHNa){=}CH{-}CN$$

Compound *(1)* can function as a carbene source particularly in the presence of cyanide acceptors:

$$NaCH_2CN \rightarrow :CH_2 + NaCN$$

The doubly and triply metallated acetonitriles are formed when an excess of metallating agent is used. They can be detected in the reaction mixture[2], but not isolated. Thus the reaction of a multiply metallated acetonitrile with α,ω-dibromoalkanes $Br(CH_2)_nBr$ leads to carbocyclic nitriles *(2)* together with compounds of type *(3)*.



(2) n = 3-6 *(3)*

[1] *U. Wannagat* and *H. Niederprüm*, Chem. Ber. *94*, 1540 (1961).

[2] *C. Krüger* and *E. G. Rochow*, Angew. Chem. *75*, 793 (1963); Angew. Chem. internat. Edit. *2*, 617 (1963).

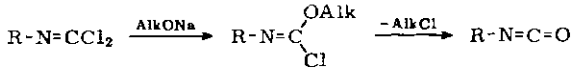
55

Reactions with Isocyanide Dichlorides

E. Kühle and *B. Anders*, Leverkusen (Germany)

Isothiocyanates are obtained in good yields from isocyanide dichlorides with sodium sulfide solution at room temperature or with phosphorus pentasulfide in an inert solvent at a higher temperature

Isocyanates are accessible from isocyanide dichlorides and acid anhydrides. The alkoxy compounds obtained from isocyanide dichlorides and alkoxide solutions also give isocyanates with elimination of alkyl chloride.



Carbodiimides are formed by heating isocyanide dichlorides with primary amine hydrochlorides.

Isonitriles can be prepared from isocyanide dichlorides and organic compounds of trivalent phosphorus.

56

Rheological Properties of Grinding Pastes

W. Liehr, Krefeld-Uerdingen (Germany)

Grinding pastes rich in pigment and containing dilute solutions of binder are usually recommended for high-speed ball mills. The method of flow-point determination of *Daniel* is proposed for finding suitable compositions for the grinding pastes. Pastes compounded in this manner are difficult to use in sand and pearl mills. The addition of binder solution in excess of that required to attain the flow point has been proposed, in order to obtain almost Newtonian behavior. The flow properties of pigment-binder systems have now been studied with a rotation viscometer.

It has previously been observed that the flow properties of grinding pastes change during dispersion. We followed this change with degree of dispersion using the hysteresis method of determining flow curves at various constant concentrations of binder, but with different ratios pigment: binder: solvent, dispersed in a sand mill.

The results obtained were partly expected: the viscosity decreases with increasing proportion of binder solution; it decreases with increasing temperatures; higher structural viscosity is found with higher proportions of pigment. Some peculiar rheological properties were, however, also observed: if the pastes, which become warm during dispersion, are measured immediately, they are found to be thixotropic. With increasing dispersion time and decreasing particle size the initially high viscosities decrease.

If the measurements are made some time later dilatancy is initially observed for the same sample, but on prolonged shearing a structure is destroyed and thixotropy is restored. This time dependence, which is opposite to that of rheopexic systems, might therefore be designated "antirheopexic". The flow anomalies become less pronounced with decreasing proportions of pigment in the pastes, the dilatancy decreases, and Newtonian behavior is approached. Similar observations on polymer solutions of various concentrations have been described.

57

Preparation of Aryl Esters

J. Lorenz, Marienberg (Germany)

When triphenyl phosphite is heated with a carboxylic acid at 150–250 °C, an exothermic reaction takes place to the phenyl ester of the carboxylic acid. The phosphite loses two phenyl groups; excess of acid acts as an "inert" solvent. The best yields are obtained when heating is stopped when the reaction begins, or by working in a diluent such as decalin.

Aliphatic and aromatic monocarboxylic acids can he used, with yields of 70–90 %. Oxalic, fumaric, and acetylenedicarboxylic acid decompose; phthalic acid gives mainly the anhydride. Adipic and terephthalic acid give the diphenyl esters in yields of 72 and 40 %, respectively. Salicylic, *p*-chlorobenzoic, nicotinic, and 4-thiapimelic acid can be converted into the phenyl esters in yields of 68, 50, 38, and 65 %, respectively NH_2- or SH-substituted acids can not. Phosphites made from substituted phenols or thiophenols also give the corresponding aryl or thioaryl esters.

The high activation energy and the exothermic nature of the reaction suggest as high-energy intermediates a mixed anhydride $(C_6H_5O)_2P-O-CO-R$ (in the first stage) and $(C_6H_5O)(O)(H)P-O-CO-R$ (in the second stage). The reaction of potassium acetate with triphenyl phosphite gives phenyl acetate, which would not be expected if the reaction proceeded *via* a phosphonium ion $(C_6H_5O)_2(H)P^+$-O-CO-CH_3. In the presence of one mole of pyridine, the reaction of 2 moles of acetic acid with one mole of triphenyl phosphite gives the phenyl ester (68 %) exothermically already at 100 °C. The fact that only two of the phenyl groups are transferred is due to the high acidity of monophenyl phosphite relative to the carboxylic acids.

58

Evolution of Fission Products from Neutron-Irradiated Uranium Dioxide at High Temperatures

F. Lux, D. Graw, and *J. Vogel*, München (Germany)

The investigations, based on *Hahn*'s emanation method, of the behavior of irradiation products of uranium in heterogeneous reactions of neutron-irradiated uranium compounds with gases or liquids containing a complexing agent[1] have been extended to reactions of solid uranium compounds with solids. The formation of uranium carbide from neutron-irradiated uranium dioxide and graphite in a Tammann furnace under argon was studied. The argon was circulated over copper and uranium turnings at 420 °C to remove any traces of oxygen.

With unirradiated UO_2, UC_2 was formed after 5 min at 1750 °C, as shown by X-ray diffraction. Neutron-irradiated UO_2 was at first heated without admixture of graphite to 1300–1900 °C in alumina or graphite crucibles. Fission products were given off already below the temperature for UC_2 formation (1750 °C), depending on the crucible material (cf. Table 1).

Table 1. Fission products given off from irradiated UO_2 (grain size 1 μ) after 4 h.

T [°C]	Crucible material	Fraction of fission product given off [a] Sr	Ba	Te	Mo	Ru	La	Ce	Nd
1460	Graphite	42.5	41.5	93.7	0	0	0	0	0
	Al_2O_3	0	0	100	95.6	88.7	0	0	0
1620	Graphite	98	99	100	0	0	0	0	0
	Al_2O_3	20	28	100	100	97	0	0	0
1880	Graphite [b]	100	100	100	0	0	74	48	37

[a] Zr, Nb, and Np were not observed in any case.
[b] Here the UO_2 reacts completely with the crucible to UC_2.

The emanation of fission products depends chiefly on whether, owing to "microscopic solid-state reactions" of the products of irradiation with other solids such as the crucible, these products can be immediately removed from the surface of the UO_2 grains, since diffusion from within the grains is sufficiently rapid at the high temperatures employed. In a graphite crucible the BaO, for example, present in the UO_2 is reduced to metallic barium which immediately evaporates. BaO-removal in an alumina crucible occurs only at temperatures where the vapor pressure of BaO is sufficiently high. The oxides of *e.g.* Mo and Ru are however more volatile than the metals themselves. Thus the sequences in which the fission products are removed are found to be in the order of the vapor pressures of the elements in graphite crucibles, and of the oxides in alumina crucibles, except for a shift observed with lanthanum. The rate at which the fission products are given off is inversely proportional to the grain size.

[1] *F. Lux* and *F. Ammentorp-Schmidt*, Radiochim. Acta *4*, 112 (1965); *F. Lux* and *F. Ammentorp-Schmidt*, Angew. Chem. *77*, 732 (1965); Angew. Chem. internat. Edit. *4*, 707 (1965).

59

Preparation and Properties of Diprimary Alkylenediphosphines

L. Maier, Zürich (Switzerland)

Diprimary alkylenediphosphines *(1)* can be easily prepared by reduction of alkylenediphosphonates with $LiAlH_4$.

$$(RO)_2OP(CH_2)_xPO(OR)_2 \rightarrow H_2P(CH_2)_xPH_2$$
(1), x = 1–4

Previous reports[1] that *(1)*, x = 1 and 2, are unstable above −78 °C are incorrect. The infrared spectra of alkylenediphosphines show a P−H absorption band at 2270–2290 cm^{-1}; the ^{31}P-NMR spectrum has a triplet of intensity ratio 1:2:1 which is shifted with increasing x to higher fields; *e.g.* x = 1: +121.8 ppm, x = 2: +130.8 ppm, x = 3: +138.6 ppm. The ^1H-NMR spectrum confirms the structure *(1)* of the alkylenediphosphines.

With strong acids the alkylenediphosphines give phosphonium salts, *e.g. (2)*:

$$H_2P(CH_2)_3PH_2 + H_3PO_4 \rightarrow [H_2P(CH_2)_3PH_3]^+H_2PO_4^- \quad (2)$$

In the presence of free-radical initiators they add onto olefins, forming ditertiary alkylenediphosphines, which can be oxidized with H_2O_2 to the dioxides *(3)* and characterized as such.

$$H_2P(CH_2)_xPH_2 + 4\ CH_2{=}CHR \rightarrow (RCH_2CH_2)_2P(CH_2)xP(CH_2CH_2R)$$
$$\downarrow H_2O_2/\text{Acetone}$$
$$(RCH_2CH_2)_2(O)P(CH_2)_xP(O)(CH_2CH_2R)_2 \quad (3)$$

(3a), x = 3, R = n-C_6H_{13}, m. p. 145–150 °C

(3b), x = 4, R = n-$C_{10}H_{21}$, m.p. 91–91.8 °C

With *N*-hydroxymethyldialkylamines, prepared from formaldehyde and secondary amines, the diprimary alkylenediphosphines *(1)* give alkylenebis(dialkylaminomethylphosphines) *(4)* in excellent yields.

$$H_2P(CH_2)_xPH_2 + 4\ R_2NCH_2OH \rightarrow (R_2NCH_2)_2P(CH_2)_xP(CH_2NR_2)_2$$
$$(4),\ x = 1\text{–}4,\ R = C_2H_5$$

The ^1H-NMR spectrum of alkylenebis(diethylaminomethylphosphines) *(4)* contain three complex bands, quantitative analysis of which proves the structure of the products.

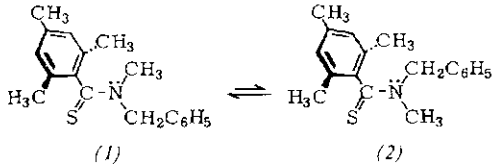
[1] *A. J. Leffler* and *E. G. Teach*, 133rd ACS Meeting, San Francisco, April 1958. Abstracts of Papers, p. 29 N.

60

Separation of Rotational Isomers of Amides, Thioamides, and Nitrosamines

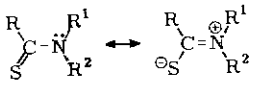
A. Mannschreck, Heidelberg (Germany)

The thioamides, *e.g. (1)* and *(2)*, of mesitylenecarboxylic acid can be separated chromatographically and identified by their NMR spectra; *(1)*: m.p. 58.5–60 °C, *(2)*: m.p. 98–99 °C. The crystalline substances are stable, but in solution an equilibrium mixture containing 68 % of *(1)* at 50 °C is formed. The equilibration is a first order process with a half-life of



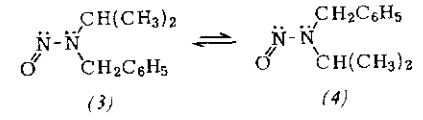
(1) *(2)*

24.7 ± 2.8 h in $CDCl_3$ at 50 °C. The free energies of activation of the isomers were found to be $\Delta G^{\ddagger}_{(1)} = 27.3$ and $\Delta G^{\ddagger}_{(2)} = 26.8$ kcal/mole. For the corresponding oxygen compounds the values are 22.9 and 22.3, respectively[1], *i.e.* they isomerize faster. In the corresponding thioformamides the equilibrium is also established faster than in *(1)* and *(2)*, so that they could not be completely separated[2]. Thus, apart from the thioamide resonance,



the mesityl group contributes to the hindrance of rotation around the C–N bond in *(1)* and *(2)*. This is one of the reasons that isomers of non-sulfur containing formamides, acetamides, and benzamide have so far not been enriched.

For nitrosamines[3], considerable enrichment of isomers was achieved, *e.g.* of *(3)* and *(4)*. The crystals, m.p. 20–22 °C, obtained directly from the synthesis of the compound consist of about 94 % of *(3)*.



(3) *(4)*

The equilibrium [81 % of *(3)*] is attained with a half-life of 8.2 ± 2.0 min in CCl_4 at 36 °C. From an equilibrium mixture of the isomers in CS_2, mainly *(3)* crystallizes out at −60 °C. In the filtrate *(4)* is enriched to 75 % since at this temperature it is converted only slowly into *(3)*.

[2] *W. Walter* and *G. Maerten*, Liebigs Ann. Chem. *669*, 66 (1963); *W. Walter*, *G. Maerten*, and *H. Rose*, Liebigs Ann.Chem., in press.

[3] In collaboration with *G. Albert*.

61

Addition Reactions of Cyanic Esters

D. Martin, Berlin-Adlershof (Germany)

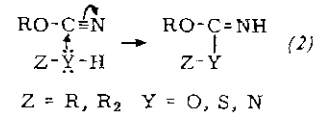
Sterically unhindered esters of cyanic acid give the following reactions:

1. *Isomerization*: On being heated, or on treatment with Lewis acids or H-acidic compounds, alkyl cyanates isomerize to isocyanates, which react further to esters of isocyanuric acid.

2. *Trimerization*: On being heated with acids or tertiary amines, aryl cyanates isomerize to aryl cyanurates.

3. *Nucleophilic Additions*:

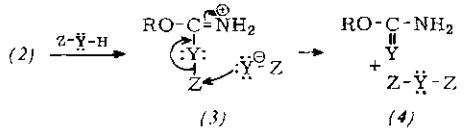
a) At the C-atom: They proceed particularly easily because of the neighboring electron-attracting O and N atoms. The compounds *(2)* obtained by the addition of the nucleophile Z–Y–H *(1)* are stable when the bonding pair of electrons between Z and Y is not available for a secondary reaction.



(1) *(2)*

Z = R, R_2 Y = O, S, N

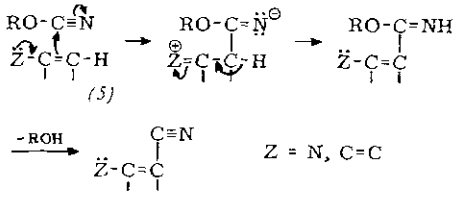
If Z is an acyl group, the primary adduct *(2)* is immediately protonated to *(3)* by another molecule of *(1)*. The bonding electron pair from Z is now available for charge equalization, and *(3)* reacts with $Z{-}Y^{\ominus}$ to *(4)*.



(3) *(4)*

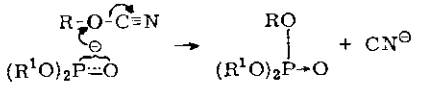
Z = H, Acyl, Sulfonyl, Phosphoryl, Y = O, S

In reactions with compounds *(5)* containing electron-rich double bonds, *i.e.* enamines, pyrroles, aromatic hydrocarbons, carbanions, cyanide ions, CH-acidic compounds, or Grignard reagents, cyanic esters act as nitrile group donors.



(5)

b) At the O-atom: Phosphoric di- and triesters attack cyanates at the O-atom with elimination of cyanide:



4. *Cycloadditions*: In contrast to nitriles, cyanates react smoothly with 1,3-dipoles under cycloaddition. Tetrazoles are formed with azides, 1,2,3-triazoles with diazo compounds, 1,2,4-triazoles with nitrilimines, and 1,2,4-oxadiazoles with nitrile oxides.

5. *Electrophilic Additions*: In the cases studied so far, these are more difficult than with nitriles. *N*-Phenylnitrilium cations add onto aryl cyanates yielding quinazolines. Triethyloxonium tetrafluoroborate yields small amounts of phenetole with phenyl cyanate.

62

Injection and Extraction Processes at Semiconductor Electrodes

R. Memming and *G. Schwandt*, Hamburg (Germany)

Electrons and positive holes participate in reactions at semiconductor electrode surfaces, *i.e.* such reactions can occur *via* various energy bands of the semiconductor (conduction or valence band). Quantitative information on this participation is obtained by the "thin slice method" described below.

On the side opposite the semiconductor surface to be studied there is a pn-junction. When minority carriers are injected into the semiconductor at the phase boundary (*e.g.* electrons in the case of p-germanium), they diffuse into the crystal and thence to the pn-junction. The injected charge carriers are accelerated in the internal electric field of the pn-junction. If the junction is short-circuited, this gives rise to a current. This method has been frequently used to detect qualitatively the injection of charge carriers. It is suitable for quantitative determination of the injection current if the mean free path of the minority carriers in the semiocnductor is known.

The "thin slice" method has been applied to germanium and silicon in various electrolytes. Thus in solutions in methanol (in contrast to aqueous solutions) it can be shown that the reactions occurring at anodically polarized germanium electrodes depend on the nature of the halide ions present.

The method is suited not only to the study of injection and extraction processes during an electrochemical reaction, but also to the observation of the recombination of electrons and holes at the surface. Electron-hole pairs are generated at the surface by illumination and detected by the pn-junction. The short-circuit current is a measure of the rate of recombination *via* surface states. The position of such centers within the forbidden zone can thus be determined.

63

Mechanism of the Electrolytic Reduction of Hydrogen Peroxide on Germanium

W. Mindt and H. Gerischer, München (Germany)

From an analysis of the current-potential curve of the electrolytic reduction of H_2O_2 on germanium it was deduced that the transfer of electrons depends on a free-radical surface state of the germanium. This radical state originates in a transition region between a hydroxide-like and a hydride-like surface structure as a consequence of the surface reaction:

$$\text{GeOH} + 2H^+ + e^- \rightleftharpoons \text{Ge-H} + H_2O + p^+$$

This reaction proceeds *via* the radical form Ge·, which effects the reduction of H_2O_2 according to the reaction:

$$\text{Ge}\cdot + H_2O_2 + e^- \rightleftharpoons \text{Ge-OH} + OH^-$$

It was further shown that only the electrons of the conduction band take part in this reduction.

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The Determination of Potassium and Argon in Iron Meteorites by Neutron Activation Analysis

O. Müller and *J. Zähringer*, Heidelberg (Germany)

Several iron meteorites were dated using the potassium-argon method. Because of the very low potassium content of these meteorites, potassium and argon were determined by neutron activation analysis:

$$K^{41}(n,\gamma)\ K^{42} \xrightarrow[12.4\ h]{\beta^-,\gamma} Ca^{42} \qquad Ar^{40}(n,\gamma)\ Ar^{41} \xrightarrow[1.8\ h]{\beta^-,\gamma} K^{41}$$

The concentrations found were: argon 10^{-8}–10^{-7} ml/g; potassium 10^{-8}–10^{-7} g/g meteorite.

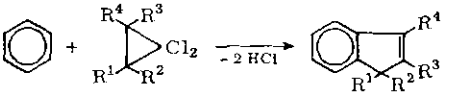
The ages of iron meteorites determined by the potassium-argon method are about 6×10^9–7×10^9 years, *i.e.* they are considerably older than stone meteorites (maximum age 5×10^9 years). This points to a different history of formation of the two types of meteorites.

65

A Simple Indene Synthesis involving Dihalocyclopropanes

F. Nerdel and *J. Buddrus*, Berlin (Germany)

Dihalocyclopropanes *(1)* that carry alkyl or aryl groups condense with aromatic compounds in the presence of strong Lewis acids, affording indenes *(2)*, with concurrent 1,2-migration of an alkyl or aryl group. Ring closure requires a



(1) *(2)*

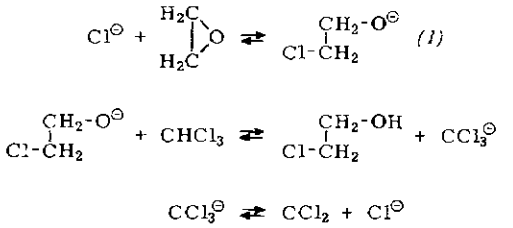
strong Lewis acid ($AlCl_3$ is better than $FeCl_3$), to loosen the halogen (Cl, F) that is fairly firmly retained on the cyclopropane ring. In this way, 1,1-dichloro-2,2-dimethylcyclopropane gives 2,3-dimethylindene. The reactions occur at room temperature. At least 1.1 moles of $AlCl_3$ are used per mole of cyclopropane. Two layers are formed during the reaction: the lower is a complex of indene, $AlCl_3$, HCl (HF), and the aromatic starting compound; the upper contains only the aromatic starting compound. Yields range from 45 to 67 %; they are highest when the aromatic compound and dihalopropane carry several alkyl groups.

66

A New Method of Generating Carbenes

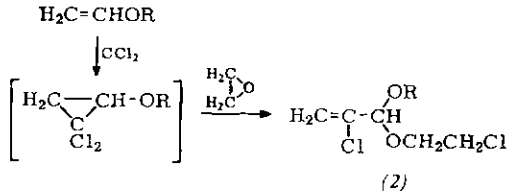
F. Nerdel and *J. Buddrus*, Berlin (Germany)

Epoxide rings can be opened with anions to form "bases"[1]. We found that the pseudobase *(1)* can eliminate hydrogen halide from haloforms, liberating carbenes which can be captured with alkenes.



(1)

Equimolar amounts of ethylene oxide, chloroform, and alkene are heated at 150 °C in an autoclave, and the product is isolated by distillation. No reaction is observed in the absence of alkene. Evidently the formation of carbenes is reversible. With vinyl ethers, α-haloacrolein acetals *(2)* are obtained *via* a cyclopropane, which is unstable at high temperatures.



(2)

[1] *J. N. Brönsted, Mary Kilpatrick,* and *M. Kilpatrick*, J. Amer. chem. Soc. *51*, 439 (1929).

67

The Reaction of Iron(III) Chloride with $LiAlH_4$

H. Neumaier, München (Germany)

Iron(III) chloride reacts quantitatively with $LiAlH_4$ in ether solution at −116 °C according to

$$FeCl_3 + 3\ LiAlH_4 \rightarrow Fe(AlH_4)_2 + AlH_3 + 3\ LiCl + 0.5\ H_2$$

Iron(II) aluminum hydride is reasonably stable at room temperature. At higher temperatures it decomposes to the elements, with a significant increase in the rate of hydrogen evolution at 90–100 °C. The P–T diagram of the thermolysis shows no break or region of constant pressure, which makes the existence of the intermediate $FeAl_2H_6$ postulated by *Schaeffer*[1] appear improbable.

[1] *G. W. Schaeffer, J. S. Roscoe,* and *A. C. Stewart*, J. Amer. chem. Soc. *78*, 729 (1965).

68

The Stability of Boron Azides

P. I. Paetzold, München (Germany)

The thermal stability of boron azides L_2BN_3 decreases in the sequence L = NR_2 > OR > R > Cl > Ar. The extent of the rearrangement

$$L_2BN_3 \rightarrow N_2 + {}^1/_n\ (LB{-}NL)_n$$

on thermal decomposition follows the opposite sequence. The rate constants k_1 of the first-order decomposition of the azides Ar_2BN_3 depend on steric and electronic parameters of the aromatic substituents. The yields of rearrangement product, the values of k_1, the derived activation parameters, the migration tendency of the ligands on boron in mixed azides L_2BN_3[1], and the stabilizing influence of Lewis bases allow the following conclusions to be drawn: Boron azides are the more unstable the more electrons are withdrawn from the azide group and the stronger the anchimeric assistance by the migrating ligands during the elimination of nitrogen; the neighboring-group effect becomes weaker with increasing strength of the boron-ligand bond.

[1] *P. I. Paetzold*, Angew. Chem. *7b*, 598 (1964).

69

Carbonato Compounds of Praseodymium(IV) and Terbium(IV)

Sw. Pajakoff, Wien (Austria)

In the thermal decomposition of praseodymium(III) and terbium(III) carbonates in an oxygen atmosphere at 250 to 350 °C, carbonates and oxide carbonates of the quadrivalent metals are formed, which decompose further at higher temperatures:

$$Pr_2(CO_3)_3{\cdot}2\ H_2O \xrightarrow{250-275\,^\circ C} \underset{\text{light green}}{Pr_2(CO_3)_3} \xrightarrow{280-300\,^\circ C} \underset{\text{yellow}}{Pr_2(CO_3)_4}$$

$$\xrightarrow{300-320\,^\circ C} \underset{\text{yellow-brown}}{Pr_2O_4{\cdot}CO_2} \xrightarrow{320-350\,^\circ C} \underset{\text{yellow-brown}}{Pr_2O_4{\cdot}0.5\ CO_2} \xrightarrow{350-380\,^\circ C}$$

$$\underset{\text{brown-yellow}}{Pr_2O_4{\cdot}0{,}5\ CO_2Pr_2O_4} \xrightarrow{380-400\,^\circ C} \underset{\text{light brown}}{Pr_2O_4} \xrightarrow{420-450\,^\circ C} \underset{\text{dark brown}}{Pr_6O_{11}}$$

$$Tb_2(CO_3)_3{\cdot}2\ H_2O\ 250\,^\circ C \xrightarrow{250\,^\circ C} \underset{\text{white}}{Tb_2(CO_3)_3} \xrightarrow{280-300\,^\circ C}$$

$$\underset{\text{yellowish white}}{Tb_2(CO_3)_4} \xrightarrow{300-350\,^\circ C} Tb_2O_4{\cdot}0.5\ CO_2 \xrightarrow{350-400\,^\circ C} \underset{\text{light brown}}{Tb_2O_4}$$

$$\xrightarrow{400-450\,^\circ C} \underset{\text{brown}}{Tb_6O_{11}} \xrightarrow{450-600\,^\circ C} \underset{\text{dark brown}}{Tb_4O_7}$$

In the oxidation of the oxides and hydroxides of praseodymium and terbium in alkali carbonate solutions (>2.5 M K_2CO_3) with ozonized oxygen, hydrogen peroxide, or alkali peroxymonosulfate, yellow, water-soluble carbonato complexes of the quadrivalent metals are formed. From these complexes the following compounds were synthesized:

$K_4[Pr(CO_3)_4]{\cdot}4H_2O$	yellowish-white
$K_6[Pr(CO_3)_5]{\cdot}2H_2O$	light yellow
$K_6[Tb(CO_3)_5]{\cdot}4H_2O$	yellowish-white
$Ba_3[Pr(CO_3)_5]{\cdot}3H_2O$	light yellow
$Ba_3[Tb(CO_3)_5]{\cdot}2H_2O$	yellowish-white

From these compounds new complexes with mixed ligands were prepared:

[Pr-carbonato-oxalato]
[Pr-carbonato-fluoro]
[Pr-carbonato-hydroxo]
[Tb-carbonato-fluoro]
[Tb-carbonato-hydroxo]

The carbonates and oxide carbonates of praseodymium(IV) and terbium(IV) behave differently towards complex-forming aminopolycarboxylic acids and hydroxycarboxylic acids than do carbonates of the tervalent rare earths. This effect can be used to separate praseodymium and terbium from the neighboring rare earths.

70

Action of Hexamethylenetetramine on the Catheptic Endo- and Exopeptidases of Fish Tissues

A. Purr, München (Germany)

Hexamethylenetetramine inhibits the plant endopeptidase papain. Optimum inhibition occurs between pH 4.5 and 5.5. The inhibition is probably due to a reaction of the SH groups of the enzyme with formaldehyde, formed from hexamethylenetetramine in weakly acidic media.

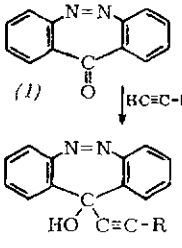
The pH optimum for the inhibition of the catheptic endo- and exopeptidases of fish tissues (*e.g.* carp liver) by hexamethylenetetramine is 4.0, but inhibition is still strong at pH 5.5. Experiments with physiologically harmless substitutes for hexamethylenetetramine show that the peptidases are inhibited particularly by glyoxylic acid, methyl glyoxal, and sorbic acid. The activity of the substances decreases in the sequence glyoxylic acid > methyl glyoxal > formaldehyde > hexamethylenetetramine > sorbic acid.

71

Reactions of Dibenzo[c,f]-1,2-diazepin-11-one

W. Ried and *St. Piesch*, Frankfurt/Main (Germany)

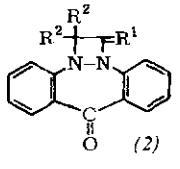
The compound *(1)* [1] undergoes none of the usual carbonyl reactions and does not react with Grignard reagents. It reacts with acetylene in liquid ammonia and with monosubstituted alkynes in dioxanes at 80 °C to give the corresponding ethynols in good yields. Alkynols do not react with *(1)*.



(1)

R = H, $-CH_2N(CH_3)_2$, C_6H_5

The azo chromophore fixed in the *cis*-position in *(1)* reacts with ketenes to *(2)*.

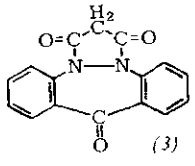


(2)

R^1 = O, N-$C_6H_4CH_3$
R^2 = H, CH_3, C_6H_5

The reaction goes best with diphenylketene, less well with dimethylketene, and in poor yields with unsubstituted ketene. A smooth reaction is also obtained with *p*-tolyldiphenylketenimine.

The azo group in *(1)* can be hydrogenated to the hydrazo group with weakly active Raney nickel. The product reacts with malonoyl chloride to *(3)*, a deep violet substance which gives purple solutions in chloroform and methylene dichloride and blue solutions in acetone and methanol. Addition of ammonia to solutions in acetone or methanol changes the color to orange.



(3)

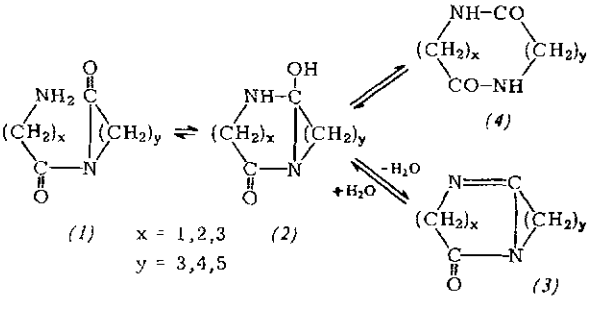
[1] *R. B. Johns* and *K. R. Markham*, J. chem. Soc. (London) *1962*, 3712.

72

Syntheses of Cycloamides and Cyclopeptides with Medium-Sized Rings

M. Rothe, *K.-D. Steffen*, and *J. Rothe*, Mainz (Germany)

N-(Aminoacyl)lactams *(1)* and *N*-(aminoacyl)cyclopeptides cyclize to various products, depending on the length of their side group and the ring size. If a 5-, 6-, or 7-membered ring can be formed, cyclols *(2)* occur as intermediates. α-Aminoacyl-*(1)*, x = 1, and *o*-aminoaroyl-lactams give bicyclic amidines *(3)*; glycyl- and anthranoylcaprolactam give *e.g.* 5-oxopentamethylenimidazoline *(3)*, x = 1, y = 5, and 6-oxopentamethylenedihydroquinazoline, respectively. β-Aminoacyl-lactams *(1)*, x = 2[1] and -cyclopeptides are converted by aminoacyl insertion into macrocyclic peptides *(4)*; after introduction of two β-alanyl groups into the cyclodipeptide of β-alanine and rearrangement, the cyclotetrapeptide is formed. γ-Aminoacyl-lactams *(1)*, x = 3, cyclize by reaction of the free amino group with the carbonyl group in the ring or in the side chain. Medium-sized rings are thus accessible without recourse to the dilution principle, *e.g.* the ten-membered cyclodi-γ-aminobutyryl *(4)*, x = y = 3. δ- and ε-aminoacyl-lactams *(1)*, x = 4 or 5, eliminate the side chain; in compounds with longer aminoacyl groups, polycondensation or, in dilute solution, ring closure occurs.



(1) x = 1,2,3 y = 3,4,5 *(2)* *(4)* *(3)*

The aminoacyl group can be introduced by acylation of free or trimethylsilylated lactams and cyclopeptides with *N*-protected amino-acid chlorides or by lactam formation from activated *N*-protected dipeptides with C-terminal γ- or δ-amino acids.

Diglycylsarcosine dimerizes to cyclo(diglycylsarcosyldiglycylsarcosyl) (decomp. > 350 °C).

[1] Cf. also *V. K. Antonov*, *Ts. E. Agadzhanyan*, *T. R. Telesnina*, *M. M. Shemyakin*, *G. G. Dvoryantsnva*, and *Yu. N. Sheinker* Tetrahedron Letters *1964*, 727.

73

New Enzymatic Baking Agents

A. Rotsch, Detmold (Germany)

Malt baking agents increase the sugar content of the dough by degradation of the starch, accelerate fermentation, increase the volume of the baked product, and improve color, crust, storage properties, and taste of the products. Fungus amylases have also been used as baking agents. They improve mainly the crumb consistency and usually increase the volume. Doughs treated with these do not tend to relax or to become sticky, and can be readily handled by machines.

Proteolytic enzyme preparations degrade the gluten of excessively strong, gluten-rich flour and can be used particu-

larly in the production of baker's ware for diabetics and sometimes of hard biscuits and crackers. They sometimes have adverse effects, however, when accompanying some malt baking agents in the processing of weak German wheat flour.

After the importance of the cereal gums (water-soluble pentosans) consisting mainly of arabinose and xylose to the rheological behavior of doughs and for the adjustment of the water content in dough and bread had been recognised, pentosanase-containing preparations were developed, which allow the controlled degradation of the gums during fermentation and in the first stage of baking, and effect improved loosening, better crumb consistency, and volume increase. The results obtained with such a pentosanase from *Aspergillus oryzae* in wheat bread and other baked goods show it to be valuable particularly in the processing of rye doughs. The preparation was free from protein- or starch-degrading enzymes.

74

Electrochemical and Direct Fluorination of Substituted Hydrocarbons

P. Sartori, K. P. Ehlers, and *G. Steiner*, Aachen (Germany)

Hydrocarbons can be perfluorinated by the action of elementary fluorine directly or *via* fluorides of metals in high oxidation states, or by electrolysis in anhydrous hydrogen fluoride.

In carboxylic acids and carbonyl fluorides, the carbonyl group impedes substitution of neighboring H atoms to such an extent that the action of fluorine causes almost quantitative chain cleavage to COF_2 and partly and fully fluorinated alkanes, formed by radical recombination.

Chloroalkanes, particularly 1,2-dichloropropane, can be converted into chloroperfluoroalkanes by fluorine in the gas phase. The occurrence of more highly chlorinated products indicates intermediate elimination and readdition of chlorine.

The success of electrochemical fluorination depends decisively on the solubility or the fineness of the dispersion of the starting material in hydrogen fluoride. Thus gaseous alkanes can be perfluorinated by bubbling them through the electrolyte. The carbonyl group in acid fluorides imparts sufficient solubility in HF for a perfluorination with good yield.

Chloroalkanes are poorly soluble in hydrogen fluoride. Electrochemical fluorination in suspension leads to a number of only partially fluorinated compounds, since these are carried out of the mixture by the electrolysis gases before fluorination is complete. The chloro-substituent is retained.

75

Optical Induction in Six-Membered Cycloadditions

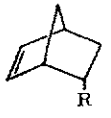
J. Sauer and *J. Kredel*, München (Germany)

The optical induction occuring in six-membered cycloadditions was studied using cyclopentadiene *(1)*, (−)-menthyl acrylate *(2)*, and (−)-menthyl fumarate *(3)*. In various solvents (triethylamine, dioxane, 1,2-dimethoxyethane, acetone, methylene chloride, methanol) *(1)* and *(2)* react to give mixtures of the isomeric Diels-Alder adducts *(4a)* and *(5a)*, which are reduced by $LiAlH_4$ to *(4b)* and *(5b)*, respectively. The ratio *(4a)*:*(5a)* depends on the solvent (Berson scale). Decreasing temperature and increasing polarity of the solvent favor the formation of *(4a)*. At −70 °C, in the presence of catalytic amounts of $AlCl_3{\cdot}O(C_2H_5)_2$ in methylene chloride, practically pure *(4a)* or *(4c)*, respectively, are formed in high yields from *(1)* and *(2)* or from *(1)* and methyl acrylate together with 1 % of the exo-isomers *(5a)* or *(5c)*[1].

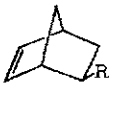
[1] Other Lewis acids, *e.g.* $BF_3{\cdot}O(C_2H_5)_2$, $SnCl_4$, and $TiCl_4$, behave similarly.

Compounds *(4b)* and *(5b)* are obtained in about 8 % and 3–7 % optical purity, respectively, the latter yield depending on the solvent. With decreasing temperature and in the presence of $AlCl_3{\cdot}O(C_2H_5)_2$ the optical yield of *(4b)* increases to about 70 %; the amount of the catalyst has no influence on the degree of optical induction. On reduction, (+)-*(4b)* and (+)-*(5b)* were always obtained; assignments of absolute configurations could be made.

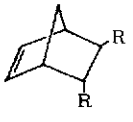
In the system *(1)* + *(3)* the sign of the rotation of the diol *(6b)* obtained by reduction of *(6a)* depends on the solvent in which the diene addition is carried out. In methylene chloride the laevorotatory form of *(6b)* is obtained; in acetone, dioxane, and in methylene chloride in the presence of $AlCl_3{\cdot}O(C_2H_5)_2$ the dextrorotatory enantiomer is obtained. The induction is less marked than for the reaction of *(1)* with *(2)*; it reaches a value of 45 % at −70 °C in methylene chloride [1 equiv. of catalyst]. Chemical determination of the absolute configurations of the pure enantiomers of *(6c)*, obtained by resolution of the racemate, and of the derived pure optically active compounds *(6b)*, *(6d)*, *(7a)*, and *(7c)* was not possible[2].



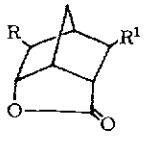
(4a): R = CO_2-Menthyl
(b): R = CH_2OH
(c): R = CO_2CH_3
(d): R = CO_2H



(5a): R = CO_2-Menthyl
(b): R = CH_2OH
(c): R = CO_2CH_3



(6a): R = CO_2-Menthyl
(b): R = CH_2OH
(c): R = CO_2H
(d): R = CO_2CH_3



(7a): R = I; R^1 = CO_2H
(b): R = I; R^1 = CO_3-t-C_4H_9
(c): R = H; R^1 = CO_2H

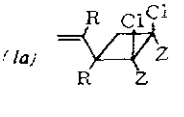
[2] *Note added in proof;* The laevorotatory forms of *(6c)* and *(4d)* have the same configuration.

76

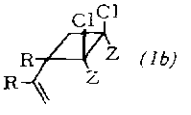
Chemistry and Stereochemistry of the Photocycloadducts of Dichloromaleic Imide and Anhydride with Acyclic 1,3-Dienes

H.-D. Scharf and *F. Korte*, Birlinghoven (Germany)

Dichloromaleimide and dichloromaleic anhydride undergo a Diels-Alder reaction when heated with 1,3-dienes to give derivatives of 1,2-dichloro-1,2,3,6-tetrahydrophthalic acid. Under UV-illumination the same reagents undergo exclusively 1,2-cycloaddition to derivatives of 3-alkenyl-1,2-dichlorocyclobutane-1,2-dicarboxylic acid, *(1a)* and *(1b)*.



(1a)



(1b)

R = H, CH_3 Z = CO_2R

Z-Z = CO-O-CO, CO-NH-CO

In the dehalogenation or *(1a)* or *(1b)*, Z = CO_2CH_3, with Ni $(CO)_4$ in C_6H_6/DMF at 80 °C, the corresponding dimethyl 3-alkenylcyclobutene-1,2-dicarboxylates or (by thermolysis)

the dimethyl 1,3,5-hexatriene-2,3-dicarboxylates would be expected to be formed. Instead, a rearrangement to 4,5-disubstituted 1,4-cyclohexadiene-1,2-dicarboxylates is observed.

This novel formation of Diels-Alder products by rearrangement can also be extented to the photocycloadducts of cyclic 1,3-dienes.

77

Mechanism of C-Nitrosation of Phenol in Various Solvents

Hermann Schmid, *G. Muhr*, and *P. Riedl*, Vienna (Austria)

The initial rate of *C*-nitrosation of phenol by nitrous acid in aqueous solution to *p*-nitrosophenol was determined by stopping the reaction with sodium hydroxide and photometric determination of *p*-nitrosophenol in the resulting solution. The rate equation (at constant ionic strength) is

$$\text{rate} = k[C_6H_5OH][HNO_2]$$

At constant ionic strength the rate is independent of hydrogen-ion concentration in the range 10^{-5}–0.5 mole/l; log k is proportional to the ionic strength.

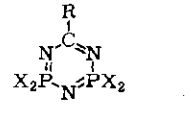
Addition of methanol decreases the rate owing to removal of nitrous acid by the formation of methyl nitrite. This effect was used to determine the position of the methyl nitrite equilibrium. The free energy, entropy, and enthalpy of the *C*-nitrosation in aqueous solution were determined and suggest the following activation process: Phenol, which in the ground state already has a high electron density at the *o*- and *p*-positions, polarizes the nitrous acid, whereby the positive nitrosyl ion adds to the negative carbon atom of the benzene ring. The rearrangement of the activated complex to nitrosophenol takes place by proton shift from the C-atom with the nitroso group to the hydroxide ion.

The nitrosation of phenol by nitrous acid in 70 % sulfuric acid, in which phenol is not oxidized or sulfonated, was followed directly by photometry. Here the nitrite acidium ion acts as the nitrosating agent.

78

Cyclophosphazenes Containing Carbon: Derivatives of a New Heterocyclic System

A. Schmidpeter and *R. Böhm*, München (Germany)



(1a), R = $(CH_3)_2N$, X = C_6H_5

(1b), R = C_6H_5, X = Cl

2,2,4,4-Tetraphenyl-6-dimethylamino-2,4-diphospha-1,3,5-triazine *(1a)* is formed in good yield by cyclocondensation of *N,N*-dimethylguanidine with tetraphenylimidodiphosphinyl trichloride:

$$4\ (CH_3)_2NC(NH)NH_2 + \{N[C_6H_5)_2PCl]_2\}Cl \rightarrow 3[(CH_3)_2NC(NH_2)_2]Cl + \textit{(1a)}$$

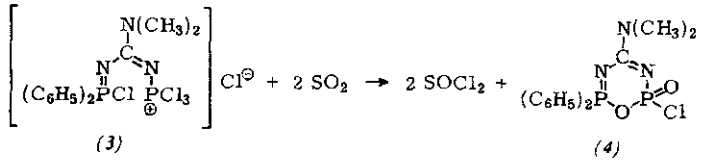
P-chlorinated derivatives *(1b)* are accessible *via* condensation products *(2)* of an amidinium hexachloroantimonate and PCl_5[1].

$$[C_6H_5C(NPCl_3)_2]SbCl_6 + 2\ NH_4Cl \rightarrow 4\ HCl + NH_4SbCl_6 + \textit{(1b)}$$
(2)

[1] *A. Schmidpeter*, *K. Düll*, and *R. Böhm*, Angew. Chem. *76*, 605 (1964).

Compound *(1b)* resembles $(NPCl_2)_3$ in its properties; at 255 °C it polymerizes with elimination of benzonitrile.

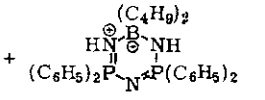
The unexpected reaction of *(3)* with *two* moles of SO_2 can be explained by the formation of the oxygen-containing heterocycle *(4)*.



(3) *(4)*

The transamination of dibutylboramide with tetraphenylimidodiphosphinyl diimide is an example for a ring closure which leads to a "hetero"-cyclophosphazene and which does

$$(C_4H_9)_2BNH_2 + H_2N\text{-}(C_6H_5)_2P{=}N\text{-}(C_6H_5)_2P{=}NH \rightarrow NH_3 +$$



(5)

not occur directly at a phosphorus atom. It yields the borophosphazadiene *(5)*, the ring structure of which is shown by its ^{31}P-NMR spectrum.

79

Exchange Reactions in Solid Co, Rh, and Ir Complexes Initiated Thermally and by the ^{80m}Br Nuclear Transition

G. B. Schmidt, *W. Herr*, and *K. Rössler*, Köln (Germany)

Whereas "activated" exchange reactions occur in crystalline rhodium and iridium pentamminebromo halides as a consequence of the ^{80m}Br nuclear-isomeric transition[1], the thermal exchange of Br atoms in these complex salts is very slow even at 210 °C (about 8 % exchange in 24 hours in $[Rh(NH_3)_5Br]Br_2$). By contrast, there is a rapid exchange of covalent for ionic halogen in solid *cis*- and *trans* $[Co(en)_2Cl_2]Cl$ and *trans*-$[Co(en)_2Br_2]Br$ labelled with ^{36}Cl and ^{82}Br, respectively, between 100 and 170 °C, as well as in solid *trans*-$[Rh(en)_2Cl_2]Cl$ between 170 and 300 °C. The exchange rates in the three cohalt complexes studied were almost the same, *e.g.* $t_{1/2} \approx 4$ h at 150 °C. For *trans*-$[Rh(en)_2Cl_2]Cl$, $t_{1/2} = 13$ h at 250 °C. The activation energies for these exchange reactions were found to be 30 to 34 kcal/mole.

Previous irradiation with ^{60}Co γ-rays or with X-rays does not noticeably affect the exchange rate in *trans*-$[Rh(en)_2Cl_2]Cl$, whereas the rate of exchange of the corresponding cobalt complex increases markedly with the radiation dose: thus $t_{1/2}$ at 150 °C decreases after irradiation with 150 kV X-rays (2×10^4 to 1×10^6 R) to 60 and 6 min, respectively, from 220 min for the unirradiated compound. X-rays are about ten times more effective than γ-rays. The exchange presumably occurs according to a jump mechanism involving lattice defects.

[1] *G. B. Schmidt* and *W. Herr*, Z. Naturforsch. *18a*, 505 (1963).

80

Basic Salts of Bivalent Tin

H. G. Schnering and *H. Pelshenke*, Münster (Germany)

Precipitations from heterogeneous and from homogeneous solution, determinations of halogen[1] and tin, and chemical and X-ray characterization show that the following compounds exist:

$Sn_9Cl_4O_7 = 2SnCl_2 \cdot 7SnO$ *(1)*: pale yellow microcrystalline; isotypic with *(3)*; the compound is the primary hydrolysis product from $SnCl_2$ solutions; when kept in solution it changes completely into compound *(2)*, which regenerates *(1)* when heated at 230 °C (in vacuum); at 525 °C compound *(1)* decomposes endothermally into SnO and $SnCl_2$.

$Sn_4Cl_3(OH)_3O = 3Sn(OH)Cl \cdot SnO$ *(2)*: colorless hexagonal plates; sensitive to light when moist; this is probably the only basic chloro-compound of bivalent tin that is stable in acidic solution; at 230 °C it decomposes endothermally into $SnCl_2$ and *(1)*. Crystals of $Sn_4Cl_3(OH)_3O$ are hexagonal-rhombohedral with a = 10·032 Å and c = 44·092 Å, belonging to space group D_{3d}^5; determination of the complicated structure is not yet complete.

$Sn_9Br_4O_7$ *(3)*: yellow, mostly microcrystalline but also forms six-sided platelets; compounds *(3)* and *(1)* are isotypic and are strongly disordered in some directions; according to a single-crystal photograph, compound *(3)* may be hexagonal, with a = 9·2$_3$ and c = n × 9·55 Å, where the value of n is uncertain.

Attempts to prepare a bromo-compound analogous to *(2)* failed.

[1] Cf. *H. Schäfer* and *K. D. Dohmann*, Z. anorg. allg. Chem. *300*, 1 (1959).

81

Synthesis and Properties of some New Phenyltinarsines, Stibines, and Bismuthines

Herbert Schumann and *Max Schmidt*, Marburg (Germany)

Organotin chlorides or $SnCl_4$ react with sodium diphenylarsine, -stibine, or -bismuthine in liquid ammonia to phenyltinarsines, -stibines, and -bismuthines, which can be crystallized from benzene after removal of the ammonia:

$$(C_6H_5)_nSnCl_{4-n} + 4\text{-}n\ NaX(C_6H_5)_2 \rightarrow (C_6H_5)_nSn[X(C_6H_5)_2]_{4-n} + 4-n\ NaCl$$

X = As, Sb, Bi
n = 0–4

From triphenylstannyl-lithium and phenylchloroarsines, -stibines, and -bismuthines, or with $AsCl_3$, $SbCl_3$, and $BiCl_3$ in tetrahydrofuran, the compounds

$[(C_6H_5)_3Sn]_3X$, $[(C_6H_5)_3Sn]_2XC_6H_5$, and $(C_6H_5)_3SnX(C_6H_5)_2$, X = As, Sb, Bi,

are obtained in pure form after separation from precipitated lithium chloride.

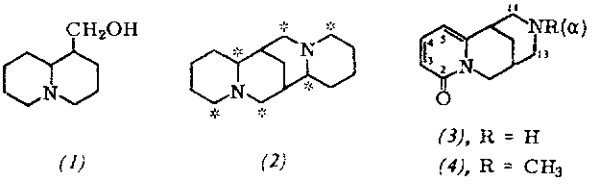
The analogous germanium and lead derivatives are obtained by starting from organogermanium and organolead compounds. Most of the new compounds are very sensitive to air and moisture and are immediately oxidized in air to esters of arsinic acids or to polymers containing Sn–O–Sb or Sn-O-Bi linkages, respectively.

82

Biosynthesis of Lupine Alkaloids

H. R. Schütte, Halle/Saale (Germany)

The lupine alkaloids lupinine and sparteine, as well as the oxygen-containing derivatives of the latter, are formed from two and three molecules of lysine, respectively, *via* cadaverine. The latter, which had previously not been detected in the plant, could be determined by reverse dilution analysis in *Lupinus luteus* after feeding of [2-^{14}C]lysine. We sought the source of the nitrogen in the biosynthesis of lupine alkaloids in *Lupinus luteus* by feeding of [2-^{14}C, ^{15}N]lysine. In the sparteine isolated, the ratio $^{14}C:^{15}N$ was about three times greater than in the lysine used. This is expected if a symmetrical intermediate is assumed, *e.g.* cadaverine, in which the α-nitrogen of lysine is uniformly distributed, and if one takes into account that there are then 6 radioactive carbon atoms [asterisks in formula *(2)*] to two nitrogen atoms. This finding supports previous results that lysine is incorporated into sparteine *via* the symmetrical intermediate cadaverine.



(1) *(2)* *(3)*, R = H *(4)*, R = CH_3

[2-^{14}C]Lysine and [1,5-$^{14}C_2$]cadaverine are incorporated in cytisine *(3)* by *Cytisus laburnum*. Oxidative degradation showed that 20 % of the total radioactivity occurs at C-2, and that C-3, C-4, and C-5 are not radioactive. The radioactivity at C-13 is decisive. In the synthesis of *(3)* from a lupinine-like precursor, this atom should not be radioactive, whereas in biosynthesis by degradation of sparteine *(2)*, 20 % of the radioactivity should be found here also. Oxidation gave a mixture of two isomeric cytisamides, in which the C-atoms 11 and 13 had been converted into carbonyl groups. This mixture was separated. Reaction with phenyl-lithium and subsequent oxidation led to elimination of the carbon atoms 11 and 13 which each contained 20 % of the radioactivity of the original alkaloid.

Labelled cytisine was also obtained by feeding sparteine. The methyl group of methylcytisine *(4)* does not become radioactive after feeding of sparteine or of cadaverine and lysine. This group is therefore introduced subsequently by methylation.

83

Infrared Studies on Hydroxides

E. Schwarzmann, Göttingen (Germany)

In hydroxides containing no hydrogen bonds, the OH stretching vibration occurs in the range 3700–3600 cm^{-1}, and the OH torsional vibration between 300 and 500 cm^{-1}. Hydrogen bonding gives rise to a decrease of the stretching frequency with increasing strength of the bond (*i.e.* decreasing O(H)···O distance) and to an increase in the torsional frequency (provided the bond is linear). A multiplicity of OH bands in the infrared spectrum is therefore often due to hydrogen bonds of various lengths.

Coupling of OH stretching vibrations with each other can also cause a splitting of bands. The same applies to torsional vibrations. Thus the splitting of OH stretching and torsional bands of partially deuterated hydroxides containing a single type of OH^- ion (*i.e.* one hydrogen bond length only) decreases with increasing degree of deuteration and often the bands coalesce to a single band with decreasing coupling. In some hydroxides with very short hydrogen bonds [*e.g.* InO(OH), γ-MnO(OH)], a multiplicity of OH stretching bands is observed, with a splitting of several hundred cm^{-1}, which cannot be explained by vibrational coupling, since it remains in partially deuterated compounds. Resonance effects between neighboring vibrational levels, such as occur in the tunneling motion of a proton in a potential well with a double minimum, and an interaction of the OH stretching vibration with the first overtones of the OH torsional vibration, may be the cause.

84

A Stable Ninhydrin Reagent for Automatic Determination of Amino Acids

E. Schwerdtfeger, Geisenheim/Rheingau (Germany)

In the automatic amino-acid determination according to *Spackmann et al.*[1], difficulty is experienced owing to the sensitivity of the ninhydrin reagent to oxygen and light. These difficulties can be avoided if the partial reduction of ninhydrin is carried out immediately before the color reaction with the amino acids by means of reducing agents added to the eluting buffer. The potassium cyanide first used for this purpose is partly retained by the cation exchange column, so that the color yields of the amino acids first eluted from the column are somtimes too low. The use of ascorbic acid instead of potassium cyanide eliminates these difficulties. The color yields of the reactions with amino acids are constant and correspond to those obtained with the reagent described by *Spackman et al.* The optimum concentration of ascorbic acid in the elution buffer is 0.01–0.02 %. The ninhydrin reagent is a 2 % solution of ninhydrin in a mixture of 37.5 % ethylene glycol, 25.0 % of 4 M acetate buffer (pH 5.5), and 37.5 % of water. It is insensitive to air and diffuse daylight, and forms no insoluble deposits in the tube connections.

[1] *D. H. Spackman, W. H. Stein*, and *S. Moore*, Analyt. Chem. *30* 1190 (1958).

85

New Reactions with Trichloromethanesulfenyl Chloride

A. Senning, Aarhus (Denmark)

N-Trichloromethanesulfenyl derivatives can be prepared under mild conditions from amides and CCl_3SCl. For example, in the reaction of benzamide with CCl_3SCl at about 100 °C, 5-phenyl-1,3,4-oxathiazol-2-one is formed (together with benzonitrile), which on pyrolysis decomposes to benzonitrile, CO_2, and sulfur. *N,N',N''*-Trisulfonylguanidines $(RSO_2NH)_2C{=}N{-}SO_2R$ are obtained from sulfonamides and CCl_3SCl. Cyclization attempts with CCl_3SCl and 1,2-diacylhydrazines were unsuccessful. Only the 1,2-bis(trichloromethanesulfenyl)hydrazine derivatives are obtained; the mono-derivatives are accessible from the monopotassium salt of the 1,2-diacylhydrazine.

Depending on the conditions, urotropine and CCl_3SCl give two isomeric 1,3-bis(trichloromethanesulfenyl)hexahydro-1,3,5-triazines. With triethylamine and CCl_3SCl a sequence of substitution and addition-elimination reactions leading to *cis*- or *trans*-1-diethylamino-1,2-bis(trichloromethylthio)-ethylene is observed.

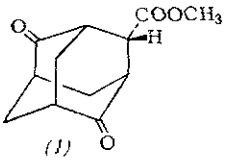
N-(Trichloromethanesulfenyl)ketimines can be prepared by treating the magnesium salt of the ketimine (obtained by addition of a Grignard reagent to a nitrile) with CCl_3SCl. Sulfenimines $(RS)_2NH$ can be substituted with CCl_3SCl and other sulfenyl chlorides to give esters of trithioorthonitrous acid $N(SH)_3$. Nucleophilic substitution of metal acetylacetonates with CCl_3SCl leads to the corresponding fully substituted trichloromethylthioacetylacetonates.

86

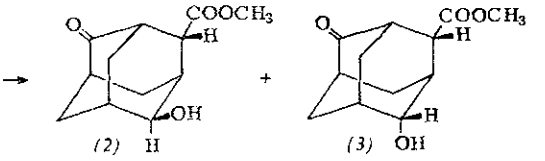
Synthesis of the Two Stereoisomeric β-Adamantanonecarboxylic Acids

G. Snatzke and *D. Marquarding*, Bonn (Germany)

Methyl adamantane-4,8-dione-2-carboxylate *(1)* can be reduced with $NaBH_4$ in isopropanol to two of the four possible hydroxyketo esters.

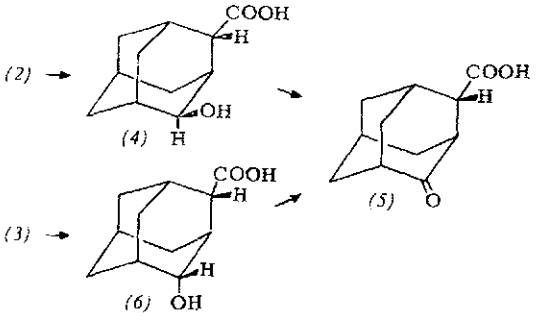


(1)



(2) *(3)*

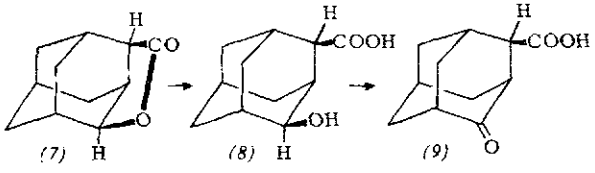
Only the keto group to which the ester group is equatorial is attacked on reduction, since the Clemmensen reduction of the keto group and oxidation of the hydroxy group in *(2)* and *(3)* gives the same β-adamantonecarboxylic acid *(5)*.



(4) *(5)* *(6)*

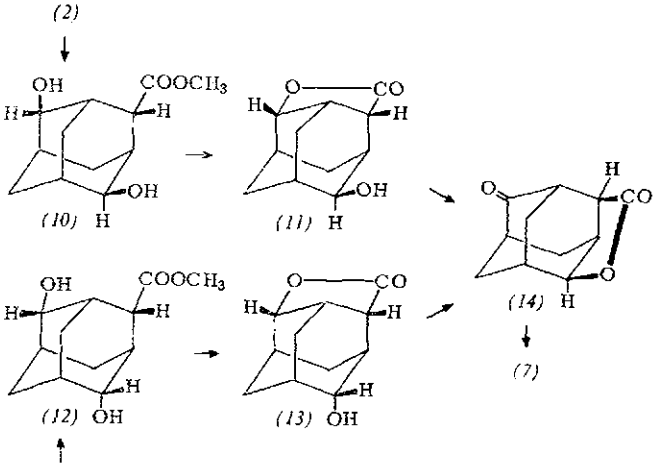
In the ester *(2)* the OH group and the α-hydrogen to the ester group are arranged 1,3-diaxially [as in the compounds *(4)*, *(10)*, and *(11)*], as the low chemical shift of the proton at C-2 in the NMR spectrum shows.

The second β-adamantonecarboxylic acid was prepared *via* the lactone *(7)*, which is formed in 20 % yield in the Clemmensen reduction of *(1)*.



(7) *(8)* *(9)*

Substantially better yields of *(7)* are obtained if the ester *(2)* or *(3)* is reduced in methanol with $NaBH_4$ to *(10)* or *(12)*, respectively. Both compounds form a lactone which can be converted into *(7)* *via* *(14)*.



(10) *(11)* *(12)* *(13)* *(14)*

The esters *(10)* and *(12)* are also obtained directly from *(1)* by reducing the latter in methanol with an excess of $NaBH_4$.

87

Surface Reactions of Gases with Semiconductors

M. J. Sparnaay, Eindhoven (Holland)

Gas adsorption on semiconductor surfaces often effects a change in the surface charge distribution. Thus the negative charge of a pure germanium surface is increased when oxygen at about 10^{-6} mm pressure is admitted. The negative surface charge is compensated by a positive space charge. The free energy of such electrical double layers can be calculated approximately. It is of the order of 1 kcal/mole and depends on the doping.

Surface structures can be investigated by diffraction of slow electrons, as well as by adsorption methods. Thus *Boonstra* found that at room temperature, one HCl or HBr molecule is adsorbed per two germanium atoms at the surface of a powdered germanium crystal. One molecule of H_2O, H_2Se, and H_2Se is adsorbed per four Ge surface atoms, and one molecule of NH_3 or PH_3 per six Ge atoms. Above 100 °C the adsorbed molecules react fairly rapidly with the Ge atoms.

88

Isomerization of Thionophosphates

H. Teichmann, Berlin (Germany)

When trialkyl thionophosphates are heated for several hours at 130 °C or higher they are converted *via* the isomeric trialkyl thiolophosphates into mixtures of sulfur-free trialkyl phosphates, esters of condensed phosphoric acids, their sulfonium salts, and dialkyl sulfides.

The first stage, *viz.* the autocatalytic isomerization of the thionophosphates, is an intermolecular $O \rightarrow S$ transalkylation. From an equimolar mixture of trimethyl and triethyl thionophosphate, the mixed thiol esters $(CH_3O)_2PO(SC_2H_5)$ and $(C_2H_5O)_2PO(SCH_3)$ are formed concurrently with the isomers $(CH_3O)_2PO(SCH_3)$ and $(C_2H_5O)_2PO(SCH_3)$; ligand exchange at the phosphorus atom of the thiolophosphates does not occur under the conditions used. Trimethyl and triethyl thionophosphate decompose about equally fast at 130 °C over *ca.* 70 h, as shown by gas chromatographic analysis; the concentration ratio during this time remains at about 1 $(C_2H_5O)_2PO(SCH_3)$: 0.5 $(CH_3O)_2PO(SCH_3)$: 0.25 $(CH_3O)_2PO(SC_2H_5)$:0.25 $(C_2H_5O)_2PO(SC_2H_5)$. This shows that thiolophosphates participate from the start in the alkylation of the thiono sulfur, preferably the methoxy-containing esters, corresponding to their higher alkylating power.

Methyl diphenyl thionophosphate, in contrast to the trimethyl analogue, is practically stable at 130 °C, although it is a considerably stronger methylating agent. This stability is due to the lack of alkylating properties in the isomeric $(C_6H_5O)_2PO(SCH_3)$; addition of $(CH_3O)_2PO(SCH_3)$ initiates a rapid decrease in thiono sulfur content in methyl diphenyl and trimethyl thionophosphates.

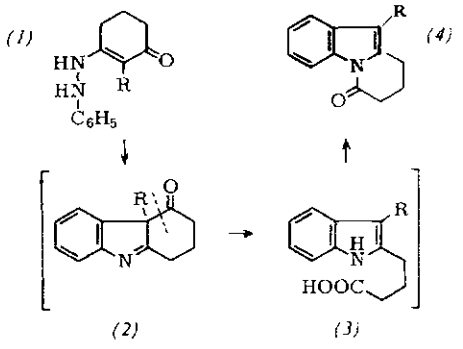
The transformation of trialkyl thionophosphates to their (even less thermostable) thiol isomers, usually described as "isomerization", should be interpreted as a special case of the Pishchimuka reaction, *i.e.* the reaction of thionophosphates with alkylating agents *via* quasi-phosphonium intermediates to thiolophosphates.

89

New Rearrangements in the Indole Series

H.-J. Teuber, Frankfurt/Main (Germany)

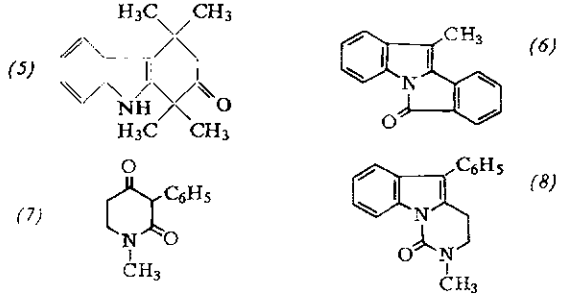
Monophenylhydrazones *(1)* of 2-substituted 1,3-cyclohexanediones, which in accordance with Bredt's rule do not yield pyrazoles, react in the Fischer synthesis by way of 1,2,3,4-tetrahydro-4-oxo-4a*H*-carbazoles *(2)* and 3-alkyl-2-indolebutyric acids *(3)* to afford 3-alkyl-3-indolebutyric acid lactams *(4)*; these can be hydrolysed to *(3)* (*D. Cornelius, E. Worbs*). Dihydro-2,5,5-trimethylresorcinol reacts analogously; the 2,2,5,5-tetramethyl derivative, however, gives *(5)*.



(1) *(2)* *(3)* *(4)*

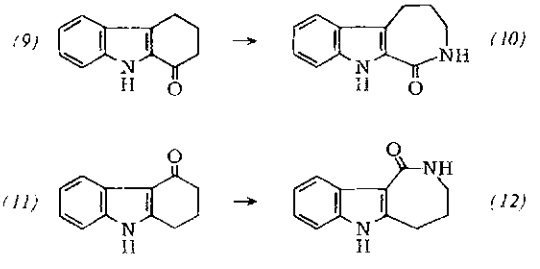
R = CH_3, C_2H_5, C_3H_7, allyl, 2-cyanoethyl, benzyl

2-Methyl-1,3-indanedione affords *(6)*. The β-keto-lactam *(7)* gives *(8)*.



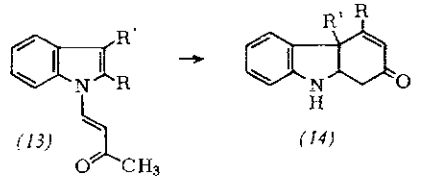
(5) *(6)* *(7)* *(8)*

In the Beckmann or Schmidt rearrangement, tetrahydro-1-, -2-, -3-, or -4-oxocarbazoles[1] afford azepinoindole derivatives [for instance, *(9)* → *(10)*, and *(11)* → *(12)*] (*U. Wölcke*).



(9) *(10)* *(11)* *(12)*

2,3-Disubstituted 1-(3-oxo-2-butenyl)indoles *(13)*[2] are rearranged to *(14)* with opening of the indole ring by methanolic HCl (*U. Reinehr, D. Cornelius*).



(13) *(14)*

R = R' = CH_3

R + R' = $-(CH_2)_4-$

[1] Cf. *H.-J. Teuber* and *D. Cornelius*, Liebigs Ann. Chem. *671*, 127 (1964).

[2] *H.-J. Teuber, D. Cornelius*, and *H. Pfaff*, Chem. Ber. *96*, 2617 (1963).

90

Mechanism of the Reaction of Metal Hexacarbonyls with n- and π-Electron Donors

H. Werner and *R. Prinz*, München (Germany)

The kinetics of the reactions of metal hexacarbonyls of the group VIb elements with n-donors such as amines or phosphines, and with π-donors such as aromatic six-membered rings or oligoolefins were studied spectrophotometrically. The substitutions with n-donors take place according to a two-step dissociation mechanism; in the first, rate-determining step a CO group is eliminated from the hexacarbonyl, and in the second, fast step the resulting pentacarbonyl fragment adds the donor L to form the substituted compound. When polydentate donors (diphosphines, diamines, or triamines) are used, the substitution of further CO groups is also rapid, since the rate constants observed agree very well with those for the reactions of metal hexacarbonyls with monodentate ligands. For the reaction:

$$M(CO)_6 + (C_6H_5)_2PC_2H_4P(C_6H_5)_2 \rightarrow [(C_6H_5)_2PC_2H_4P(C_6H_5)_2]M(CO)_4 + 2\,CO$$

the following activation parameters were obtained: M = Cr: E_a = 38.5 kcal/mole, $\Delta S^{\neq}$ = +17.3 e.u.; M = Mo: E_a = 30.1 kcal/mole, $\Delta S^{\neq}$ = +1.0 e.u.; M = W: E_a = 36.4 kcal/mole, $\Delta S^{\neq}$ = +4.0 e.u.

The reaction of molybdenum hexacarbonyl with π-donors is also first order in $Mo(CO)_6$ and practically independent of the donor concentration. This again suggests a primary dissociation of $Mo(CO)_6$ to $Mo(CO)_5$ and CO. Owing to the low nucleophilicity of the 6-ring aromatic compounds, the reverse reaction

$$Mo(CO)_5 + CO \rightarrow Mo(CO)_6$$

competes in this case with the substitution

$$Mo(CO)_5 + Ar \rightarrow ArMo(CO)_5 \quad (Ar = \text{aromatic compound})$$

so that the rate constants depend on the nature of the aromatic ligand. For example, for the reaction of $Mo(CO)_6$ with benzene at 112 ± 0.2 °C in n-decane/cyclohexane, $k = 1.92 \times 10^{-5}$ sec^{-1}; for the reaction with mesitylene, $k = 2.72 \times 10^{-5}$ sec^{-1} [1].

The rate constant of the reaction with π-donors depends on the initial concentration of $Mo(CO)_6$. With increasing dilution the overall reaction rate increases, which can be explained by the decreasing importance of the reverse reaction, the rate of which depends on the concentrations of $Mo(CO)_5$ and CO. This increase of rate on dilution is evidence against an S_N2 reaction.

[1] *H. Werner* and *R. Prinz*, J. organomet. Chem., in press.

91

The Chemistry of Silyl Azides

N. Wiberg, *K. H. Schmid*, and *Wan-Chul Joo*, München (Germany)

The reactions of silyl azides to be described can be summarized in essence by Equations (a) and (b) (R = methyl, ethyl, n-butyl, phenyl, dimethylamino, methoxy).

$$R_3Si\text{-}\overset{\ominus}{\underset{\cdot\cdot}{N}}\text{-}\overset{\oplus}{N}{\equiv}N: + :X \rightarrow R_3Si\text{-}\overset{\ominus}{\underset{\cdot\cdot}{N}}\text{-}\overset{\oplus}{X} + N_2 \quad (a)$$

$$R_3Si\text{-}N_3 + Y\text{-}Z \rightarrow R_3Si\text{-}Y + Z\text{-}N_3 \quad (b)$$

The elimination of nitrogen [reaction (a)] can be effected either thermally above 300 °C (no group X present) or chemically with trialkylphosphines (X = R_3P) or magnesium salts of organic anions (X = $C_6H_5^{\ominus}$, *o*-, *m*-, or *p*-$CH_3C_6H_4^{\ominus}$, 2,4,6-$(CH_3)_3C_6H_2^{\ominus}$ *etc.*). Thermolysis of silyl azides leads to resin-like, heterogeneous products. *N*-silylphosphazenes are obtained by reaction with phosphines:

$$R'_nSi(N_3)_{4-n} + (4-n)\,R_3P \xrightarrow{100-150\,^\circ C} R'_nSi(NPR_3)_{4-n} + (4-n)\,N_2 \quad (c)$$

The reaction of silyl azides, which are very sensitive to hydrolysis, with Grignard reagents in diethyl ether proceeds by two routes, which yield easily hydrolysable *N*-silyl-*N*-organylmagnesium amide bromide dietherates (d) and tetraalkylsilanes (e).

$$R'_3Si\text{-}N_3 + RMgBr \xrightarrow[C_2H_5OC_2H_5]{100\,^\circ C} \begin{cases} R'_3Si\text{-}N(MgBr)R + N_2 & (d) \\ R'_3Si\text{-}R + MgN_3Br & (e) \end{cases}$$

Reaction (d) is an example of the general reaction (b), *i.e.* replacement of the azide group. This substitution is rapid and quantitative with organic anions as Lewis bases, if they are used as their lithium salts (YZ = RLi), with Brönsted acids (YZ = YH), or according to Eq. (f) with Lewis acids (YZ = Hal–$EHal_n$, E = element).

$$R_3Si\text{-}N_3 + Hal\text{-}EHal_n \rightarrow R_3Si\text{-}Hal + N_3\text{-}EHal_n \quad (f)$$

The following azide-bridged, explosive azide halides were prepared according to reaction (f), among others: $(SbHal_4N_3)_2$ (Hal = F, Cl [1]); $(TiHal_2(N_3)_2)n$ (Hal = Cl, Br); $(BHal_2N_3)_3$ (Hal = Cl, Br) [2]; $SnCl_n(N_3)_{4-n}$ (n = 2,3), and $AlCl_n(N_3)_{3-n}$ (n = 0,1,2).

[1] *N. Wiberg* and *K. H. Schmid*, Angew. Chem. *76*, 380 (1964); Angew. Chem. internat. Edit. *3*, 444; (1964).

[2] *P. I. Paetzold*, *M. Gayoso*, and *K. Dehnicke*, Chem. Ber. *98*, 1173 (1965).

92

Infrared Spectra of ^{15}N-Labelled Iminophosphoranes

W. Wiegräbe and *H. Bock*, München (Germany)

In the course of investigations of the P=N double bond [1] it proved necessary to make a definite assignment to the P=N stretching frequency, for which conflicting values have been reported. To this end we synthesized the ^{15}N-labelled iminophosphoranes *(1)*–*(3)* by the following method:

$$C_6H_5\text{-}{}^{15}NH_3Br + Br_2P(C_6H_5)_3 \xrightarrow[-3\,HBr]{(C_2H_5)N_3} C_6H_5\text{-}{}^{15}N{=}P(C_6H_5)_3 \quad (1)$$

$$Ts\text{-}{}^{15}NH_2 + Br_2P(C_6H_5)_3 \xrightarrow[-2\,HBr]{(C_2H_5)_3N} Ts{}^{15}N{=}P(C_6H_5)_3 \quad (2)$$

$$Ts\text{-}{}^{15}NH_2 + PCl_5 \xrightarrow[-2\,HCl]{125\,^\circ C} Ts\text{-}{}^{15}N{=}PCl_3 \quad (3)$$

(Ts = *p*-toluenesulfonyl)

The spectra were measured in the range 5000–400 cm^{-1} and complete assignments could be made. P=N stretching bands occur at 1344 *(1)*, 1147 *(2)*, and 1199 *(3)* cm^{-1}. They are easily identified by isotope shifts of 15–20 cm^{-1}. The S–N stretching frequency with Δν = 4–6 cm^{-1}, is found at 784 *(2)* and 762 *(3)* cm^{-1}, compared to 902 cm^{-1} in tosyl amide, which was also studied.

The P=N double bond is reinforced by substituents with (–I) effect at the phosphorus and with (–M) effect at the nitrogen.

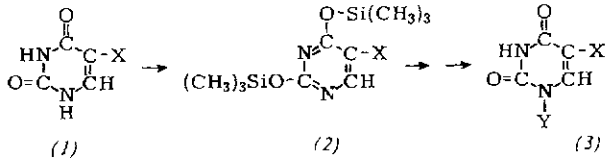
[1] *H. Bock* and *W. Wiegräbe*, Angew. Chem. *74*, 327 (1962); Angew. Chem. internat. Edit. *1*, 265 (1962); Angew. Chem. *75*, 789 (1963); Angew. Chem. internat. Edit. *2*, 484 (1963); *W. Wiegräbe* and *H. Bock*, Chem. Ber., in press.

93

Synthesis of Pyrimidine Nucleosides via Silyl Derivatives

E. Wittenberg, Rostock (Germany)

In the reaction of uracil or of its 5-X derivatives *(1)* with hexamethyldisilazane, the bistrimethylsilyl compounds *(2)* are formed quantitatively. Their structures were proved by their ultraviolet and infrared spectra.



(1) *(2)* *(3)*

X = H, CH_3, F, Cl, Br, I, $-CH_2OCH_2C_6H_5$

Y = CH_3, glucopyranosyl, galactopyranosyl, arabinopyranosyl, ribofuranosyl, deoxyribofuranosyl.

The compounds *(2)* react with methyl iodide in benzene in the presence of $AgClO_4$ almost exclusively to *N*(1)-methylpyrimidines *(3)*. In the reaction of *(2)* with acylated halogenosugars (glucopyranose, arabinopyranose, galactopyranose, ribofuranose, 2-deoxyribofuranose), acylated trimethylsilylnucleosides are formed, which are hydrolysed to the acylated nucleosides. The free nucleosides are obtained, usually in good yields, by removing the acyl group with sodium methoxide or ammonia.

94

Formation of Nitrite from Nitrate in Vegetables

W. Wodsak, Hamburg (Germany)

Some vegetables, *e.g.* spinach, are rich in nitrate. The nitrate content depends *inter alia* on nature and amount of fertilizer employed. If there is a deficiency of molybdenum and manganese in the soil, insufficient nitrate reductase is formed; the degradation of nitrate is then inhibited. Manganese favors the formation of vitamin C, which promotes the degradation of nitrate to amino compounds.

Nitrate is harmless even to infants. Nitrite, however, is strongly toxic. It oxidizes hemoglobin to methemoglobin, which cannot transport oxygen. Nitrite is practically never formed in the organism of adults, since the nitrate is absorbed before it can be reduced by the intestinal flora. In the infant dyspepsia which is accompanied by proliferation of the flora of the lower intestinal regions can lead to the reduction of nitrate before it is absorbed.

In fresh spinach, unfavorable storage conditions (dense packing, lack of oxygen) can lead to the formation of up to 40 mg NO_2/100 g. The nitrite content of deep-frozen spinach immediately after thawing is seldom above 1 mg/100 g, provided it is properly prepared. The same applies to tinned spinach. In spinach sold in glass containers as baby food, nitrite was never detected. The nitrite content of spinach which has been prepared for eating may however increase considerably on storage, especially in originally deep-frozen spinach because of the high bacterial count. Up to 15 mg NO_2/100 g were found after 24 h at 20 °C, but very little if the sample had been sterilized.

95

Stereospecific Retention in Nuclear Reactions on cis/trans-Isomeric Cobalt Complexes

G. K. Wolf, Heidelberg (Germany)

Zuber, Rauscher, et al. found some years ago that, after capture of thermal neutrons by isomeric cobalt complexes, retention and subsequent thermal healing are stereospecific, *i.e.* if the neutron-activated atoms recombine with the same ligands after the nuclear reaction, the complexes always have the original configuration.

To elucidate this phenomenon in *cis*- and *trans*-[Co(ethylenediamine)$_2$Cl$_2$]NO$_3$, recoil atoms with different recoil energies were generated by carrying out nuclear reaction with thermal neutrons (0.025 eV) up to 45 MeV neutrons.

The proportion of radioactive cobalt occurring as *trans*-[Co(ethylenediamine)$_2$Cl$_2$]$^{\oplus}$ in the irradiated target material was determined by precipitation as the perchlorate, the *cis*-isomer by precipitation as the nitrate, and Co^{2+} by extraction with 8-hydroxyquinoline in chloroform. Thermal healing was followed for 30 h.

In reactions with cobalt atoms of low recoil energy (10—100 eV), the parent compound is formed stereospecifically together with Co^{2+} and other products. The parent compound is formed exclusively from Co^{2+} on subsequent tempering. At high recoil energies (up to 10^5eV) the other steroisomer is also formed in smaller amounts. All other products are formed from Co^{2+} on subsequent healing.

These results suggest that in nuclear reactions with thermal neutrons the energy transferred locally to the lattice is insufficient for positional exchange processes to occur among the ligands. Such exchange is observed only at higher neutron energies.

96

Structural Studies on Serine-Specific Transfer-RNA

H. G. Zachau, D. Dütting, and *H. Feldmann*, Köln (Germany)

Soluble ribonucleic acid from yeast contains several serine-specific transfer ribonucleic acids (serine t-RNA). The serine t-RNA present in largest amount was purified by repeated countercurrent distribution and split with pancreas and T_1 ribonucleases. The mono- and oligonucleotides were isolated by column chromatography. The composition and base sequence of most of the oligonucleotides could be determined by further enzymatic degradation. Eleven odd nucleotides were found: one each of *N*(2)-dimethyl-Gp, 5-methyl-Cp, rTp, Ip, 2′-O-methyl-Gp, 2′-O-methyl-Up, two of 4,5-dihydro-Up, and three of Ψ-Up. With the aid of these odd nucleotides and the $(Ap)_nGp$ sequences, base sequences up to 23 nucleotides could be determined. Some of the odd nucleotides occur in close proximity in serine t-RNA.

Comparison of the known fragments of serine t-RNA with the base sequence of an alanine t-RNA recently elucidated by *Holley et al.* shows that some of the odd nucleotides and many oligonucleotide sequences are different. There are, however, also some striking similarities, *e.g.* *N*(2)-dimethyl-Gp and Ip are separated by 9 nucleotides in both t-RNA's.

[VB 958/265 IE]

German version: Angew. Chem. 77, 1013 (1965)

The conformations and configurations of complicated organic molecules were examined by *O. Exner* and *V. Jehlička* by measurement of their dipole moments. In order to extend the restricted information obtained from the individual values, the dipole moments of an unsubstituted and a *p*-chloro or *p*-nitro derivative were compared graphically with the dipole moments of the individual configurations and conformations calculated from their bond moments and angles. The method was tested on some simple examples (ω-bromoacetophenone, phenylacetic acid, and ethyl benzimidate) and then applied mainly to determine the steric structure of acylated hydroxylamines (benzhydroxamic acid and its chloride, *N,O*-dibenzoylhydroxylamine, benzamidoxime, and *N,N*-diethylbenzamidoxime). / Coll. czechoslov. chem. Commun. *30*, 639, 652 (1965) / –Hz. [Rd 365/574 IE]

The hydroxylation of proline at the level of microsome-bonded protein was detected by *B. Peterofsky* and *S. Udenfried*. In a cell-free system from chick embryo, the radioactivity from [^{14}C]proline recurred in the hydroxyproline of collagen. Although radioactive proline can be detected in the collagen after only very short incubation times, the radioactive hydroxyproline is found only after about 30 min, when about 70% of the proline is already incorporated. The system consists of microsomes, a soluble enzyme fraction, a non-enzymatic cofactor, which has not yet been identified, and a hydrogen donor, *e.g.* ascorbic acid or 2-amino-4-hydroxydimethylpteridine. The proline hydroxylase is present in the microsomal fraction. Puromycin acts as an inhibitor if added at the start of the incubation but not if added after the 30-min induction period. / Proc. nat. Acad. Sci. USA *53*, 335 (1965) / –Hö. [Rd 372/581 IE]

The interactions among lactic dehydrogenase subunits was studied by *N. O. Kaplan* et al. The occurrence of five isoenzymes in lactic dehydrogenase (LDH) is at present explained by the formation of LDH from two components with different charges, there being four subunits per LDH molecule. Since there are five possible modes of combination, five isoenzymes with different electrophoretic mobilities result. When two isoenzymes with different mobilities – even from different sources – are mixed and the solution is frozen and rethawed several times, a new combination of the subunits is formed which results in new isoenzyme bands. This process is termed hybridization and is dependent on the presence of orthophosphate plus halide or thiocyanate. A decrease of activity is observed in the series $SCN^{\ominus}, I^{\ominus} > Br^{\ominus} > Cl^{\ominus} >>> F^{\ominus}$. The phosphate cannot be replaced by arsenate, pyrophosphate, or sulfate. Inactivation of the enzyme during the process is prevented by DPN, DPNH, or acetylpyridine-DPNH. Acetylpyridine-DPNH is found to inhibit the hybridization. The dissociation and combination steps are thought to be associated with changes in the conformation of the subunits. Hybridizations between LDH isoenzymes from different sources, *e.g.* from chickens and beef, from beef and dogfish, or from chickens and dogfish, lead to products with unreduced enzymatic activity. There must therefore be great similarities between the LDH subunits from these various species. / Biochemistry *4*, 271 (1965 / –Hö.
[Rd 306/515 IE]

Dipeptides were made via the phenylhydrazides of N-acyl-α-amino acids by *H. B. Milne* and *W. Kilday*. The hydrazides can be oxidized – preferably in the dark – with *N*-bromosuccinimide in dichloromethane to give red, highly unstable phenyldiimides of the *N*-acyl-α-amino acids. These diimides can acylate nucleophilic coreactants, *e.g.* water, alcohols, or aniline, in a heterolytic reaction with release of nitrogen and benzene to give the free *N*-acylamino acids or their esters or anilides, respectively. Their reaction with amino esters leads to 40.5–71.4% yields of dipeptide esters. For example, carbobenzoxyglycyl phenylhydrazide *(1)* is oxidized in 83% yield to the diimide *(2)*, m.p. 61–62 °C, which when treated with the hydrochloride of glycine ethyl ester *(3)* and diethylamine in dichloromethane affords 61% ethyl carbobenzoxyglycylglycinate *(4)*, m.p. 80–81 °C.

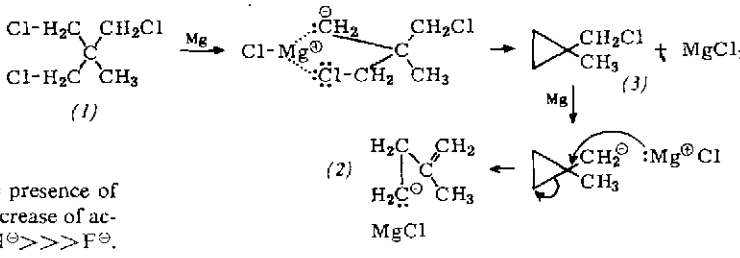
$$\text{Cbo–NHCH}_2\text{CO–NH–NH–C}_6\text{H}_5 \rightarrow \underset{(1)}{\qquad} \underset{(2)}{\text{Cbo–NHCH}_2\text{CO–N=N–C}_6\text{H}_5}$$

$$(2) + \text{H}_2\text{NCH}_2\text{COOC}_2\text{H}_5 \rightarrow \underset{(3)}{\qquad} \underset{(4)}{\text{Cbo–NHCH}_2\text{CO–NHCH}_2\text{COOC}_2\text{H}_5} + \text{N}_2 + \text{C}_6\text{H}_6$$

$\text{Cbo} = \text{C}_6\text{H}_5\text{–CH}_2\text{–OCO–}$

When the amino acids are optically active, a small amount of racemization is observed. The unstable diimides need not be isolated. The progress of the reaction can be followed spectrophotometrically by measuring the disappearance of the red color. / J. org. Chemistry *30*, 64 (1965) / –Bi.
[Rd 299/508 IE]

Polymetallophilic compounds react simultaneously at several positions in the molecule with metals to form organometallic compounds in a direct reaction. *E. L. McCaffery* and *S. W. Shalaby* synthesized 2-methyl-2-chloromethyl-1,3-dichloropropane *(1)* by treating the corresponding trihydroxy compound with thionyl chloride and pyridine. When 1 mole of *(1)* is treated with 2 moles of magnesium, *(1)* rearranges to form the Grignard derivative *(2)*, which reacts with CO_2, water, benzonitrile, and phenyl isocyanate to give the expected products. The rearrangement of *(1)* to *(2)* probably proceeds via a cyclopropane derivative *(3)*. / J. organometallic Chem. *3*, 101 (1965) / –Kr. [Rd 308/517 IE]



n-Propanol increases the virus-inactivating effect of peroxyacetic acid, according to findings of *M. Sprössig* and *H. Mücke*. No fast-acting disinfectants with a broad activity spectrum are known. In addition to its bactericidal and fungicidal properties, peroxyacetic acid has a striking antiviral activity. The activity of Type I poliomyelitis viruses decreases by a factor $\geq 10^4$ within 90 sec in a 0.2% solution of peroxyacetic

acid containing 33 % n-propanol. n-Propanol alone has practically no effect on the viruses even after treatment for 240 sec, and 0.2 % peroxyacetic acid alone produces a decrease of only about 1:10 after 90 sec or about $1:10^3$ after 240 sec. The inactivation is probably accelerated in the presence of the alcohol as a result of better penetration of the peroxyacetic acid into vital centers of the virus. / Acta biol. med. german. *14*, 199 (1965) / –De. [Rd 312/521 IE]

The resynthesis of insulin from *S*-sulfurated insulin A and B chains has been achieved by *D. Yu-cang* and *J. Rong-Qing* with a recovery of activity of 12 I.U. per milligram of protein, *i.e.* 50 % of the activity of crystalline insulin. The insulin A and B chains are obtained in the form of their *S*-sulfonates by cleavage of the native hormone with Na_2SO_3 and $Na_2S_2O_4$ in the presence of urea and can be purified by precipitation at pH 6.4 (B chain) and by zone electrophoresis on cellulose powder at pH 7.0 (A chain). The best yields of regenerated insulin are obtained with a molar ratio of A:B chains of 3:2 by reduction with a 28-fold excess of mercaptoethanol at pH 5.0 for 6 min at 100 °C, precipitation and washing of the reduced insulin chains at pH 3.8, and subsequent re-oxidation at 3–5 °C in glycine buffer at pH 10.6. / Scientia sinica *14*, No. 2 (1965) / –De. [Rd 313/522 IE]

The immunochemical activity of chymotryptic peptides from sperm whale myoglobin has been investigated by *M. J. Crumpton* and *J. M. Wilkinson*. The apomyoglobin was decomposed by chymotrypsin in a dialysis bag, and the fragments were simultaneously removed. The test for immunochemical activity was the inhibition of the precipitation of metmyoglobin and apomyoglobin by two different metmyoglobin antisera. Eight fragments were isolated and purified and their location in the myoglobin was determined. Two of the fragments inhibited the precipitation of metmyoglobin and apomyoglobin by both antisera, five that of apo- and/or metmyoglobin by one antiserum, and six that of the apomyoglobin by one or both antisera. The inhibitory effect of any fragment never went beyond 15 % precipitation; the test with a mixture of all the fragments produced the greatest inhibition of 80 %. These values remained unaltered when the fragments were heated beforehand at 100 °C. In order to achieve half of the strongest inhibition possible, an excess of fragments had to be used. The extent of this excess increased as the molecular weight of the fragments decreases; for example, it was 80:1 for a fragment with a molecular weight of 793 but only 12:1 for a fragment with a molecular weight of 2051. Generally ratios of 2000:1 to 3000:1 are required for haptenes in order to effect 50 % of the maximum inhibition. / Biochemical J. *94*, 545 (1965) / –Hö. [Rd 320/529 IE]

The role of dicyanogen diamide in peptide synthesis during the course of chemical evolution has been studied by *G. Steinman*, *R. M. Lemmon*, and *M. Calvin*. Dicyanogen diamide can be formed under primaeval terrestrial conditions from HCN and is capable of converting orthophosphate into pyrophosphate, glucose and phosphoric acid into glucose-6-phosphate, and adenine and phosphoric acid into adenylic acid. Moreover, in the presence of HCl it transforms alanine into alanylalanine. The yield of alanylalanine after incubation for 20 h at 20 °C and pH 2.0 in the dark was 1.2 %; in addition, a trace of alanylalanylalanine was also found. The course of the condensation corresponds to that of the polymerization of amino acids by carbodiimides. / Science Washington) *147*, 1574 (1965) / –De. [Rd 314/523 IE]

Sex-specific differences in the concentrations of serum amino acids have been observed by *H. Oepen* and *I. Oepen* in the blood of clinically healthy humans. Women generally have a lower level of serum amino acids than men. Cysteic acid and taurine could be detected in larger amounts in women than in men both before and after hydrolysis, but cysteine only before hydrolysis of the serum peptides. The values for free valine, isoleucine, and leucine, and after hydrolysis those for phenylalanine and tyrosine, were much lower in women than in men; less strikingly lower values were found for 13 other amino acids. Since the monoamino monocarboxylic acids (Val, Leu, and Ileu), the cyclic alanine derivatives (Phe and Tyr), and the amino acids containing sulfur (Cy, cysteic acid, and Tau) each occur as distinct groups, these sex-specific differences in concentration must apparently have some function. / Klin. Wschr. *43*, 211 (1965) / –De. [Rd 315/524 IE]

The formation of antibodies against alcohol dehydrogenase has been studied by *H. Werchau* and *H. Kröger*. They examined the influence of protein-synthesis inhibitors on the synthesis of antibodies against the alcohol dehydrogenase (ADH) from rabbit spleen cells *in vitro*. Rabbits were immunized with intravenous injections of ADH. After 10–12 weeks a second injection of ADH was given and the animals were killed 3 days later. Their spleen cells were isolated and maintained in cultures. Incubation with ADH led to the formation of ADH antibodies after about 6 h. After ca. 40 h, the ADH was about 70 % inhibited. The active component of the spleen cell supernatant was found only in the γ-globulin fraction. Additions of puromycin (25 μg/ml) or actinomycin (1 μg/ml) effected complete blockage of the antibody synthesis. Partial blockage was caused by 6-mercaptopurine, 5-iododeoxyuridine, and other nucleic-acid antimetabolites in concentrations around 10^{-3} M. It is therefore assumed that a DNA-dependent RNA synthesis is required for the production of the antibodies and that specific peptide sequences are formed on the RNA following the normal scheme of protein synthesis. / Biochem. Z. *341*, 184 (1965) / –Hö. [Rd 316/525 IE]

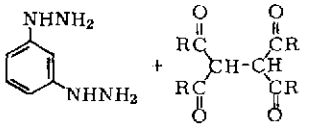
The mode of degradation of isoprenoids by bacteria has been elucidated by *W. Seubert* and *E. Fass*. With geraniol and farnesol the first step is the oxidation of the hydroxymethyl to a carboxyl group, the second the activation of the latter to the corresponding β-methylacyl-CoA. In the third step, the β-methyl group is carboxylated by a biotin enzyme, and in the fourth and fifth steps, hydration of the α,β-double bond and elimination of acetic acid with formation of a β-ketoacyl-CoA occur. The latter compound reacts in the sixth step once again with CoA–SH and is then split into acetyl-CoA and a δ-methyl-acyl-CoA which is then shortened by two carbon atoms in the reaction sequence which corresponds to one turn of the Lynen fatty acid spiral. Thus the starting point of the "isoprenoid spiral", a β-methacrylyl-CoA derivative is again attained and the degradation process starts anew. The spiral ends with dimethylacrylyl-CoA, which yields acetoacetic acid and acetyl-CoA following the scheme of degradation of leucine. Proof of this degradation route was obtained by characterization of the 7-methyl-3-oxo-6-octenoyl-CoA formed from the geranyl-CoA as the dinitrophenylhydrazone of the methylheptenone produced by thioester cleavage and decarboxylation. / Biochem. Z. *341*, 35 (1965) / –Hö. [Rd 317/526 IE]

Polystyrenes with *p*-vinyl and *p*-isopropenyl groups were prepared by *D. Braun* and *H.-G. Keppler*. Their investigations were based on copolymers of styrene and *p*-(β-bromoethyl)-styrene or styrene and *p*-(α-hydroxyisopropyl)styrene. – β-Bromoethyl groups can be converted into vinyl groups by dehydrobromination in methanolic KOH at 130 °C, and isopropenyl groups are produced by dehydration of α-hydroxyisopropyl groups with acetic anhydride at 135 °C in *p*-xylene. Vinyl monomers, *e.g.* styrene, can be grafted onto polymers made from these styrene derivatives by either radical or anionic mechanisms. Cross-linking free-radical copolymerization can be used to make castings with a low degree of cross-linking which do not exhibit orientational

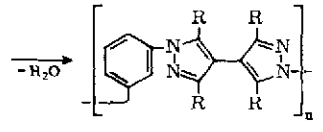
double refraction. The Vicat temperature for a cross-linked polystyrene made from a 5 % solution of a polystyrene with 11.3 mole-% vinyl groups in styrene was 95 °C, while that of a non-cross-linked polystyrene produced under the same conditions was 87.5 °C. / Makromolekulare Chem. *82*, 132 (1965) / –Hl. [Rd 321/530 IE]

The reactivity of methacrylates in radical copolymerization was studied by *J. C. Bevington* and *B. W. Malpass* using ^{14}C and ^{3}H. The polymerization was carried out at 60 °C with azobisisobutyronitrile as initiator. The relative reactivity compared with the poly(methyl methacrylate) radical is greater than 1 for most esters (methyl methacrylate as standard = 1.00) and increases with the possibilities of stabilization of the polymeric free radicals by resonance (ethyl methacrylate 1.09, phenyl methacrylate 1.79). Calculation of the monomer constants using the equation of *Bamford* [1] gives values in agreement with those of *Bamford* and *Jenkins* [2]. The change in monomer reactivity with temperature appears to be of importance for inhibition of growth at higher polymerization temperatures. / European Polymer J. *1*, 19 (1965) / –Hl. [Rd 322/531 IE]

Thermostable polyphenylpyrazoles have been made by *J. P. Schaefer* and *J. L. Bertram*. The starting materials are first precondensed in equimolar amounts at low temperatures under nitrogen and then cured at high temperatures and a pressure of 0.1 mm. For instance, *m*-dihydrazinobenzene *(1)*



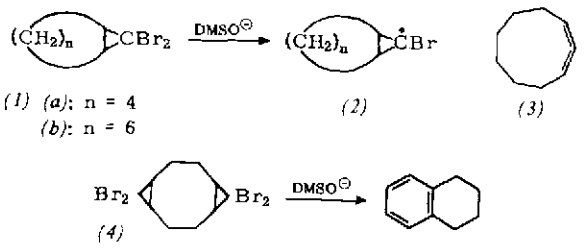
(1) *(2)*



(3)

is heated with tetraacetylethane *(2)* for 1 h at 80–120 °C and then for 10 h at 140–350 °C; the intrinsic viscosity of the resultant polymer in formic acid at 30 °C is 1.5 dl/g. No loss of weight occurs with these polyphenylpyrazoles up to 400 °C. Infrared and mass spectra were used to establish the structure *(3)* for the polymer. / J. Polymer Sci. (Polymer Letters) B *3*, 95 (1965) / –Hl. [Rd 326/535 IE]

Debromination of 1,1-dibromocyclopropanes by sodium methylsulfinylmethide has been studied by *C. L. Osborn, T. C. Shields, B. A. Shoulders, C. G. Cardenas*, and *P. D. Gardner*. Since the $CH_3SOCH_2^{\ominus}$ anion is an effective nucleophile for the elimination of bromine, it seemed likely that it would form carbenes from 1,1-dibromo compounds. 7,7-Dibromobicyclo[4.1.0]-heptane *(1a)* reacts with excess sodium methylsulfinylmethide in dimethyl sulfoxide at room temperature to yield 72 % 7-bromobicyclo[4.1.0] heptane *(2a)*, the *trans*-isomer predominating. Analogous reaction of 9,9-dibromobicyclo-[6.1.0]nonane *(1b)* for 2.5 h affords 71 % *trans*- and *cis*-9-bromobicyclo[6.1.0]nonane *(2b)*. An excess of sodium methylsulfinylmethide converts *(2b)* within 4.5 h in 66 % yield into 1,2-cyclononadiene *(3)*. Similarly, 9,9-dibromobicyclo[6.1.0]-



(1) *(a)*: n = 4 *(b)*: n = 6 *(2)* *(3)* *(4)*

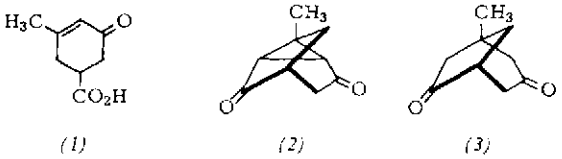
non-4-ene yields 64 % 1,2,6-cyclononatriene, and 5,5,10,10-tetrabromotricyclo[7.1.0.0^{4,6}]decane *(4)* yields 40 % tetralin. / Chem. and Ind. *1965*, 766 / –Ma. [Rd 327/536 IE]

A new method of decarboxylating aliphatic acids to the next lower alkyl halide is given by *J. K. Kochi*. The acids are heated with a metal halide and lead tetraacetate under nitrogen in refluxing benzene, acetonitrile, or hexane/benzene.

$$RCOOH + Pb(OAc)_4 + MX \rightarrow RX + CO_2 + Pb(OAc)_2 + HOAc + MOAc$$

The reaction is complete within a few minutes with LiCl and $CaCl_2$, but KCl and NaCl require prolonged heating because of their low solubility in organic solvents. The decarboxylation is fastest with tertiary and secondary carboxyl groups. The amount of methyl chloride formed from the acetic acid produced as by-product is insignificant in these cases. Acids with primary carboxyl groups also give high yields of chloroalkane but more methyl chloride is formed as by-product. Excess acid must be used to ensure maximum utilization of the lead tetraacetate. The metal halide is consumed in an equimolar amount with the Pb(IV) acetate. Decarboxylation to alkyl bromides and iodides occurs with metal bromides and iodides with simultaneous formation of bromine and iodine. For example, isobutyric acid → 98 % isopropyl chloride [based on $Pb(OAc)_4$]; pivalic acid → 72 % t-butyl chloride; cyclobutanecarboxylic acid → cyclobutyl chloride 98 %; cyclohexanecarboxylic acid → 100 % cyclohexyl chloride. / J. Amer. chem. Soc. *87*, 2500 (1965) / –Ma. [Rd 344/553 IE]

The intramolecular addition of an α-keto carbene onto an alkenone double bond was investigated by *D. Becker* and *H. J. E. Loewenthal*. 3-Methylcyclohex-3-ene-5-one-1-carboxylic acid is converted into the corresponding methyldiazo ketone by treatment with oxalyl chloride in benzene in the presence of pyridine and subsequent reaction with diazomethane. Decomposition of the diazo ketone in boiling



(1) *(2)* *(3)*

cyclohexane in the presence of anhydrous $CuSO_4$ produces the tricyclic diketone *(2)*, m.p. 46.5–47 °C, in 38 % yield. Hydrogenation of *(2)* with Pd/C in methanol leads rapidly to 71 % 1-methylbicyclo[3.2.1]octane-3,6-dione *(3)*, m.p. 64 °C. / Chem. Commun. *1965*, 149 / –Ma. [Rd 337/546 IE]

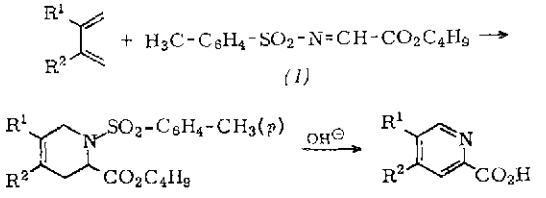
Tertiary phosphine oxides catalyse the isomerization of epoxides to ketones. This was observed by *D. E. Bissing* and *A. J. Speziale*, who also found that triphenylphosphine oxide is much less effective in this respect than tributylphosphine oxide. *trans*-Stilbene oxide yields 67 % benzyl phenyl ketone and traces of diphenylacetaldehyde and *cis*-stilbene, but the occurrence of *trans*-stilbene as an intermediate during the reaction can be concluded from the transient appearance of

[1] *C. H. Bamford, A. D. Jenkins*, and *R. Johnston*, Trans. Faraday Soc. *55*, 418 (1959).

[2] *C. H. Bamford* and *A. D. Jenkins*, Trans. Faraday Soc. *59*, 530 (1963).

its NMR spectrum. *trans*-4-Octene oxide is converted by heating for 10 days at 160 °C in a sealed tube under nitrogen in the presence of *m*-chlorobenzaldehyde into 4-octanone in 85 % yield. *cis*-4-Octene is isomerized a little more slowly. / J. Amer. chem. Soc. *87*, 1405 (1965) / –Ma. [Rd 333/542 IE]

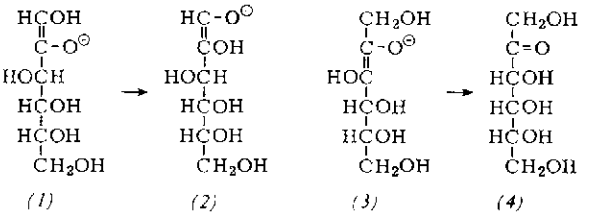
N-Butoxycarbonylmethylene-*p*-toluenesulfonamide is a new dienophile which was found by *R. Albrecht* and *G. Kresze* to be suitable for the preparation of pyridine, piperideine, and piperideine derivatives using the Diels-Alder reaction. The sulfonamide *(1)* is made by heating butyl glyoxylate with *N*-sulfinyl-*p*-toluenesulfonamide in benzene in the presence of $AlCl_3$ and reacts with butadienes to yield piperideine



(1)

derivatives which on hydrolysis with alkali form pyrideine derivatives and *p*-toluenesulfinic acid. Cyclic dienes result in 2-aza bicyclic compounds. / Chem. Ber. *98*, 1431 (1965) / –Ma. [Rd 334/543 IE]

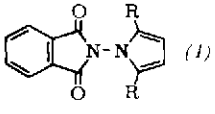
Dicyclohexylcarbodiimide was used as a new reagent for epimerizing and isomerizing sugars in neutral solution by *S. Passeron* and *E. Recondo*. Heating of fructose in anhydrous methanol with dicyclohexylcarbodiimide leads to a mixture of glucose, mannose, and D-psicose *(4)*, the latter in 25 % yield. As a Brønsted base, the diimide probably deprotonates the fructose to give the anion *(1)*, which isomerizes to the anion *(2)*, being then in equilibrium with glucose and



(1) *(2)* *(3)* *(4)*

mannose. The psicose *(4)* can arise analogously from the anion *(3)*. Analogously, D-galactose yields D-tagatose as main product together with a little sorbose. / J. chem. Soc. (London) *1965*, 813 / –Ma. [Rd 255/464 IE]

N-Aminophthalimide has been used for unequivocal syntheses of N-aminopyrroles by *R. Epton*. The phthaloyl group of the reagent can be readily removed. Condensation of *N*-aminophthalimide with acetonylacetone in hot acetic acid yields 96 % *N*-phthalimido-2,5-dimethylpyrrole *(1)*, m.p. 184 to



(1)

184.5 °C. Hydrazinolysis of *(1)* gives 65 % *N*-amino-2,5-dimethylpyrrole, m.p. 51–52 °C. Condensation of *N*-aminophthalimide and 2,5-dimethoxytetrahydrofuran results in 40 % *N*-phthalimidopyrrole, m.p. 223–224 °C, which then yields 70 % *N*-aminopyrrole, b.p. 174–174.5 °C/750 mm. / Chem. and Ind. *1965*, 425 / –Ma. [Rd 287/496 IE]

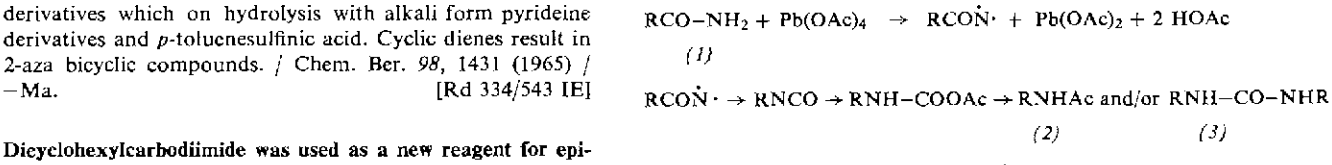
A mass-spectrometric amino-acid sequence analysis enabled *E. Lederer* et al. to establish the structure of the lipoprotein fortuitin. This natural product obtained from *Mycobacterium fortuitum* was already known to have the amino-acid composition $Val_3Thr_2Ala_1Pro_1$ and to contain two *N*-methylleucine residues (MeLeu), a methyl ester group (Me), two acetyl groups (Ac), and a long-chain fatty acid. The mass spectrum revealed that the substance, which was hitherto thought to be homogeneous, consists of two components differing by two methylene groups in the fatty acid moiety. The complete structure is

CH_3-$(CH_2)_n$-CO-Val-MeLeu-Val-Val-MeLeu-Thr(Ac)-Thr(Ac)-
-Ala-Pro-OMe

n = 18 or 20

The amino acids all have the L-configuration; the configuration of the MeLeu is however still unknown. / Biochem. biophysic. Res. Commun. *18*, 469 (1965) / –Hö. [Rd 318/527 IE]

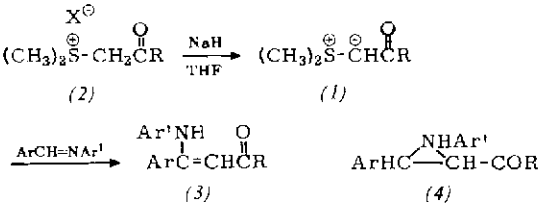
The reaction of lead tetraacetate with unsubstituted primary amides leads to acylamines. On reaction of a primary amide *(1)* with lead tetraacetate in benzene or benzene/acetic acid, *B. Acott* and *A. L. J. Beckwith* obtained a mixture of the *N*-acetylamine *(2)* and a dialkylurea *(3)*. No reaction took place with benzamide.



(1) *(2)* *(3)*

Yields: R = n-butyl: 45 % acylamine/5 % dialkylurea; pentyl 40/5; cyclohexyl 65/8; heptadecyl 61/9; benzyl 67/0; 9-decenyl 53/3; 24-nor-5β-cholanyl 81/0. / Chem. Commun. *1965*, 161 / –Ma. [Rd 338/547 IE]

Carbonyl-stabilized sulfonium ylides *(1)* have been made by *A. J. Speziale, C. C. Tung, K. W. Ratts*, and *A. Yao*. The ylides *(1)* are obtained by treating sulfonium salts *(2)* with NaH in tetrahydrofuran. Their reaction with Schiff bases leads to substituted β-anilinocinnamamides and β-anilinocinnamates *(3)*, which can be identified by their NMR spectra and hydrolysis products. The aziridine *(4)* is proahably an intermediate of the formation of *(3)*. The carbonyl-stabilized



(2) *(1)* *(3)* *(4)*

X = Halogen; R = OC_2H_5

sulfonium ylides are valuable nucleophiles for use in syntheses. / Abstracts 149th Meeting Amer. Chem. Soc. *1965*, 44P / –Ma. [Rd 339/548 IE]

Chloroarsines with t-butyl groups were obtained by *A. Tzschach* and *W. Deylig* by direct synthesis from $AsCl_3$ and t-C_4H_9MgCl in ether with exclusion of air and moisture; the yields were over 50 %.

$$AsCl_3 + t\text{-}C_4H_9MgCl \rightarrow t\text{-}C_4H_9AsCl_2 + MgCl_2$$

$$AsCl_3 + 2\ t\text{-}C_4H_9MgCl \rightarrow (t\text{-}C_4H_9)_2AsCl + 2\ MgCl_2$$

The products are colorless liquids that can be distilled in vacuum and which dissolve in all common organic solvents. The chloroarsines can be reduced with $LiAlH_4$ in diethyl ether at –10 °C to the corresponding arsines, *e.g.* t-$C_4H_9AsH_2$, b.p. 65–67 °C, in 65 % yield or $(t\text{-}C_4H_9)_2AsH$, b.p. 49 to 50 °C/16 mm, in 41 % yield. The arsines are liquids which are extremely sensitive to air and which can be metallated by phenyl-lithium to the corresponding lithium arsides. / Z. anorg. allg. Chem. *336*, 36 (1965) / –La. [Rd 340/549 IE]

Paramagnetische Elektronenresonanz (Electron Paramagnetic Resonance). By *S. A. Altschuler* and *B. M. Kosyrew*. Translated from the Russian by *A. Lösche* and collaborators. Verlag Harri Deutsch, Zürich-Frankfurt/Main 1964. 1st edit., VII + 383 pp., 53 figs. linen DM 54.– (about $13.75).

After a brief introduction and a survey of experimental methods, the major part of this book deals with the electron spin resonance spectra of ionic crystals: with the theory in Chapter III (50 pp.), with experimental results in Chapter IV (105 pp.), and with relaxation and line widths in Chapter V (80 pp.).

The remainder of the book deals with the EPR spectra of metals and semiconductors and with defects in crystals (Chapter VI, 37 pp.), and with stable free radicals and radicals produced by radiation (Chapter VII, 28 pp.). The closing chapter (45 pp.) is devoted to allied phenomena such as dynamic nuclear polarization and molecular amplifiers.

In common with all other publications that have appeared on this subject, the present monograph gives a particularly detailed discourse on the particular aspects of electron paramagnetic resonance in which the authors are specialists. Since here the main accent is on ionic crystals, the main attraction should be for solid state physicists; physicochemical applications receive less consideration, and biological aspects none at all. A prominent feature of the book is the tables in Chapters IV and V which take up over eighty pages and which form a work of reference augmented with numerous citations of results published until the appearance of the Russian edition in 1959. In the German edition, which bears the date "January 1962" in the foreword, numerous more recent publications have been cited. It is unfortunate that the long time that has elapsed between this date and the final appearance of the book (1964) has nevertheless resulted in some loss of actuality. In conclusion, attention should be called to the fact that there are almost no original spectra included in the book. The reviewer is of the opinion that the gain in clarity obtained from the printing of typical spectra would justify higher production costs for the book.

K. Hausser [NB 397/255 IE]

Titrationen in nichtwäßrigen Lösungsmitteln (Titrations in Non-aqueous Solvents). By *W. Huber*. Methoden der Analyse in der Chemie (Methods of Analysis in Chemistry). Edited by *F. Hecht*, *H. Kaiser*, and *H. Kriegsmann*. Vol. 1. Akademische Verlagsgesellschaft, Frankfurt/Main 1964. 1st edit., XII + 280 pp., 79 figs., 14 tables, linen DM 35.– (about $ 9.–).

This is the first volume in a new series of monographs on analytical methods in chemistry intended to acquaint their readers with the current status of selected analytical methods. The book deals with the quantitative determination of acids and bases by titration in non-aqueous solvents. In the first – mainly theoretical – section, the general fundamentals, the methods of determining end-points, instrumentation, and reagents are discussed. The second section gives a detailed description of the practical execution of acid-base titrations, arranged mainly according to classes of compounds. The final section contains tables listing mainly dissociation constants measured in water for the most diverse compounds. The author has succeeded in presenting a treatise on acid-base equilibria tailored to suit the practical worker; it is intended to direct the experimenter toward suitable titration techniques even for very strong or very weak acids and bases on the basis of dissociation constants (Section III). Unfortunately the author, allegedly to avoid confusion, has employed the outdated basicity constants K_B as a measure of base strength. For the sake of uniformity, it would have been better to have given data on the acidity constants of the conjugate acids. The book should appeal to the practical worker who has long ago completed his undergraduate chemical studies; it will also offer many an incentive to the expert in this field.

W. Simon [NB 373/231 IE]

Vitamine. Chemie und Biochemie (Vitamins. Chemistry and Biochemistry). Edited by *J. Fragner*. Translated from the Czechoslovakian by *H. Liebster*. Vol. I. VEB Gustav Fischer Verlag, Jena 1964. 1st German edit., 890 pp., 48 figs., 117 tables, linen DM 87.60 (about $22.00).

A group of Czechoslovakian scientists have undertaken the task of writing a monograph on the chemistry and biochemistry of the vitamins. The first volume of the two-volume Czech edition which appeared in 1961 is now available in German. It is divided into a general and a specialized section. In the first part, after a historical introduction, the nomenclature and classification of vitamins, the relationships between their structures and biological activities, their biogenesis, vitamins in biochemical systems, vitamins in the diet, the occurence of vitamins, fundamentals for vitamin assays, and the applications of vitamins are discussed. In the specialized section, which will be continued in the second volume, the individual vitamins are considered, and again the chapters are divided into historical introduction and nomenclature, chemistry, biochemistry, assay, and applications of each vitamin.

The 26 authors who cooperated in compiling the book have considered an astounding number of publications, and patent literature has often been consulted. The tabular summaries given are especially valuable.

The great expectations with which one begins to read the book are however unfortunately disappointed in several parts. The text is often too digressive, the historical development is placed too far in the forefront, and the literature has not been appraised critically enough. Some of the biochemical chapters are particularly unsatisfactory. Here no clear-cut distinction is made between experimentally established results and mere hypotheses, and many inaccuracies and errors have slipped in. For example, in the general chapter on the biogenesis of vitamins, the modern aspects of product inhibition, repression, and induction are not mentioned; instead, inhibition is explained using outdated examples from reaction kinetics. The biogenesis of flavonoids is misrepresented on p. 83 – phloroglucinol is not an intermediate – but is reproduced correctly on p. 531. Despite the reasons presented by the authors, it is still not understandable why "bioflavonoids" and "essential fatty acids" are dealt with in a handbook on vitamins. The participation of lipoic acid (the formula for the dehydro derivative on p. 91 is incorrect) in photosynthesis is presented as a fact, even though *Calvin* considers it as highly dubious. It is stated on p. 94 that the Schiff base is formed non-enzymatically during amino-acid activation. On p. 95, the activation of benzoic acid *via* its CoA ester is reproduced erroneously. The isomerization of isopentenyl pyrophosphate is caused by an enzyme and not by $H^{\oplus}$ ions (see p. 325). The occurrence of lycopersin as an intermediate in carotenoid biosynthesis is strongly disputed (p. 327). In the chapters on the bioflavonoids, the formulae of hesperidin and eriodictin are drawn with D-rhamnose instead of with L-rhamnose, and on p. 534, a "catechin component" of rutin is alleged. In this and in other chapters, little attention is paid to the stereochemistry of the compounds described.

The authors claim that the literature has been reviewed in general until 1961. However, the structure for activated methionine is still given only tentatively (p. 723), and the formula for the vitamin B_{12} coenzyme is lacking.

The print and quality of the book are good, but the reproduction of formulae is sometimes poor and contains many errors. Although the shortcomings outlined above show that the

book is not entirely satisfactory, it will nevertheless be a great help to the specialist in the vitamin field provided he exercises caution in its use. *H. Grisebach* [NB 405/263 IE]

Silicate Science. By *W. Eitel.* Vol. 1: Silicate Structures. Academic Press, New York-London 1964. 1st edit., XII + 666 pp., numerous figs., several tables, price of single volume in linen $ 24.00.

For decades, "Die physikalische Chemie der Silicate" (The Physical Chemistry of Silicates) by *W. Eitel* was the standard textbook in the field of silicate chemistry. It appeared in several German editions and finally in an English edition in 1954. In the meantime, the results of experimental studies of silicates have assumed unprecedented dimensions: over 20000 publications have appeared within the past 15 years alone!

In his new work, "Silicate Science", the author attempts to catch up on this lag in reviews of original publications. The present volume is the first of a planned series of five. Chapters 1–3 correspond to the content of his older monograph and contain a general description of the Si–O bond together with a survey of the crystal structures of silicates, with particular emphasis on isomorphic and isotypical relationships to non-silicate systems. Epitaxic phenomena are also dealt with. The systematic classification is built up on the *Bragg* system and its supplementation by *Zoltai*; however, the work of *Below* and his school is also given due attention. The second section is devoted to clay minerals, particularly their structures. In the last section, which makes up over half the book, the problems of colloid chemistry and the surface properties involved in silicate chemistry are discussed. In this connection, aluminum oxide/silicon dioxide gels and cracking catalysts are described.

The author has managed to review the vast literature in this field in magnificent fashion. It should be emphasized that in all chapters, whenever the views of different research groups do not concur, the different experimental methods and interpretations are presented together. The reader thus has the opportunity of appraising the arguments for himself. For this reason, the book offers a summary of information that is valuable not only for those who wish to acquaint themselves with special topics of this subject but also for experts in this field. It deserves a place in every chemical library. However, it does not provide a modern textbook of silicate chemistry, which is still lacking.

Armin Weiss [NB 384/242 IE]

Colorimetric Determination of Elements. Principles and Methods. By *G. Charlot.* Elsevier Publishing Co., Amsterdam-London-New York 1964. 1st edit., IX + 449 pp., 72 figs., 12 tables, linen DM 56.– (about $ 14.–).

This book is in the main a translation of the second French edition of 1961, a few sections having been revised by the author. In the general section (154 pp.) – somewhat inaptly entitled "Theoretical Background" – Beer's law and the fundamentals of the techniques and equipment used in photometry, fluorimetry, turbidimetry, and nephelometry are discussed. The general physical principles are dealt with only summarily; details concerning apparatus are not given. On the other hand, the author goes further into the sources of error and accuracy of photometric estimations, but again practical aspects are dealt with less thoroughly than the formal mathematical concepts. This section also includes chapters on extraction, ion exchange, chromatography, separations via the gas phase ($1^1/_2$ pages and 2 tables), and electrolytic processes. Although it must be admitted that separations are often intimately connected with photometric estimations, a general reference to paper chromatography and ion-exchange chromatography on about 1 page each are useful only to readers who are totally unfamiliar with these processes. The section on the separation of traces (2 pp.) is also poor. In the second section (280 pp.), procedures for determining 65 elements are described; these are all reliable, well tested methods. However, some methods which might have been preferred by experienced analysts have been omitted. For some elements, several practical procedures are described in detail, but for others, little more than short headings and literature references are given. For the sections on the separation of the elements, this abbreviated style has been used throughout. Occasionally only a literature reference is given for the examination of some natural and synthetic products.

The vast number of literature references given, which are mostly linked with a condensed description of the content of the papers concerned, is the best feature of this book. Some parts could have been improved by more careful editing. Although the book has little hope of ousting the established works on photometric analysis, it is valuable, particularly because of its second section, for rapid reference to the solution to certain problems. *H. Bode* [NB 358/216 IE]

Spectroscopy and Photochemistry of Uranyl Compounds. By *E. Rabinowitch* and *R. L. Belford.* International Series of Monographs on Nuclear Energy, edited by *J. V. Dunworth*, Division XII: Chemistry, Vol. I. Pergamon Press, Oxford - London - Edinburgh - NewYork - Paris - Frankfurt 1964. 1st edit., X + 370 pp., numerous illustrs. and tables, linen £4.0.0 (about $ 11.–).

This monograph reviews the current status of knowledge of the spectroscopy and photochemistry of hexavalent uranium. Chapter 1 deals with the spectroscopy of solid uranyl salts. Following an introductory section on the structure of crystalline uranyl compounds, discussions are given on their fluorescence, absorption, and infrared spectra. Chapter 2 deals with the spectroscopy of uranyl compounds in solution. Chapter 3 describes the intensity and decay of uranyl fluorescence and Chapter 4 the photochemistry of uranyl compounds, while Chapter 5 gives a short presentation of the theory of the electronic structure of the uranyl ion.

The material is presented mainly in chronological order within each section. The main contributions are naturally derived from publications which appeared after 1940. A practically complete list of references is given for the literature from 1833 (!) to 1961; work that appeared after completion of the manuscripts is listed in an appendix covering publications up to the end of 1963.

Naturally, monographs of this type appeal to only a very limited readership. However, they usually are indispensible aids for the experts in their specific fields, and this is particularly true of the present volume. All associated with the chemistry and especially with the spectroscopy of uranium or of actinides in general will he grateful to the authors for their efforts in compiling this book.

G. Koch [NB 364/222 IE]

Inorganic Ion Exchangers. By *C. B. Amphlett.* Topics in Inorganic and General Chemistry. Edited by *P. L. Robinson.* Monograph 2. Elsevier Publishing Co., Amsterdam-London-New York 1964. 1st. edit., XI + 141 pp., 36 figs., 32 tables, linen about DM 23.– (about $ 5.50).

This book has appeared as the second volume of a large series of individual monographs on inorganic and general chemistry. The use of inorganic ion exchangers has acquired increasing importance in recent years on account of their high thermal stability and resistance to radiation.

After a short historical introduction and a general survey, ion exchange on clay minerals, zeolites, and salts of heteropolyacids are dealt with. The major portion of the book is devoted to the exchange properties of zirconium phosphates and related compounds, on which the author has done a considerable amount of research. The exchange equilibria, ion separations and selectivities, suitability for water purification, and the preparation of ion-exchange membranes are discussed for zirconium phosphates. Despite the condensed nature of the text, the author has succeeded in illuminating the problems

concerned and in pointing out the principles. The book can therefore be recommended to anyone who wants to familiarize himself with this field or to have a ready source of information on it. However, the attention of the reader is called in the foreword to the fact that the book is not a comprehensive survey; nonetheless, the chapter on zirconium phosphates covers more than 100 literature references.

Armin Weiss [NB 396/254 IE]

Progress in Boron Chemistry. Edited by *H. Steinberg* and *A. L. McCloskey*. Vol. 1. Pergamon Press, Oxford-London-Edinburgh-New York-Paris-Frankfurt 1964. 1st edit., VII + 487 pp., numerous figs. and tables, linen £7.0.0 (about $ 19.50).

This volume initiates a new series of progress reports dedicated to research on the element boron and its compounds. In the first of the ten chapters in this first volume, *R. J. Brotherton* gives a detailed report on "The Chemistry of Compounds with Boron-Boron Bonds". *T. D. Coyle* and *F. G. A. Stone* then give a critical assay of "Some Aspects of the Coordination Chemistry of Boron", *G. W. Campbell* describes "The Structures of Boron Hydrides", and *H. A. Soloway* the applications of "Boron Compounds in Cancer Therapy". The following contribution by *M. J. S. Dewar* on "Heteroaromatic Boron Compounds" is very short. The evolution of the chemistry of "Organoperoxyboranes" is described by *A. G. Davies*. The interesting and variegated research in the chemistry of "Organoboron Heterocycles" is reviewed authoritatively by *R. Köster*. In their chapter on the "Reactions of Diazoalkanes with Boron Compounds", *C. E. Bawn* and *A. Ledwith* report on the catalytic activity of Lewis acidic boron compounds. The "Chemistry of Boronic and Borinic Acids" is dealt with cursorily by *K. Torsell*, and in conclusion, *R. Schaeffer* gives a convincing demonstration of the value of "Nuclear Magnetic Resonance Spectroscopy of Boron Compounds" in clarifying structural questions.

The quality of the contributions is variable, and it is to be hoped that the editors will be less lenient in the selection of topics and in the coordination of the essays in future volumes. The reports in this first volume will undoubtedly be attractive to all boron chemists, but the book will probably not appeal to a broader readership, *e.g.* advanced students, as suggested on the dustcover. This circumstance is aggravated by the high cost of the volume, which is of de luxe quality. In effect, most of the chapters offer too little information for specialists but too much for others, and thus the question arises whether it is sensible to publish progress reports on individual elements in the form of a series.

H. Nöth [NB 359/217 IE]

The Solvent Extraction of Metal Chelates. By *Jiří Starý*. English edition edited by *H. Irving*. Pergamon Press, Oxford-London-Edinburgh-New York-Paris-Frankfurt 1964. 1st edit. XIV + 240 pp., 46 figs., 31 tables, linen £3.0.0 (about $ 8.30).

The author of this book works in the Department of Nuclear Chemistry of the University of Prague (Czechoslovakia). His book, which is introduced by a foreword by *H. Irving*, Leeds (England), differs in many aspects from other monographs on the analytical applications of extraction of chelates and even supplements them; it is therefore most useful.

The work opens from a very general standpoint, the first few chapters dealing with the theory of metal chelates and their partition between water and an organic solvent (50 pp.); the properties and possible applications of numerous chelating agents are then described (128 pp.), and in conclusion, methods for the selective extraction of about 50 metals are given in highly condensed form (16 pp.).

A long list of publications (25 pp.) contains numerous references which are not easily accessible in the western world. Despite its length, the list is not exhaustive; for instance, no mention is made of the dialkyl phosphates, although the corresponding dithio compounds are discussed. The theoretical section is difficult to read and is not well written from a didactic point of view, for often important premises for derivations, tables, and figures are not mentioned. Apart from these flaws, the worker in this field will find a great many incentives in this book.

Werner Fischer [NB 404/262 IE]

New Biochemical Separations. Edited by *A. T. James* and *L. J. Morris*. van Nostrand, London-Toronto-New York-Princeton, N. J., 1964. 1st edit., IX + 424 pp., numerous illustrs. and tables, linen £4.4.0 (about $ 11.75).

The two editors, who are members of the Unilever research team at Sharnbrook (England), here wish to give a survey of the methods of separating some natural products that have been newly developed or decisively improved in the past decade. The authors generally have participated actively in these advances. The result is a vivid, up-to-date presentation by competent authorities. Obviously the topics dealt with have been stringently limited, and hence a readily surveyable, well organized presentation of the material has resulted.

The work begins with a review of the methods that can be used to detect radioactively labelled substances emerging from gas chromatographic separations. Each of the remaining 16 chapters – of varying length – deals mainly with the application of a method of separation to a single class of substances. The main emphasis is placed on applications of gas chromatography (A), thin-layer chromatography (B), and gel filtration (C) to the separation of steroids (methods A and B), alkaloids (A and B), carbohydrates (A and C), fatty acids (A), gall acids (A and B), amino acids (A, B, and C), proteins and peptides (B and C), triterpenes (B), and lipids (B). New separatory methods have led to great advances in the chemistry of fats and allied compounds, and hence a separate chapter on paper and partition chromatography is devoted to each of these classes of substances. In keeping with the interests of the editors, fats and allied materials receive the closest attention of all the compounds in the book.

The book has 148 figures, including numerous reproductions of original thin-layer chromatograms, and 76 tables and is therefore of exquisite appearance. It contains a wealth of information on the behavior of biologically interesting substances during the separatory operations mentioned above, well expressed in numerical or graphic form. Perhaps only the title of the book is somewhat inaccurate; perhaps it ought to have been called "A Selection of Modern Methods for Separating Natural Products".

H. Determann [NB 371/229 IE]

An Introduction to the Chemistry of Carbohydrates. By *R. D. Guthrie* and *J. Honeyman*. Claredon Press, Oxford 1964. 2nd edit., VI + 144 pp., linen £1.1.0 (about $ 3.–).

This little textbook maintains the aim of its first edition, which appeared 16 years ago, namely to give an introduction to the chemistry of carbohydrates in a highly compact form. The original organization of the material has been preserved, but every chapter has been brought fully up to date. New sections are included on the conformations of monosaccharides and the application of physical methods.

The didactically skillful development of the subject matter and the clear and concise style have resulted in a presentation which is easy to read, despite the vast amount of factual information it contains, particularly because the graphic representation of the formulae given are in accordance with the latest developments in this field. An especially valuable feature of the book is that it deals with the principles of conformation, not as usual in a separate chapter, but by introducing them in the ordinary text whenever they become of importance for the stereochemical interpretation of the course of a reaction.

The book can be recommended not only to students as an introductory text, but also to those who wish to inform themselves rapidly on the latest developments in carbohydrate chemistry.

F. W. Lichtenthaler [NB 376/234 IE]

Comprehensive Biochemistry. Edited by *M. Florkin* and *E. H. Stotz*. Vol. 12: Enzymes. General Considerations. Section III: Chemistry of Biological Compounds. Elsevier Publishing Co., Amsterdam-London-New York 1964. 1st edit., XII + 304 pp., numerous illustrs. and tables, linen DM 47.50 (about $ 12.00).

The third section of this comprehensive textbook [1] contains discussions of the mechanisms of enzymatic reactions. In accordance with the overall planning of the book, here too individual facts are reported only after the regularities derived from them have been outlined. Because of this deductive presentation, many facts may be missed by some readers, but this system has the great advantage that widely dispersed results are dealt with together. This offers great benefits, particularly in the discourse on the relationships between structure and reactivity. The first volume contains fundamental chapters explaining general aspects of enzymatic reactions. However, some of the text requires concentrated study and demands considerable previous knowledge – but not more than may be reasonably expected for use of a text book with the aims of the present series. In addition, the abstract nature of the deductive presentation is comfortably modified by intermittent sections on methods and their biochemical applications, together with instructive examples. in the fundamentals of the modes of reaction of enzymes in The firm foundations of modern enzymology are to be found aspects such as their stereochemistry (*Hirschmann*) and their reactivities, considered from the thermodynamic (*Wurmser-Banerjee*) and kinetic (*Dawes*) viewpoints, which are treated here with equal elegance. Redox potentials (*Wurmser-Banerjee*) and the effects of complex formation with metals on enzymatic activity (*Vallee*) are important topics which are given individual treatment. The connections between enzyme structure and function are particularly well investigated for ribonuclease and chymotrypsin and are reviewed in exemplary fashion by *Hirs*. His chapter simultaneously illustrates the methods of acquiring and interpreting kinetic data, which were discussed on a general basis in the preceding sections. This coordination is particularly fortunate. Although we are still far from knowing any common denominator for enzymatic functions, a few general theories of enzymatic catalysis can be conceived (*Wilson*); these include the hypothesis of induced fit, the formation of a reactive transition state in the enzyme-substrate complex (*Reiner*), and the course of reactions in enzyme-bonded steps. All the sections give a thorough, stimulating interpretation on a high standard and by clever overlapping cover the entirety of this vast field. Both the authors and editors have again done a good job and developed the tools for following the modern developments in molecular and dynamic biochemistry.

L. Jaenicke [NB 381/239 IE]

[1] Cf. Angew. Chem. *76*, 868 (1964).

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New Products of Reaction of Organometallic Compounds with Sulfur, Selenium, Tellurium, and Phosphorus

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Bond fission of molecular sulfur, selenium, and tellurium by lithiotriphenylmetal compounds (of Ge, Sn, Pb) is summarized. The products are suitable as starting materials for synthesis of new "ether analogues". Transphenylation with tetraphenylstannane is interpreted as a high-temperature variant of the usual fission of chalcogen molecules by nucleophilic reagents. In principle, transphenylation can be applied also to other elements, as is illustrated for phosphorus. In the syntheses achieved, many of the tin-phosphorus compounds arising as intermediates can be isolated.

I. Introduction

The strikingly easy fission, by nucleophilic reagents, of sulfur-sulfur bonds in compounds ("modifications") of sulfur with itself and in sulfane chains has been ascribed by us to a marked tendency of the sulfur atom to expand its octet, thereby forming multiple bonds between sulfur atoms. The stability and behavior of such sulfur-sulfur bonds, and the appearance of favored electrophilic centers in sulfur chains, are readily interpreted in terms of this assumption of a delocalized electron system[1]. This hypothesis provides a simple explanation of the formation of fission products of sulfur $(S)_x$ by nucleophilic reagents such as SO_3H^-, SH^-, SR^-, CN^-, $RC\equiv C^-$, NO_2^-, $HAsO_3^{2-}$, NR_2^-, *etc.* Such fission reactions of S–S bonds have not only analytical but also considerable preparative importance; they can be rationally extended to the sulfur homologues selenium and tellurium.

Among the particularly good "thiophilic" reagents are carbanions such as occur in organolithium and Grignard compounds. Molecular sulfur reacts spontaneously with these carbanions, yielding mercaptides or thiophenoxides. We asked ourselves whether analogous reactions could be carried out with compounds that are formally derived from organometallic compounds in that the metalated carbon atom is replaced by germanium, tin, or lead. The expected covalent chalcogen compounds should be very reactive and should open a simple preparative route to the little investigated field of organometallic derivatives (with germanium, tin, or lead) of chalcogens.

[1] *M. Schmidt*, Österr. Chemiker-Ztg. *64*, 236 (1963).

II. Chalcogen Fission by Lithiotriphenyl-germane, -stannane, and -plumbane

The formation of formal analogues of triphenylmethyllithium by replacement of the tertiary carbon atom by Ge, Sn, or Pb is illustrated by the well-known lithiotriphenylstannane[2–19]. This is best prepared by treat-

[2] *C. A. Kraus* and *W. V. Session*, J. Amer. chem. Soc. *47*, 2361 (1925).

[3] *R. F. Chambers* and *P. C. Scherrer*, J. Amer. chem. Soc. *48*, 1054 (1926).

[4] *C. A. Kraus* and *S. L. Forster*, J. Amer. chem. Soc. *49*, 457 (1927).

[5] *C. A. Kraus* and *W. H. Kahler*, J. Amer. chem. Soc. *55*, 3537 (1933).

[6] *H. Gilman* and *R. V. Joung*, J. org. Chemistry *1*, 315 (1963).

[7] *G. Wittig*, *R. Mangold*, and *G. Felletschin*, Liebigs Ann. Chem. *560*, 116 (1940).

[8] *G. Wittig* and *F. J. Meyer*, Liebigs Ann. Chem. *571*, 167 (1951).

[9] *H. Gilman* and *S. D. Rosenberg*, J. Amer. chem. Soc. *74*, 531 (1952).

[10] *H. Gilman*, *L. Summes*, and *R. W. Leeper*, J. org. Chemistry *17*, 630 (1952).

[11] *H. Gilman* and *E. Bindschadler*, J. org. Chemistry *18*, 1675 (1953).

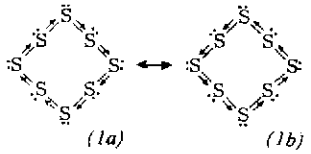
[12] *H. Gilman* and *C. A. Gerow*, J. Amer. chem. Soc. *77*, 5509, 5740 (1955).

ing chlorotriphenylstannane with an excess of lithium in tetrahydrofuran [18,19]; the primary product, formed according to Eq. (a), is hexaphenyldistannane, which is then more slowly cleaved according to Eq. (b).

$$2\,(C_6H_5)_3SnCl + 2\,Li \rightarrow (C_6H_5)_3Sn{-}Sn(C_6H_5)_3 + 2\,LiCl \quad (a)$$

$$(C_6H_5)_3Sn{-}Sn(C_6H_5)_3 + 2\,Li \rightarrow 2\,(C_6H_5)_3SnLi \quad (b)$$

Germanium [20] and lead compounds [21] can be similarly obtained. These reactive "metal organyls" R_3MLi have not yet been isolated in pure free form. However, their solutions in tetrahydrofuran can be readily obtained on removal of lithium chloride and the excess of lithium under dry nitrogen. Even under mild conditions the compounds R_3MLi (M = Ge, Sn, or Pb) react exactly like carbanions with sulfur, selenium, and tellurium in tetrahydrofuran, moisture being excluded. This reaction [see Scheme (c)] can be illustrated for tin/sulfur. The bonding in the S_8 ring is symbolized as in structures *(1a)* and *(1b)*. One of the electronically equivalent but



(1a) *(1b)*

still electrophilic sulfur atoms in the S_8 ring is attacked by, *e.g.*, the nucleophilic $SnR_3^{\ominus}$ anion (R = C_6H_5), whereby ring cleavage leads to the octasulfane derivative *(2)*. This unsymmetrical anion *(2)* is then degraded

$$R_3Sn{-}S{-}S{-}S{-}S{-}S{-}S{-}S{-}S^{\ominus} \rightarrow R_3Sn{-}S{-}S_5{-}S^{\ominus} + R_3SnS^{\ominus}$$
(2) $+ {}^{\ominus}\overset{\uparrow}{S}nR_3$

$$R_3Sn{-}S{-}S_5{-}S^{\ominus} \rightarrow R_3Sn{-}S{-}S_4{-}S^{\ominus} + R_3SnS^{\ominus}$$
$+ {}^{\ominus}\overset{\uparrow}{S}nR_3$

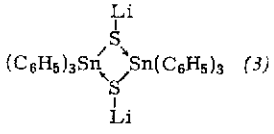
etc. (c)

$$R_3Sn{-}S{-}S^{\ominus} \rightarrow R_3SnS^{\ominus} + R_3SnS^{\ominus}$$
$+ {}^{\ominus}\overset{\uparrow}{S}nR_3$

$$S_8 + 8\,LiSnR_3 \rightarrow 8\,Li{-}S{-}SnR_3$$

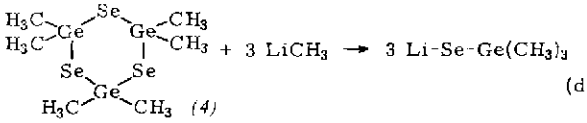
stepwise by an S_N2 mechanism: the ion $SnR_3^{\ominus}$, acting as nucleophile, attacks the electrophilic center, namely the terminal S atom with its formal octet [the negative charge is equally distributed over the $R_3Sn{-}(S)_x{-}$ chain], and ejects the weaker nucleophilic group $R_3SnS_{x-1}^{\ominus}$. In each cleavage step, down to x = 1, a new (terminal) electrophilic center is created. The first step – ring-opening – is rate-determining since it involves a formal electron decet; the further steps involve formal octets.

Selenium and tellurium react in principle like sulfur. Thus, solutions of R_3MXLi (R = C_6H_5; M = Ge, Sn, or Pb; X = S, Se, or Te) [19,21–24] in tetrahydrofuran can be obtained fairly easily. As expected, compounds R_3MXLi are sensitive to solvolysis, oxidation, and elevated temperature (condensation: $2\,R_3MSLi \rightarrow R_3M{-}S{-}MR_3 + Li_2S$) and thus can be isolated only with difficulty, if at all. Up to the present, only triphenyltin-lithium sulfide has been actually isolated [19]; it forms colorless crystals and is dimeric in benzene, probably forming a four-membered ring *(3)*. Isolation is not necessary if the compounds R_3MXLi are to be used for syntheses that can be carried out in tetrahydrofuran (see Section III).



(3)

It has not yet been possible to synthesize trimethylgermanyl-lithium chalcogenides corresponding to t-butyl mercaptides by the above procedure because the lithiotrimethylgermane, $(CH_3)_3GeLi$, needed as starting material is not yet available. *Ruidisch* [25] prepared trimethylgermanyl-lithium chalcogenides in a different way: dichlorodimethylgermane and triethylammonium sulfide in benzene solution afford the cyclic, trimeric dimethylgermanium sulfide; the corresponding selenide, $[(CH_3)_2GeSe]_3$ *(4)*, is formed from sodium selenide [26]. These cyclic inorganic compounds are smoothly and quantitatively cleaved by methyl-lithium, yielding the desired "mercaptides" according to reaction (d).



(d)

(4)

$(CH_3)_3GeSLi$ [25] (decomp. ≈ 85 °C) and $(CH_3)_3GeSeLi$ [27] (decomp. ≈ 65 °C) can be obtained as colorless solids. $(C_6H_5)_2SnCl_2$ reacts with lithium, in principle like

[13] *H. Gilman, D. J. Peterson,* and *D. Wittenberg,* Chem. and Ind. 1479 (1958).

[14] *H. Gilman* and *D. Wittenberg,* J. org. Chemistry *23,* 1063 (1958).

[15] *H. Gilman* and *G. D. Lichtenwalter,* J. Amer. chem. Soc. *80,* 608 (1958).

[16] *C. Tamborski, F. E. Ford,* and *W. L. Lehn,* J. org. Chemistry *27,* 619 (1962).

[17] *H. Gilman, O. L. Marrs,* and *S. J. Sim,* J. org. Chemistry *27,* 4232 (1962).

[18] *H. Schumann, K. F. Thom,* and *M. Schmidt,* Angew. Chem. *75,* 138 (1963); Angew. Chem. internat. Edit. *2,* 99 (1963).

[19] *H. Schumann, K. F. Thom,* and *M. Schmidt,* J. organomet. Chemistry *1,* 167 (1963).

[20] *M. C. Henry* and *W. E. Davidson,* J. org. Chemistry *27,* 2252 (1962).

[21] *M. C. Henry* and *A. W. Krebs,* J. org. Chemistry *28,* 225 (1963).

[22] *H. Schumann, K. F. Thom,* and *M. Schmidt,* J. organomet. Chemistry *4,* 22 (1965).

[23] *H. Schumann, K. F. Thom,* and *M. Schmidt,* J. organomet. Chemistry *2,* 361 (1964).

[24] *H. Schumann, K. F. Thom,* and *M. Schmidt,* J. organomet. Chemistry *4,* 28 (1965).

[25] *I. Ruidisch* and *M. Schmidt,* Chem. Ber. *96,* 1424 (1963).

[26] *M. Schmidt* and *H. Ruf,* J. inorg. nuclear Chem. *25,* 557 (1963).

[27] *I. Ruidisch* and *M. Schmidt,* J. organomet. Chemistry *1,* 160 (1963).

$(C_6H_5)_3SnCl$, yielding $(C_6H_5)_2SnLi_2$ (not isolated), which with sulfur affords the unusually sensitive and reactive $(C_6H_5)_2Sn(SLi)_2$ [28].

III. Condensation of Chalcogen Cleavage Products with Organylmetal Halides

As expected, the organylmetal chalcogenides described above (which, however, were not all isolated in substance) are very reactive. Their interesting properties can be illustrated by their behavior with triorganylmetal chlorides of the germanium, tin, and lead series. In solution they react readily, forming symmetrical and unsymmetrical formal analogues of thio-, seleno-, and telluro-ethers according to reaction (e).

$$R_3MX{-}Li + Cl{-}M'R_3 \rightarrow LiCl + R_3M{-}X{-}M'R_3 \qquad (e)$$

$R = C_6H_5$ or CH_3; M, M' = Ge, Sn, or Pb; X = S, Se, or Te

This reaction opens a simple preparative route to a class of compounds of which only a few representatives have been synthesized, by a considerably more circuitous method. No covalent germanium-, tin-, or lead-tellurium compound has been described previously. Table 1 summarizes the compounds obtained by reaction (e).

Other reactive halogen compounds behave analogously, as shown by the synthesis of *SS*-diphenyltin bis(thiobenzoate) *(5)* [28].

$$(C_6H_5)_2Sn(SLi)_2 + 2\ Cl{-}C(=O){-}C_6H_5 \rightarrow 2\ LiCl + C_6H_5{-}C(=O){-}S{-}Sn(C_6H_5)_2{-}S{-}C(=O){-}C_6H_5 \quad (5)$$

The hexaphenyl compounds listed in Table 1 all crystallize readily; the sulfur compounds are colorless, the selenium compounds have a yellow tinge, and the tellurium compounds are yellow. They are readily soluble in anhydrous organic solvents such as benzene, dioxane, tetrahydrofuran, and chloroform. Particularly noteworthy is their thermal stability and, in many cases, their resistance to solvolysis.

Table 1. "Ether analogues" prepared by double decomposition according to reaction (e).

Compound	M.p. [°C]	Ref.
$(C_6H_5)_3Ge{-}S{-}Ge(C_6H_5)_3$	138	[20]
$(C_6H_5)_3Ge{-}S{-}Sn(C_6H_5)_3$	137	[19]
$(C_6H_5)_3Ge{-}S{-}Pb(C_6H_5)_3$	129	[22]
$(C_6H_5)_3Sn{-}S{-}Sn(C_6H_5)_3$	144	[29]
$(C_6H_5)_3Sn{-}S{-}Pb(C_6H_5)_3$	138	[19]
$(C_6H_5)_3Pb{-}S{-}Pb(C_6H_5)_3$	140	[30]

Compound	M.p. [°C]	Ref.
$(C_6H_5)_3Ge{-}Se{-}Ge(C_6H_5)_3$	151	[22]
$(C_6H_5)_3Ge{-}Se{-}Sn(C_6H_5)_3$	145	[23]
$(C_6H_5)_3Ge{-}Se{-}Pb(C_6H_5)_3$	119	[22]
$(C_6H_5)_3Sn{-}Se{-}Sn(C_6H_5)_3$	148	[31, 32]
$(C_6H_5)_3Sn{-}Se{-}Pb(C_6H_5)_3$	138	[23]
$(C_6H_5)_3Pb{-}Se{-}Pb(C_6H_5)_3$	101	[24]

Compound	M.p. [°C]	Ref.
$(C_6H_5)_3Ge{-}Te{-}Ge(C_6H_5)_3$	120 (decomp.)	[22]
$(C_6H_5)_3Ge{-}Te{-}Sn(C_6H_5)_3$	145	[22]
$(C_6H_5)_3Ge{-}Te{-}Pb(C_6H_5)_3$	117	[22]
$(C_6H_5)_3Sn{-}Te{-}Sn(C_6H_5)_3$	150	[23]
$(C_6H_5)_3Sn{-}Te{-}Pb(C_6H_5)_3$	136 (decomp.)	[23]
$(C_6H_5)_3Pb{-}Te{-}Pb(C_6H_5)_3$	129	[24]

Compound	M.p. [°C]	B.p. [°C/mm]	Ref.
$(CH_3)_3Ge{-}S{-}Ge(CH_3)_3$	−22	68/12	[25]
$(CH_3)_3Ge{-}S{-}Si(CH_3)_3$	−27	63/10	[25]
$(CH_3)_3Ge{-}S{-}Sn(CH_3)_3$	−8	90/12	[25]
$(CH_3)_3Ge{-}Se{-}Ge(CH_3)_3$	−12	94/12	[27]
$(CH_3)_3Ge{-}Se{-}Si(CH_3)_3$	−19	79/12	[27]
$(CH_3)_3Sn{-}Se{-}Sn(CH_3)_3$	−6	72/1	[27]

Final statements cannot yet be made about the bonding in molecules of the type $R_3M{-}X{-}MR_3$. Help should come from X-ray determination, now in progress, of the valence angles at the chalcogen atom, about which information will also be provided by further evaluation of the infrared spectra [34] – these are almost identical in the NaCl region. Skeletal vibrations of the sulfur compounds occur between 250 and 400 cm^{-1} (CsBr region); their assignment is given in Table 2. Corresponding bands are to be expected at still longer wavelengths for the Se and Te compounds.

The stability of Si–O–Si bonds, which is so important in inorganic Nature, is ascribed to a noteworthy contribution by $(p{-}d)_\pi$ bonding between oxygen and

Table 2. Wave-numbers [cm^{-1}] of M–S vibrations of hexaphenyl sulfides [*]. (For clarity the phenyl and phenyl-metal vibrations are not included; st = strong, m = medium).

Assignment	Ge–S–Ge	Sn–S–Sn	Pb–S–Pb	Ge–S–Sn	Ge–S–Pb	Sn–S–Pb
ν_{as} (Ge–S–Ge)	417 st					
ν_{as} (Sn–S–Sn)		376 st				
ν_{as} (Pb–S–Pb)			336 st			
ν(Ge–S)				404 m	400 m	
ν(Sn–S)				355 m		365 m
ν(Pb–S)					317 m	305 m
ν_s(Ge–S–Ge)	385 m					
ν_s(Sn–S–Sn)		330 m				
ν_s(Pb–S–Pb)			278 m			

[*] Perkin-Elmer Model 221, CsBr optics, in Nujol suspension.

[28] *H. Schumann, K. F. Thom,* and *M. Schmidt,* J. organomet. Chemistry *2,* 97 (1964).

[29] *R. K. Ingham, S. D. Rosenberg,* and *H. Gilman,* Chem. Reviews *60,* 459 (1960).

[30] *G. Grüttner,* Chem. Ber. *51,* 1303 (1918).

[31] *M. Schmidt* and *H. Ruf,* Angew. Chem. *73,* 64 (1961).

[32] *M. Schmidt* and *H. Ruf,* Chem. Ber. *96,* 784 (1963).

[33] *H. Schumann* and *M. Schmidt,* unpublished work.

[34] *H. Schumann* and *M. Schmidt,* J. organomet. Chemistry *3,* 485 (1965).

silicon. If the bridging oxygen atom of disiloxanes is replaced by the larger sulfur atom the stability decreases drastically: Si–S bonds are extremely susceptible to hydrolysis. However, study of the new chalcogen derivatives $R_3M–X–MR_3$ of Table 1 shows that the stability increases on simultaneous increase in the size of the bridgehead atom M and the bridging atom X: the grouping Ge–S–Ge is more stable than Ge–O–Ge, although Ge–Se–Ge is, on the contrary, very sensitive to hydrolysis. Again, Sn–Se–Sn compounds do not react with water and can even be recrystallized from alcohol. Thus the relations between Sn–Te–Sn and Sn–Se–Sn groupings are similar to those between Si–S–Si and Si–O–Si groupings. In consequence the Pb–Te–Pb grouping is again very stable; the hexaphenyl derivative is not attacked even by boiling water.

Analogous observations were made for unsymmetrical "ethers." For example, Ge–Se–Pb and Sn–Te–Pb linkages resist hydrolysis, whereas compounds with Ge–Se–Ge and Sn–Te–Sn groups can be handled only in an anhydrous atmosphere. The hexamethyl compounds have similar properties.

Ascribing these findings to the $(p–d)_\pi$ constituents of the M–X–M linkages for the heavier elements (given suitable size relations in M:X), although seeming at first sight a plausible interpretation, is certainly too primitive because d-the very small energy contribution from overlap of of orbitals of the heavier atoms.

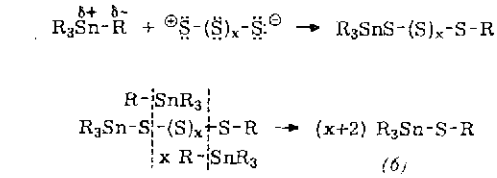
IV. Phenylation of Chalcogens by Tetraphenylstannane

Bond fission of molecular sulfur by nucleophilic reagents occurs under quite mild conditions [1]. Relations are apparently quite different if tetraphenylstannane is treated with sulfur. $Sn(C_6H_5)_4$ is one of the most stable organometallic compounds; it can, for example, be heated for several hours at about 500 °C (b.p. 425 °C/760 mm) without decomposing. Nevertheless it reacts with sulfur at as low a temperature as 200 °C. As early as 1929 *Bost* and *Borgstrom* [35] observed that diphenyl sulfide is thus formed, but, remarkably, they did not study the fate of the tin in this reaction.

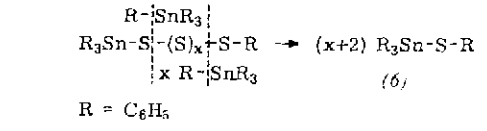
We have found [36] that the reaction takes place in a sealed tube at about 200 °C, according to the overall equation (f). At this temperature, SnR_4 is polarized by

$$3\ Sn(C_6H_5)_4 + 6\ S \rightarrow 3\ S(C_6H_5)_2 + [(C_6H_5)_2SnS]_3 \qquad (f)$$

the "polar solvent" sulfur [*] in such a way ($R_3\overset{\delta+}{Sn}–\overset{\delta-}{R}$) that a phenyl anion is foreshadowed and then, as a nucleophilic reagent, degrades the sulfur chain as shown in reactions (g). The degradation there outlined – without statement of the electron distribution in the sulfur chain – occurs analogously to Scheme (c). The triphenyltin thiophenoxide *(6)* [36] to be expected from reactions (g) is unstable at 200 °C and can therefore not be isolated. The degradation thus proceeds further in accordance with Scheme (h).

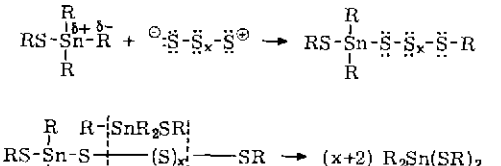


(g)

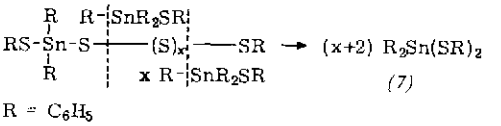


(6)

$R = C_6H_5$



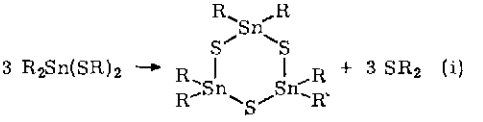
(h)



(7)

$R = C_6H_5$

Diphenyltin dithiophenoxide *(7)*, which has been prepared by a different route [36], decomposes appreciably below the reaction temperature, eliminating diphenyl sulfide to give diphenyltin sulfide (formally analogous to the silico-ketones = silicones) which is not stable as monomer and yields the trimer *(7)*.



(i)

(8)

Good yields can be obtained of the products of sulfur-degradation, during which process the degrading agent is first formed from a reaction partner that has a polarizing action at high temperatures. Tin-sulfur six-membered rings are very stable; they are not attacked by boiling water. These compounds crystallize readily and are soluble in many organic solvents. If $Sn(C_6H_5)_4$ is treated with a sufficient excess of sulfur, further phenyl anions are removed and high-polymeric products are formed in which rings *(8)* are linked by sulfur bridges [37]. A temperature in excess of 220 °C leads – in principle by the same mechanism – to complete dephenylation of the tin compound, with formation of diphenyl sulfide and alloy-like "tin sulfides" which are also obtainable from the cyclic compounds *(8)* and the higher-polymeric subsequent products:

$$(R_2SnS)_3 + 3x\ S \rightarrow 3\ SnS_x + 3\ R_2S$$

(8)

Tetrabutylstannane – and the alkyl derivatives in general – react with sulfur even at lower temperatures. At as low as approximately 150 °C, reaction (k) occurs (for reaction of organyltin chlorides with sulfur see [38]).

$$3\ (C_4H_9)_4Sn + 6\ S \rightarrow [(C_4H_9)_2SnS]_3 + 3\ (C_4H_9)_2S \qquad (k)$$

[35] *R. W. Bost* and *P. Borgstrom*, J. Amer. chem. Soc. *512*, 192 (1929).

[36] *M. Schmidt*, *H. J. Dersin*, and *H. Schumann*, Chem. Ber. *95*, 1428 (1962).

[*] Above the viscosity maximum at *ca.* 160 °C a sulfur melt has clearly a polarizing action, owing to the presence of some $^{\oplus}S–(S)_x–S:^{\ominus}$.

[37] *M. Schmidt* and *H. Schumann*, Chem. Ber. *96*, 462 (1963).

[38] *H. Schumann* and *M. Schmidt*, Chem. Ber. *96*, 3017 (1963).

Because of the lesser polarity of their "metal"-carbon bond, tetraphenyl derivatives of the lighter analogues of tin react only at higher temperatures [*]; the intermediates are no longer stable. $Ge(C_6H_5)_4$ affords GeS_x and diphenyl sulfide above 270 °C [39], and $Si(C_6H_5)_4$ affords SiS_x above 380 °C [39]. The higher reactivity of the n-butyl compounds, on the other hand, still permits isolation of trimeric, cyclic dibutylgermanium sulfide [analogous to *(8)*] and $(C_4H_9)_3Si-S-Si(C_4H_9)_3$, in addition to $(n\text{-}C_4H_9)_2S$, these products being formed by transalkylation [39].

Selenium is also phenylated by tetraphenyltin at about 200 °C. Triphenyltin selenophenoxide *(9)* [**] is isolated in good yield as intermediate [40]. Above 240 °C

$$x\,(C_6H_5)_4Sn + (Se)_x \rightarrow x\,(C_6H_5)_3Sn\text{-}SeC_6H_5 \quad (9)$$

diphenylselenium (and some R_2Se_2) are formed alongside tin selenides, and above 270 °C also selenanthrene [cf. formula *(11)*]. $Sn(C_4H_9)_4$, however, reacts at 200 °C with selenium [40] according to Equation (l), analogously

$$3\ R_4Sn + 6\ Se \rightarrow \text{(10)} + 3\ R_2Se \quad (1)$$

R = C_4H_9

(10)

to sulfur. The corresponding phenyl derivative was obtained on treatment of $R_3Sn-SeLi$ with R_2SnCl_2 [23], in accordance with reaction (m).

$$2\ R_3Sn\text{-}SeLi + R_2SnCl_2 \xrightarrow[-2\ LiCl]{} R_3Sn\text{-}Se\text{-}\underset{\displaystyle R}{\overset{\displaystyle R}{Sn}}\text{-}Se\text{-}SnR_3$$

$$\rightarrow \tfrac{1}{3}\,(R_2SnSe)_3 + R_3Sn\text{-}Se\text{-}SnR_3 \quad (m)$$

R = C_6H_5

Reaction between tellurium and tetraphenyltin sets in, slowly, only above 240 °C; after several days it leads to good yields of diphenyltellurium and tin tellurides [41]. If the temperature is raised above 310 °C, there is formed the previously undescribed and remarkably air-sensitive telluranthrene *(11)* (m.p. 188–190 °C), as well as benzene.

$$(C_6H_5)_4Sn + 2x\ Te \rightarrow SnTe_{2x-2} + 2\ C_6H_6 + \text{(11)}$$

(11)

[*] $Pb(C_6H_5)_4$ probably reacts by a free-radical mechanism [39].

[39] *M. Schmidt* and *H. Schumann*, Z. anorg. allg. Chem. *325*, 130 (1963).

[**] Existence of the sulfur analogue $(C_6H_5)_3Sn\text{-}SC_6H_5$ has been only inferred.

[40] *M. Schmidt* and *H. Schumann*, Chem. Ber. *96*, 780 (1963).

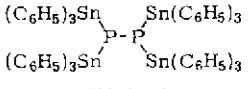
[41] *M. Schmidt* and *H. Schumann*, Z. Naturforsch. *19b*, 74 (1964).

V. Phenylation of Phosphorus by Tetraphenylstannane

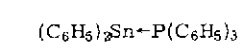
The hypothesis developed [1] for element-element bonding in sulfur chemistry is valid equally for other elements from the second Period onwards, and for those of the third and fifth main Group. Compounds of these elements with themselves act electrophilically, as do the chalcogens (cf. the reaction of P_4 with Grignard reagents discovered independently by *Rauhut* and *Semsel* [42] and by us [33]). Thus phosphorus should, like sulfur, react with tetraphenylstannane at high temperatures. The tervalency of phosphorus, of course, complicates matters and makes a direct comparison more difficult. In practice, elementary phosphorus reacts with tetraphenylstannane in a sealed tube above about 235 °C. At higher temperatures the end products are tin phosphide and triphenylphosphine, according to reaction (n) [43, 44].

$$3\ Sn(C_6H_5)_4 + 4\ P_n \rightarrow Sn_3P_{n-4} + 4\ P(C_6H_5)_3 \quad (n)$$

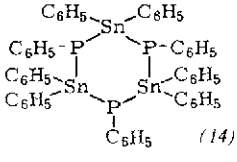
(The triphenyl derivatives of As and Sb are also readily available by this process [44].) If the temperature is kept between 235 and 250 °C and the ratio $P:Sn(C_6H_5)_4$ is varied, an intermediate product of the degradation of phosphorus by carbanions can be isolated: *(12)* (m.p. ≈110 °C, yellow, spontaneously inflammable in air), *(13)* (yellow oil, extremely sensitive to oxidation), *(14)* (m.p. 66 °C, colorless).



(12) [45]



(13) [46]



(14) [45]

Covalent tin-phosphorus compounds which, with two exceptions [47, 48], were previously unknown, generally are extremely sensitive to oxidation, which greatly increases the difficulty of isolating them from the complex reaction mixture. The products of oxidation of the tin phosphines occurring in these mixtures can, however, be obtained, cleaved with caustic soda into characteristic fragments, and thus analysed [*]. Table 3 shows the oxidized decomposition products obtained.

[*] Tin was determined [49] by X-ray emission analysis, alongside photometrically determined phosphorus.

[42] *H. Rauhut* and *P. Semsel*, J. org. Chemistry *28*, 473 (1963).

[43] *H. Schumann*, *H. Köpf*, and *M. Schmidt*, Angew. Chem. *75*, 672 (1963); Angew. Chem. internat. Edit. *2*, 546 (1963).

[44] *H. Schumann*, *H. Köpf*, and *M. Schmidt*, Z. anorg. allg. Chem. *331*, 200 (1964).

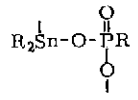
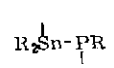
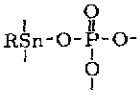
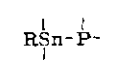
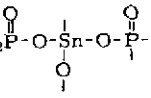
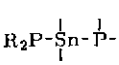
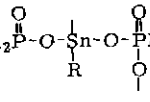
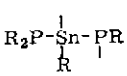
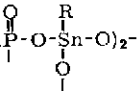
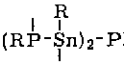
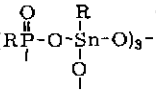
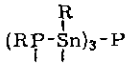
[45] *H. Schumann*, *H. Köpf*, and *M. Schmidt*, Chem. Ber. *97*, 1458 (1964).

[46] *H. Schumann*, *H. Köpf*, and *M. Schmidt*, Z. Naturforsch. *19b*, 168 (1964).

[47] *A. B. Brucker*, *F. B. Balashowa*, and *I. S. Soborovskii*, Dokl. Akad. Nauk SSSR *4*, 843 (1960).

[48] *W. Kuchen* and *H. Buchwald*, Chem. Ber. *92*, 227 (1959).

Table 3. Oxidation products isolated as secondary products from the reaction of $Sn(C_6H_5)_4$ with P_X between 235 and 260 °C (R = C_6H_5).

Fragments	Structural units of: tin phosphonate	Structural units of: original stannylphosphine
R_2SnO $RP(O)(OH)_2$		
$RSn(O)OH$ H_3PO_4		
SnO_2 $R_2P(O)OH$ H_3PO_4		
$RSn(O)OH$ $R_2P(O)OH$ $RP(O)(OH)_2$		
2 $RSn(O)OH$ 3 $RP(O)(OH)_2$		
3 $RSn(O)OH$ 3 $RP(O)(OH)_2$ H_3PO_4		

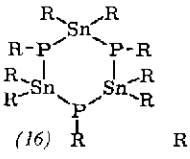
VI. Syntheses of Covalent Tin-Phosphorus Compounds

The above "direct synthesis" having shown that a variety of previously unknown tin-phosphorus compounds can exist, we wished to prepare such compounds systematically. Only phenyl groups were used to render the tin and phosphorus inert. Two series of compounds appeared suitable as models. The first is derived from triphenylphosphine by replacement of one, two, or all three phenyl groups by triphenyltin. The second is derived in the reverse direction from tetraphenylstannane, by replacement of one, two, three, or four phenyl groups by diphenylphosphino groups.

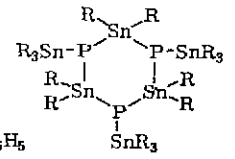
The first series of compounds is formed in tetrahydrofuran in good yield on reaction of lithiotriphenylstannane with appropriate phosphorus chlorides according to reaction (o)[50]. The colorless crystalline products *(15)* dissolve readily in anhydrous organic solvents.

$$n\,(C_6H_5)_3SnLi + (C_6H_5)_{3-n}PCl_n \rightarrow [(C_6H_5)_3Sn]_nP(C_6H_5)_{3-n} + n\,LiCl \quad (o)$$
(15)

However, the products *(15)* arise only if the phosphorus chloride is present in excess until the end of the reaction. Otherwise, the primary reaction products are cleaved by the strongly nucleophilic triphenyltin anion. In this way, although the reaction mechanism is not yet finally clarified, the cyclic compounds *(16)* (m.p. 60 °C)[49,50] and *(17)* (m.p. 101 °C)[50] are obtained in satisfactory yields alongside hexaphenyldistannane, triphenylphosphine, and lithium chloride.



(16) R = C_6H_5



The second series of compounds *(18)*[51] is formed in good yield by reaction (p). (Use of alkali-metal diphenylphosphides in place of the free phosphine leads to complications[52].) The compounds *(18)*, like the tin phosphines described above, crystallize readily and are soluble in organic solvents. Table 4 presents the organylstannylphosphines prepared by reactions (o) and (p) or, in the meanwhile, by other authors analogously[53] or from stannylamines[54].

$$(C_6H_5)_{4-n}SnCl_n + n\,HP(C_6H_5)_2 + n\,(C_2H_5)_3N \rightarrow (C_6H_5)_{4-n}Sn[P(C_6H_5)_2]_n + n\,(C_2H_5)_3N{\cdot}HCl \quad (p)$$
(18)

Table 4. Monomeric organylstannylphosphines.

Organylstannylphosphine	M.p. [°C]	B.p. [°C/mm]	Ref.
$(CH_3)_3Sn-P(C_6H_5)_2$		142/0.7	[53, 54]
$(C_2H_5)_3Sn-P(C_6H_5)_2$		168/0.7	[48, 53, 54]
$(C_2H_5)_3Sn-P(C_6H_5)C_2H_5$		100/0.2	[53]
$(C_2H_5)_3Sn-P(C_2H_5)_2$		70/0.2	[53]
$(C_3H_7)_3Sn-P(C_6H_5)_2$		177/0.6	[53]
$(C_3H_7)_3Sn-P(C_6H_5)(C_2H_5)$		126/0.3	[53]
$(C_4H_9)_3Sn-P(C_6H_5)_2$	96	192/0.6	[51, 53]
$(C_6H_5)_3Sn-P(C_6H_5)_2$	130		[50, 51, 53]
$(CH_3)_2Sn[P(C_6H_5)_2]_2$	114		[51]
$(C_4H_9)_2Sn[P(C_6H_5)_2]_2$	102		[51]
$(C_6H_5)_2Sn[P(C_6H_5)_2]_2$	80		[51, 53]
$C_6H_5Sn[P(C_6H_5)_2]_3$	117		[51]
$Sn[P(C_6H_5)_2]_4$	107		[51]
$[(C_6H_5)_3Sn]_2P-C_6H_5$	150		[50]
$[(C_6H_5)_3Sn]_3P$	201		[50]

This process is suitable also for the preparation of analogous germanium and lead compounds, *e.g.*, $(C_2H_5)_3Ge-P(C_6H_5)_2$ (b.p. 146 °C/10^{-3} mm)[55], $(C_6H_5)_3Ge-P(C_6H_5)_2$ (m.p. 108 °C)[33], $[(C_6H_5)_3Ge]_3P$ (m.p. 192 °C)[33], and $(C_6H_5)_3Pb-P(C_6H_5)_2$ (decomp. 100 °C)[56].

Covalent tin-phosphorus compounds are sensitive to oxygen (they do not react with oxygen-free water). The degree of this sensitivity depends considerably on the nature of the "shielding" organic radicals. Thus alkyl derivatives are, in general, less stable than the phenyl analogues. Tetrakis(diphenylphosphino)stannane on

[49] *C. Mahr, H. Klamberg,* and *G. Storck,* unpublished work.

[50] *H. Schumann, H. Köpf,* and *M. Schmidt,* Chem. Ber. *97,* 3295 (1964).

[51] *H. Schumann, H. Köpf,* and *M. Schmidt,* J. organomet. Chemistry *2,* 159 (1964).

[52] *H. Köpf,* Dissertation, Universität Marburg, 1963.

[53] *J. G. M. Campell, G. W. A. Fowles,* and *L. A. Nixon,* J. chem. Soc. (London) *1964,* 1389.

[54] *K. Jones* and *M. F. Lappert,* Proc. chem. Soc. (London) *1964,* 22.

[55] *F. Glockling* and *K. A. Hooton,* Proc. chem. Soc. (London) *1963,* 146.

[56] *H. Schumann, P. Schwabe,* and *M. Schmidt,* J. organomet. Chemistry *1,* 366 (1963/64).

the one hand and tris(triphenylstannyl)phosphine on the other react only slowly with air. The cyclic compounds are considerably more sensitive to oxygen. Unsymmetrical stannylphosphines can, however, be handled only in an oxygen-free atmosphere [*]. The oxidation occurs, in principle, according to reaction (q), either

$$\gtrless Sn\text{-}P\lessgtr + O_2 \rightarrow \gtrless Sn\text{-}O\text{-}\overset{\overset{O}{\uparrow}}{P}\lessgtr \qquad (q)$$

simply in air or, always quantitatively, with hydrogen peroxide in alcohol [50,51].

Infrared spectra [33] show that, with an excess of oxygen, one O atom first adds to the lone electron pair of phosphorus. Suppositions that this is the only and final reaction step [57] are contradicted by the experimental facts. It seems that the structure *(19a)* rearranges to *(19b)* in a reversal of the Arbusov rearrangement. Then a further oxygen atom adds to the phosphorus according to reaction (r), giving *(19c)*. The oxidation products of monomeric organylstannylphosphines are listed in Table 5.

$$\underset{(19a)}{\overset{\overset{O}{\uparrow}}{\gtrless Sn\text{-}P}} \rightarrow \underset{(19b)}{\gtrless Sn\text{-}O\text{-}\ddot{P}} \xrightarrow{\frac{1}{2}O_2} \underset{(19c)}{\gtrless Sn\text{-}O\text{-}\overset{\overset{O}{\uparrow}}{P}\lessgtr} \qquad (r)$$

Table 5. Oxydation products of organylstannylphosphines.

Organyltin phosphinate	M.p. [°C]	Ref.
$(CH_3)_3Sn{-}O{-}P(O)(C_6H_5)_2$	>360	[53]
$(C_2H_5)_3Sn{-}O{-}P(O)(C_6H_5)_2$	247	[53]
$(C_3H_7)_3Sn{-}O{-}P(O)(C_6H_5)_2$	226	[53]
$(C_4H_9)_3Sn{-}O{-}P(O)(C_6H_5)_2$	215	[51, 53]
$(C_6H_5)_3Sn{-}O{-}P(O)(C_6H_5)_2$	>360	[51, 53]
$(CH_3)_2Sn[O{-}P(O)(C_6H_5)_2]_2$	>250	[51]
$(C_2H_5)_2Sn[O{-}P(O)(C_6H_5)_2]_2$	372	[53]
$(C_4H_9)_2Sn[O{-}P(O)(C_6H_5)_2]_2$	>230	[51]
$(C_6H_5)_2Sn[O{-}P(O)(C_6H_5)_2]_2$	>250	[51]
$C_6H_5{-}Sn[O{-}P(O)(C_6H_5)_2]_3$	216	[51]
$Sn[O{-}P(O)(C_6H_5)_2]_4$	174	[51]
$[(C_6H_5)_3Sn{-}O{-}]_2P(O)C_6H_5$	>290	[50]
$[(C_6H_5)_3Sn{-}O{-}]_3P(O)$	150	[50]

[*] This has not always been taken into account, *e.g.*, when considering the infrared frequency data for $(C_6H_5)_3Sn{-}P(C_6H_5)_2$ and $(C_2H_5)_3Sn{-}P(C_6H_5)_2$ [53]. The bands found at 1130 and 750 cm^{-1}, and at 1145 and 760 cm^{-1}, respectively, are certainly P=O and Sn–O valence vibrations, respectively.

[57] *H. Schindlbauer* and *D. Hammer*, Mh. Chem. *94*, 644 (1963).

[58] *J. Lorberth* and *M. R. Kula*, Chem. Ber. *97*, 3444 (1964).

[59] *H. Schumann* and *M. Schmidt*, Angew. Chem. *76*, 344 (1964); Angew. Chem. internat. Edit. *3*, 316 (1964).

[60] *J. G. M. Campell, G. W. A. Fowles*, and *L. A. Nixon*, J. chem. Soc. (London) *1964*, 3026.

[61] *H. Schumann* and *M. Schmidt*, Chem. Ber., in press.

The new phosphinic esters can be cleaved, like the parent stannylphosphines, by hot sodium hydroxide solution to characteristic, readily detected fragments [50,51].

Questions about the nature of the (certainly covalent) bonding between the metal and phosphorus cannot yet be answered. Physical studies (infrared, Raman, crystal structure) should provide relevant information. Any considerable contribution from $(p{-}d)_\pi$ bonding, as required between Sn and P [53] and indeed between Sn and N [58] (2p and 5d orbitals), seems to us to be excluded by our results and by infrared and N.M.R. investigations. The same applies to the arsenic, antimony, and bismuth compounds [59, 60] listed in Table 6,

Table 6. Organylstannyl-, organogermanyl-, and organylplumbylarsines, -stibines, and bismuthines.

Compound	M.p. [°C]	B.p. [°C/mm]	Ref.
$(CH_3)_3Sn{-}As(C_6H_5)_2$		136/0.05	[54]
$(C_2H_5)_3Sn{-}As(C_6H_5)_2$		143/0.15	[60]
$(C_3H_7)_3Sn{-}As(C_6H_5)_2$		161/0.2	[60]
$(C_4H_9)_3Sn{-}As(C_6H_5)_2$		164/0.09	[60]
$(C_6H_5)_3Sn{-}As(C_6H_5)_2$	119		[61]
$(C_6H_5)_2Sn[As(C_6H_5)_2]_2$	80 (decomp.)		[61]
$C_6H_5Sn[As(C_6H_5)_2]_3$	85 (decomp.)		[61]
$Sn[As(C_6H_5)_2]_4$	70		[61]
$[(C_6H_5)_3Sn]_2As{-}C_6H_5$	115		[61]
$[(C_6H_5)_3Sn]_3As$	216		[59]
$(C_6H_5)_3Ge{-}As(C_6H_5)_2$	114		[61]
$(C_6H_5)_3Pb{-}As(C_6H_5)_2$	118 (decomp.)		[61]
$(C_2H_5)_3Sn{-}Sb(C_6H_5)_2$		146/0.18	[60]
$(C_3H_7)_3Sn{-}Sb(C_6H_5)_2$		170/0.13	[60]
$(C_4H_9)_3Sn{-}Sb(C_6H_5)_2$		180/0.15	[60]
$[(C_6H_5)_3Sn]_3Sb$	215		[59]
$[(C_6H_5)_3Sn]_3Bi$	138 (decomp.)		[59]

not discussed in this paper. The investigations to date show clearly, at any rate, that tin, germanium, and lead can, just like carbon, form stable electron-pair links with elements of the main Groups.

We are grateful to Dr. H. Köpf for collaboration and suggestions in the study of the sensitive Sn–P compounds, also to Dr. K. F. Thom for work on the tin chalcogenides. We thank Dr. H. Dersin and Miss T. Östermann for experimental help and the Fonds der Chemischen Industrie and the Deutsche Forschungsgemeinschaft for financial support.

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The Chemistry of Silicon-Sulfur Compounds

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The preparations, properties, structures, and chemical reactions of silicon-sulfur compounds are reported. The chain structure of the polymeric silicon disulfide is used as a basis from which the various classes of compounds can be derived: cyclothiasilanes, disilyl sulfides, silanethiols, and organothiosilanes. Infrared data and force constants of the Si–S bond are discussed.

Although silicon disulfide was discovered by *Berzelius* as early as 1824, the chemistry of the silicon-sulfur compounds has never attained the importance of *e.g.* the chemistry of the Si-O compounds (silico esters, silicones). There are several reasons for this. In the first place, no practical use has so far been found for compounds containing the Si-S bond; furthermore, these compounds are characterized by a penetrating odor which offers little encouragement to study them. The main reasons for their lack of practical interest are their chemical instability, particularly their sensitivity towards hydrolysis and oxidation, and their tendency not to form high-molecular weight Si-S chains carrying organic substituents or three-dimensional networks.

1. Silicon Monosulfide

Like silicon monoxide, SiS has been detected with certainty only in the gaseous state. At room temperature "SiS" is probably a mixture of silicon and silicon disulfide. Silicon monosulfide is formed in many industrial processes from silicon and substances containing sulfur. The formation of SiS can be used for the desilicification of ores containing silicon [1, 2], *e.g.*:

$$SiO_2 + C + FeS \xrightarrow{1400-1500\,^\circ C} SiS + CO + FeO \qquad (a)$$

If zinc sulfide is used instead of FeS [1], the reaction must be carried out at 1350 to 1400 °C. The silicon monosulfide formed always contains carbon, so that the process is of little preparative value. A product containing no carbon is obtained when ferrosilicon (80% Si) is treated with FeS at 1500 to 1700 °C; reports differ, however, on the properties of this product [3]. *Cambi* [4] used sulfur instead of FeS, and obtained a product that sublimed at 940 to 980 °C and 20 to 30 mm. The substance was yellow below 980 °C, but on prolonged heating above 980 °C was converted into a black form, perhaps a mixture of Si and SiS_2 produced by disproportionation:

$$2\,SiS \rightarrow Si + SiS_2 \qquad (b)$$

An interesting reaction is the formation of SiS when carbon disulfide [5] is passed over finely powdered silicon at 1000 °C. SiS also occurs as a by-product in the production of SiS_2, particularly in reactions of silicon with sulfur [6, 14], and with hydrogen sulfide [7].

SiS is an amorphous powder, which is unstable at room temperature and whose color is variously reported as being yellow, orange-red [6], dark brown [3], and black [4]; the material existing at room temperature probably is a decomposition product of SiS.

The dissociation energy D, the equilibrium interatomic distance r_o, and the force constant k_e have been determined from the ultraviolet spectrum and provide evidence of the existence of SiS in the gas phase: D = 6.47 eV [9] (ground state); D = 147.4 ± 0.3 kcal/mole [12] (ground state); r_o = 1.929 Å [10]; $k_e = 4.94 \times 10^{-5}$ dyne/cm.

Little is known about the chemical properties of SiS. Its greater volatility as compared with SiS_2 [11] and its extreme sensitivity towards hydrolysis are noteworthy. Water decomposes SiS (sometimes explosively) to H_2S and (through several intermediates) SiO_2 [8]. Hydrogen chloride [4] reacts with SiS at 240 to 260 °C with evolution of H_2S and formation of chlorosilanes (presumably trichlorosilane). SiS is decomposed by 30% KOH in accordance with Equation (c) [6].

$$SiS + 2\,OH^- + H_2O \rightarrow SiO_3^{2-} + H_2 + H_2S \qquad (c)$$

[1] *X. Siebers* and *E. I. Kohlmeyer*, Arch. Erzbergbau, Erzaufber. Metallhüttenwes. 1, *1931*, 120; *X. Siebers*, Dissertation, Technische Hochschule Berlin, 1930, p. 24; *E. J. Kohlmeyer* and *X. Siebers*, German Pat. 534984 (1930/31).

[2] *W. Oelsen* and *H. Maetz*, Mitt. Kaiser-Wilhelm-Inst. Eisenforsch. *21*, 340 (1939); *R. Dürer*, *H. Hellbrugge*, and *B. Marinček*, Arch. Eisenhüttenwes. *14*, 531 (1941); *Sh. L. Wert* and *M. W. Kamenzew*, J. allg. Chem. *26*, 307 (1956); Chem. Zbl. *1958*, 10301.

[3] *F. Wüst* and *A. Schüller*, Stahl u. Eisen *23*, 1128 (1903); *W. Fielding*, Trans. Faraday Soc. *5*, 110 (1909); *M. Haff*, Elektrochem. metallurg. Ind. *6*, 96 (1908).

[4] *L. Cambi*, Atti Accad. naz. Lincei, Cl. Sci. fisiche, mat. natur. Scz. [5] *19*, II, 294 (1910); *20*, I, 433 (1911); Chem. Zbl. II, *1911*, 263.

[5] *R. F. Barrow* and *W. Jevons*, Proc. Roy. Soc. (London) *A 169*, 45 (1939).

[6] *E. J. Kohlmeyer* and *H. W. Retzlaff*, Z. anorg. allg. Chem. *261*, 248 (1950); *W. C. Schumb* and *H. J. Bernard*, J. Amer. chem. Soc. *77*, 904 (1955).

[7] *M. Thimann*, Dissertation, Universität Berlin, 1927, p. 19; *W. Wirbelauer*, Dissertation, Universität Berlin, 1904, p. 14; *E. Tiede* and *M. Thimann*, Ber. dtsch. chem. Ges. *59*, 1703 (1926).

[8] *A. Colson*, C. R. hebd. Séances Acad. Sci. *94*, 1526 (1882); Bl. Soc. chim. [2], *38*, 56 (1882).

[9] *E. E. Vago* and *R. F. Barrow*, Proc. physic. Soc. (London) *58*, 538 (1946).

[10] *R. F. Barrow*, Proc. physic. Soc. (London) *58*, 606 (1946); *G. Herzberg*: Spectra of Diatomic Molecules. 2nd ed., D. van Nostrand Comp., New York-Toronto-London 1950, p. 570.

[11] *P. Sabatier*, C. R. hebd. Séances Acad. Sci. *90*, 819 (1880); Ann. Chim. Physique [5], *22*, 94 (1881).

[12] *S. J. Q. Robinson* and *R. F. Barrow*, Proc. physic. Soc. (London) Sect. A *67*, 95 (1954).

2. Silicon Disulfide

Silicon disulfide is at present the most widely studied silicon-sulfur compound. It was first prepared from its elements by *Berzelius*[13] in 1824. There are two principal methods available for the preparation of fairly large quantities of SiS_2:

a) In the method described by *Hämpel* and *v. Haasy*[14], an intimate mixture of finely ground silicon (200 g; 98% Si + 2% Fe) with three times as much finely ground crystalline sulfur (500 g) and BaO_2 (30 g) is placed in a thin-walled iron tube and ignited with a strip of magnesium. The yield is 74%, and the crude product contains 92 to 95% of SiS_2. Sublimation *in vacuo* at bright-red heat gives a chemically pure silicon disulfide; *Malatesta*[15] used a mixture of 4 g of Fe_2O_3 and 1 g of magnesium powder instead of BaO_2.

b) An elegant method has been described by *Schmeisser*, *Müller*, and *Burgemeister*[16] and confirmed by *Behrens* and *Ostermeier*[17]. The thermal decomposition of a mixture of $(C_2H_5S)_4Si$ and sulfur at 200 °C [Equation (d)] yields a very reactive SiS_2, which is completely free from organic impurities. 46 g of SiS_2 is obtained in

$$(C_2H_5S)_4Si + 2\,S \rightarrow SiS_2 + 2\,C_2H_5{-}S{-}S{-}C_2H_5 \qquad (d)$$

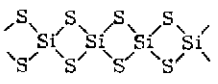
10 min from 136 g of $Si(SC_2H_5)_4$ and 96 g of sulfur. A similar reaction occurs in the absence of sulfur, but the temperatures required in this case are between 250 and 300 °C.

A number of other reactions have also been reported, but these yield only small quantities of SiS_2. They include the reaction of silicon with compounds containing sulfur[11] (*e.g.* H_2S, CS_2) at 1500 °C and the reaction of silicides[18] (*e.g.* Mg_2Si, $CaSi_2$) with sulfur or compounds containing sulfur (*e.g.* H_2S, CS_2, S_2Cl_2). Mg_2Si reacts so vigorously with S_2Cl_2 that this reaction can be used to initiate the reaction of silicon with sulfur. Silicon disulfide is also obtained by the reaction of silicates, carbon, and substances containing sulfur (S, H_2S, CS_2). The addition of carbon is unnecessary when metal sulfides are used[19].

Silverman and *Soulen*[19a] recently treated silicon with sulfur (mixing ratio 1:2.22) at 1430 °C and *ca.* 75000 atm, and obtained a product that appears, from analytical and X-ray studies, to be a new high-pressure modification of SiS_2. However, the authors were unable to rule out the possibility that this is a compound with only approximately the same composition as silicon disulfide[*]. At very high pressures they also obtained yellow and orange to green amorphous glasses which were much more resistant to hydrolysis than SiS and SiS_2.

Physical Properties of SiS_2: M.p. 1090 °C[19]; b.p. 1130 °C[6b]; d^{20} = 2.02 g/cm³[19]; d^{25} = 1.875 ± 0.01 g/cm³[21a].

The X-ray analysis carried out by *Zintl* and *Loosen*[20] showed that silicon disulfide has a fibrous structure, in which each silicon atom is in the center of a distorted tetrahedron formed by four sulfur atoms. The tetrahedra are joined by their edges to form long chains *(1)* in which two silicon atoms are linked *via* two neighboring sulfur atoms, the four atoms together forming a ring.



(1)

The three-dimensional arrangement of the SiS_2 molecules in the lattice is shown in Figure 1. The individual chains are held together by van der Waals forces.

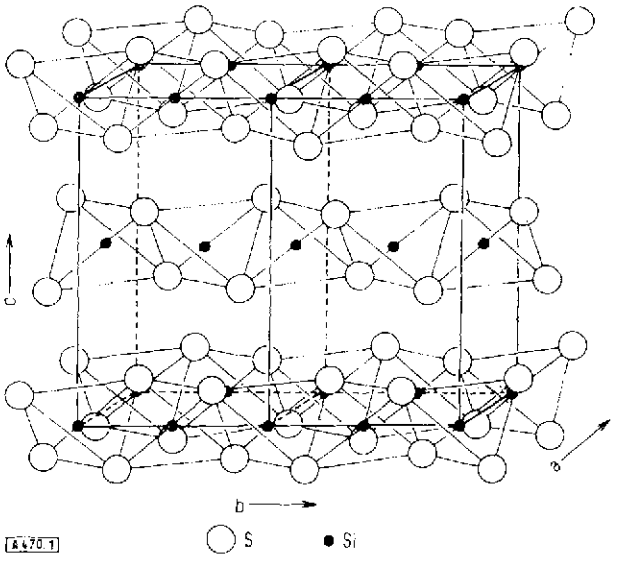


Fig. 1. Two unit cells of polymeric SiS_2 [21].

Space group D_{2h}^{25}-Jcma (Jbma); Z = 4; d_R = 2.066; a = 5.65 ± 0.01; 5.60; b = 5.54 ± 0.01; 5.53; c = 9.57 ± 0.01; 9.55 Å. Distances: Si–Si = 2.765 Å; Si–S = 2.14 Å; S–S = 3.24; 3.5; and 3.62 Å. (These last three values correpond to the S–S distances in the deformed tetrahedra.) The distance between two sulfur atoms in adjacent chains is at least 3.75 Å.

The heat of formation for the reaction

$$Si + 2\,S \rightarrow SiS_2$$

as found from the heat of reaction for the hydrolysis of SiS_2 in 6 N NaOH is $\Delta H_{298} = -59.9 \pm 0.5$ kcal/mole. The value found from the heat of solution of SiS_2 in 20% and 25% hydrofluoric acid is $\Delta H_{298} = -43.2$ kcal/mole.

Phosphorescent SiS_2 was obtained by *Tiede* and *Thimann*[21c] by the sublimation of SiS in an$_2$ atmosphere

[13] *J. J. Berzelius*, Poggendorfs Ann. Physik Chem. *1*, 216 (1824).

[14] *W. Hämpel* and *v. Haasy*, Z. anorg. allg. Chem. *23*, 32 (1900).

[15] *L. Malatesta*, Gazz. chim. ital. *78*, 702 (1948).

[16] *M. Schmeisser*, *H. Müller*, and *W. Burgemeister*, Angew. Chem. *69*, 781 (1957).

[17] *H. Behrens* and *J. Ostermeier*, Chem. Ber. *95*, 487 (1962).

[18] *H. Moissan*, C. R. hebd. Séances Acad. Sci. *134*, 1083 (1902); *E. Berger*, *ibid. 170*, 1492 (1920).

[19] *E. Tiede* and *M. Thimann*, Ber. dtsch. chem. Ges. *59*, 1703 (1926).

[19a] *M. S. Silverman* and *J. R. Soulen*, Inorg. Chem. *4*, 129 (1965).

[20] Z. physik. Chem. A *174*, 301 (1935); *W. Büssem*, *H. Fischer*, and *E. Gruner*, Naturwissenschaften *23*, 740 (1935).

[21] *E. Zintl* and *K. Loosen*, Z. Kristallogr., Mineralog. Petrogr., Abt. A., Strukturber. *3*, 35, 37–38 (1933).

[21a] *H. Gabriel* and *C. Alvarez-Tostado*, J. Amer. chem. Soc. *74*, 262 (1952).

[21b] *P. Rocquet* and *M. F. Ancey-Moret*, Bull. Soc. chim. France, Mém. [5] *21*, 1038 (1954).

[21c] *E. Tiede* and *M. Thimann*, Ber. dtsch. chem. Ges. *59*, 1706 (1926).

[*] Cf. $Ge_{0.94}S_{2.05}$ [19a].

of N_2 and in the presence of compounds containing carbon, or directly from SiO_2 and Al_2S_3 in the presence of organic substances (*e.g.* tartaric acid).

The chain structure and the low bond energy of SiS_2 are essential to an explanation of its chemical behavior (cf. Table 1). SiS_2 is stable in dry air, but is hydrolysed

Table 1. Bond energies of various Si—X bonds [21d].

Si—X	E_D [kcal/mole]	Si—X	E_D [kcal/mole]
Si—F	129.3	Si—Br	69.1
Si—O	88.2	Si—S	54.2
Si—Cl	85.7	Si—I	50.9
Si—H	70.4	Si—Si	42.2
Si—C	69.3		

even by traces of moisture. According to *Schwarz* [22], hydrolysis leads to the condensation of four molecules of the initially formed orthosilicic acid to give a cyclic tetrasilicic acid:

$$4\,SiS_2 + 12\,H_2O \rightarrow \left[(HO)_2Si\langle_{O-}\right]_4 + 8\,H_2S \qquad (e)$$

SiS_2 reacts with CO_2 [24] at 350 °C as indicated in Equation (*f*).

$$SiS_2 + 2\,CO_2 \xrightarrow{350\,^\circ C} SiO_2 + 2\,S + 2\,CO \qquad (f)$$

SiS_2 is reduced by carbon monoxide [23] to SiS. SiS_2 is stable towards hydrogen [25] and is insoluble in organic solvents such as CCl_4 or C_6H_6 [20].

The heavy metal thiosilicates Cu_8SiS_6 [25a], Ag_8SiS_6, $Ag_6Si_2S_7$ [*], $Pb_3Si_2S_7$, $Tl_8Si_3S_{10}$, and $Tl_2Si_4S_9$ [25b] have been prepared by the fusion of SiS_2 or silicon and sulfur with metal sulfides. Investigations on the system PbS/SiS_2 showed that only a ternary phase of the composition Pb_2SiS_4 exists between 800 and 1100 °C. The black platelets of this substance have a metallic luster; they are very hygroscopic, and crystallize in a monoclinic structure (space group = C_2^5h–$P2_1$; a = 6.50 Å; b = 6.65 Å; c = 17.68 Å, β = 115 °5′; Z = 4).

The alkali metal [**] and alkaline earth thiosilicates Li_2SiS_3, Li_4SiS_4, Mg_2SiS_4, Ca_2SiS_4, $CaSiS_3$, and $CaSi_2S_5$ were first prepared by *Weiss* and *Rocktäschel* [25d], by the reaction of the corresponding metal silicides with sulfur at high temperatures. They are generally white crystalline powders, which are rapidly hydrolysed in moist air, with the evolution of H_2S. Ca_2SiS_4 is very similar to Mg_2SiS_4: both crystallize in the orthorhombic system and contain isolated SiS_4 tetrahedra [***]. Li_2SiS_3 also crystallizes in the orthorhombic system, but like the corresponding oxygen silicate, consists of infinite one-dimensional SiS_3^{2-} chains.

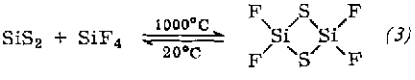
3. 1,3,2,4-Dithiadisiletanes

The 1,3,2,4-dithiadisiletanes are directly derived from the fiber structure of the polymeric silicon disulfide. Partial cleavage of the Si-S bonds in *(1)*, *e.g.* with alcohol, yields low-molecular weight compounds in which the four-membered ring that forms the basic unit in SiS_2 is still retained. The free valences may be saturated by halogens, amino groups, or organic residues.

(2)

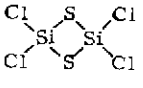
a) Tetrafluoro-1,3,2,4-dithiadisiletane

Whereas SiF_4 reacts with SiO_2 to form fluorosiloxanes [26] (main product $F_3SiOSiF_3$), *Gutmann*, *Heilmayer*, and *Utvary* [27] obtained tetrafluoro-1,3,2,4-dithiadisiletane *(3)* by the reaction of SiF_4 with SiS_2 at 1000 °C in a circulating apparatus. Heat of vaporization = 7400 cal/mole; Trouton's constant = 29.02; b.p. −18 °C; m.p. −80 °C. At 20 °C, compound *(3)* decomposes completely into the starting materials.


(3)

b) Tetrachloro-1,3,2,4-dithiadisiletane

Tetrachloro-1,3,2,4-dithiadisiletane *(4)* was obtained by *Besson* [28] on heating S_2Cl_2 and silicon to red heat in a stream of chlorine, or from chlorine and silicon disulfide. Higher yields of *(4)* are obtained if hydrogen sulfide and silicon tetrachloride in constant circulation are


(4)

[21d] *L. Pauling*: Nature of the Chemical Bond. 3rd ed., Cornell University Press, Ithaca, N.Y. 1960, p. 85.

[22] *R. Schwarz*, Z. anorg. allg. Chem. *276*, 33 (1954).

[23] *A. Ledebur*, Berg-hüttenmann. Ztg. *37*, 321 (1878).

[24] *N. D. Costeanu*, Ann. Chim. Physique [9] *2*, 193 (1914); C. R. hebd. Séances Acad. Sci. *156*, 1985 (1913).

[25] *E. Fremy*, C. R. hebd. Séances Acad. Sci. *36*, 178 (1853); Ann. Chim. Physique [3] *38*, 316 (1853).

[25a] *L. Cambi* and *G. G. Monselise*, Gazz. chim. ital. *66*, 696 (1936).

[*] $Ag_6Si_2S_7$ was also obtained by *M. F. Potenza* and *M. Elli*, Chem. Zbl. *1963*, 8481, as a blood-red compound melting at 756 °C.

[25b] *G. G. Monselise*, Gazz. chim. ital. *67*, 748 (1937); Atti X. Congr. internat. Chim. Roma *2*, 732 (1938).

[**] Na_2SiS_3 has been prepared from Na_2S and SiS_2 [14].

[25c] *P. Hagemuller* and *G. Perez*, C. R. hebd. Séances Acad. Sci. *260*, 167 (1965).

[25d] *A. Weiss* and *G. Rocktäschel*, Z. anorg. allg. Chem. *307*, 1 (1960).

[***] Space group: D_{2h}^{16}-Pnma

Mg_2SiS_4:	a = 12.64	b = 7.47	c = 5.92 Å
Ca_2SiS_4:	a = 13.49	b = 8.18	c = 6.21 Å
Mn_2SiS_4:	a = 12.61	b = 7.45	c = 5.95 Å

The Si—S distances are between 2.15 and 2.25 Å [25e].

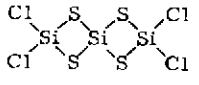
[25e] *G. Rocktäschel*, *W. Ritter*, and *A. Weiss*, Z. Naturforsch. *19b*, 958 (1964).

[26] *J. Goubeau* and *H. Grosse-Ruyken*, Z. anorg. allg. Chem. *264*, 230 (1951).

[27] *V. Gutmann*, *P. Heilmayer*, and *K. Utvary*, Mh. Chem. *1961*, 942.

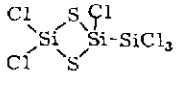
reacted at weak red heat [31]. On cooling, *(4)* crystallizes out as colorless prisms. It can be recrystallized from CS_2 in the absence of moisture.

According to *Etienne* and *Kullmann* [32], $SiCl_4$ condenses with H_2S in the presence of organic bases to form *(4)*. The formula *(4)* given by these authors is based on molecular weight determinations. Doubt has been cast on this conclusion by *Schumb* and *Bernard* [33], who thought that they had isolated an "octachlorocyclotetrasilthiane". *Panckhurst*, *Wilkins*, and *Craighead* [34] repeated the reaction at 700 to 1100 °C and confirmed the structure *(4)* [*]. They also obtained high-molecular weight liquid compounds $(SiSCl_2)_n$ by heating *(4)* to 180 °C, but these products could not be identified. When the reaction of SiS_2 with $SiCl_4$ was carried out at 900 °C, the second member of the homologous series $Si_nS_{2n-2}Cl_4$, *i.e.* $Si_3S_4Cl_4$ *(5)*, was obtained in addition to *(4)* [34a].

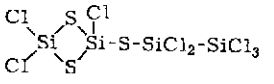


(5)

$(SiCl_2)_x$ reacts with sulfur at 170 to 180 °C to form a mixture from which, in addition to *(4)* and *(5)*, $Si_3S_2Cl_4$ (colorless liquid, b.p. 91.5–93 °C/2.5 mm) and $Si_4S_3Cl_8$ (slightly yellowish oily liquid; b.p. 136–138 °C/0.01 mm) can be isolated. These compounds have the structures *(6)* and *(7)* [34a].



(6)



(7)

Compound *(4)* is sensitive to moisture, and decomposes in accordance with Equation (g).

$$Cl_2SiS_2SiCl_2 + 4\ H_2O \rightarrow 2\ SiO_2 + 4\ HCl + 2\ H_2S \qquad (g)$$

At 220 °C it decomposes into the materials from which it is made. The Si-S bond in *(4)* is cleaved by bromine, with the formation of dibromodichlorosilane, as is expected from the cyclic structure of *(4)*.

$$(4) + 3\ Br_2 \rightarrow 2\ SiCl_2Br_2 + S_2Br_2$$

Tetrachloro-1,3,2,4-dithiadisiletane (m.p. 75 °C, b.p. 92 °C/22.5 mm) forms colorless prisms, which are soluble in $SiCl_4$ and organic solvents (benzene, chloroform, and CS_2).

[28] *A. Besson*, C. R. hebd. Séances Acad. Sci. *113*, 1040 (1891).

[31] *M. Blix* and *W. Wirbelauer*, Ber. dtsch. chem. Ges. *36*, 4220 (1903).

[32] *Y. Etienne* and *R. Kullmann*, C. R. hebd. Séances Acad. Sci. *234*, 1985 (1952); *235*, 967 (1952); Bull. Soc. Chim. France *1953*, 791.

[33] *W. C. Schumb* and *W. J. Bernard*, J. Amer. chem. Soc. *77*, 862 (1955).

[34] *D. J. Panckhurst*, *C. J. Wilkins*, and *P. W. Craighead*, J. chem. Soc. (London) *1955*, 3395.

[*] The same result was obtained by *J. Goubeau* and *W. D. Hirsemann* [67].

[34a] *A. Buschfeld*, Dissertation, Technische Hochschule Aachen, 1962.

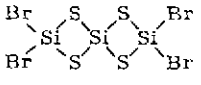
c) Tetrabromo-1,3,2,4-dithiadisiletane

Tetrabromo-1,3,2,4-dithiadisiletane *(8)* is formed by the reaction of $SiBr_4$ with H_2S, but only with $AlBr_3$ as catalyst; the yield reaches approximately 20% after five to six days at 150 °C [35]. Fractional distillation followed by recrystallization from CS_2 gives *(8)* in the form of colorless platelets (m.p. 93 °C; b.p. 150 °C/18 mm). On reaction with water, *(8)* decomposes explosively:

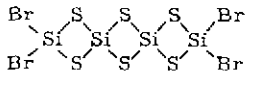
$$\underset{(8)}{Br_2SiS_2SiBr_2} + 4\ H_2O \rightarrow 2\ SiO_2 + 4\ HBr + 2\ H_2S \qquad (h)$$

Investigations on the crystal structure by *Weiss* and *Weiss* [35a] indicated that the molecular structure of *(8)* is similar to that of *(3)* and *(4)*.

In the presence of catalytic amounts of SiS_2, *(8)* reacts with H_2S to form higher sulfide bromides, $Si_nS_{2n-2}Br_4$, with loss of HBr. Compounds *(9)* [m.p. 108 °C, b.p. 164 °C/12 mm] and *(10)* [m.p. 148 °C, decomp., b.p. 171 °C/12 mm] have been isolated from a reaction mixture of this kind by distillation, fractional extraction, or



(9)



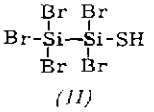
(10)

crystallization from CS_2. The higher homologues (n = 10 and 11), which are sparingly soluble in CS_2, are colorless compounds that do not crystallize well. They lose $SiBr_4$ on heating to form a mixture of higher sulfide bromides. The lower homologues (n = 3, 4) have been isolated by vacuum distillation. They also dismutate partially into $SiBr_4$ and higher homologs.

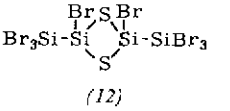
Compound *(8)* can also be obtained from $SiBr_4$ and Na_2S or P_2S_5 if the reaction is catalysed by Al_2Br_6 or $Si_2S_2Br_4$. The reactions of $SiHBr_3$ with sulfur and of SiS_2 with $SiBr_4$ also lead to *(8)*. This last reaction [Equation (i)] is reversible; at high $SiBr_4$ pressures it proceeds to the right, at lower pressures to the left. If Si_2Br_6 is used

$$(SiS_2)_n + n\ SiBr_4 \underset{< 1\ atm}{\overset{200\ °C,\ >1\ atm}{\rightleftharpoons}} n\ Si_2S_2Br_4 \qquad (i)$$

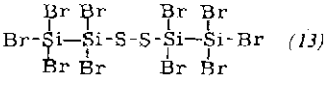
instead of $SiBr_4$, the products include the compounds *(11)*, *(12)*, and *(13)*, but these are even less stable.



(11)



(12)



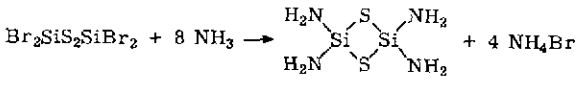
(13)

[35] *M. Blix*, Ber. dtsch. chem. Ges. *36*, 4218 (1903).

[35a] Silicium-Schwefel-Phosphate. Colloquium d. Sektion f. Anorg. Chem. IUPAC, Münster 1954. Verlag Chemie, Weinheim/Bergstr. 1955, p. 41.

d) Tetraamino-1,3,2,4-dithiadisiletane

Tetrahalogeno-1,3,2,4-dithiadisiletanes are very reactive, and the halogen atoms can be replaced by other substituents. Compound *(14)* was first prepared by the reaction of *(8)* with ammonia in dry benzene [35]. On extraction of the NH_4Br, which is soluble in liquid ammonia,

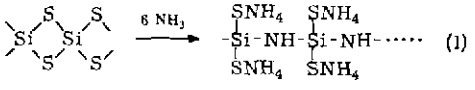


(14)

(14) was obtained as a white amorphous powder. Thermal decomposition begins at temperatures above 0 °C, and the compound is quantitatively hydrolysed by water:

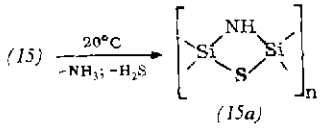
$$(NH_2)_2SiS_2Si(NH_2)_2 + 4\,H_2O \rightarrow 2\,SiO_2 + 2\,H_2S + 4\,NH_3 \quad (k)$$

According to *Behrens* and *Ostermeier* [17], an S atom in the four-membered ring can be replaced by the imino group $-NH-$ [*]. SiS_2 obtained from $(C_2H_5S)_4Si$ and sulfur at 200 °C reacts with liquid ammonia at −33 °C; three moles of NH_3 are consumed per mole of



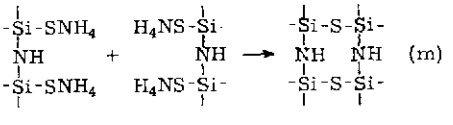
(15)

SiS_2, in accordance with Equation (l). On heating in a high vacuum at 20 °C, *(15)* loses ammonia and hydrogen sulfide, the product presumably being *(15a)*. However, the presence of this ring system has not been conclusively proved. The possibility of an intermolecular



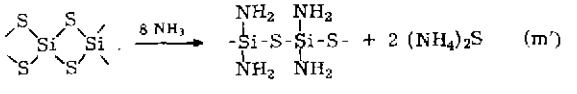
(15a)

condensation [17] in accordance with Equation (m) must also be considered.



By excess NH_3 at 60 °C, *(15)* is quantitatively desulfurized to $[Si(NH)_2]_x$.

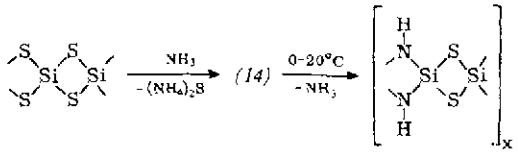
If the $(SiS_2)_n$ obtained from $(C_2H_5S)_4Si$ and sulfur is heated *in vacuo* for two hours at 450 °C, subsequent ammonolysis at −33 °C proceeds not by reaction (l), but by reaction (m'). The product *(16)* loses ammonia above



(16)

[*] According to *M. Becke-Goehring* [35b], the transition $S_8 \rightarrow S_7(NH) \rightarrow S_6(NH)_2 \rightarrow S_4(NH)_4$ is possible.

0 °C and is quantitatively converted into *(15)* at 20 °C. The chain *(16)* must not necessarily be formed, since a cyclic structure *(17)* would also be possible.

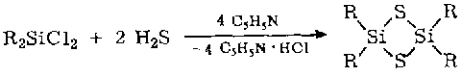


(17)

The formation of *(17)* is indicated by the fact that the properties of substance *(16)* obtained by *Behrens* and *Ostermeier* [17] are similar to those of *(14)* [35]. Moreover, no linear compounds with Si-S chains are known apart from the parent compound $R_3SiSSiR_3$, whereas four-membered rings containing N Si groupings have been described [36].

e) Tetraorgano-1,3,2,4-dithiadisiletanes

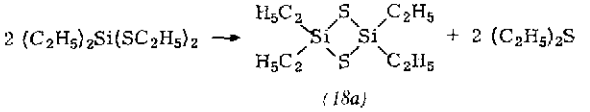
Tetraorgano-1,3,2,4-dithiadisiletanes can be prepared by the reaction of organochlorosilanes with H_2S in petroleum ether and in the presence of an HCl acceptor such as triethylamine or pyridine [37, 38].



(18)

In addition to this generally applicable method, the compounds *(18)* can be obtained by reactions of organodiiodosilanes [37] with Ag_2S in inert solvents.

Compounds of the type $R_2Si(SR)_2$, *e.g.* diethyldi(ethylthio)silane, are decomposed by heat into a tetraorgano-1,3,2,4-dithiadisiletane, *e.g .(18a)*, and a dialkyl sulfide [39]. The alcoholysis of $(SiS_2)_n$ with t-butanol yields tetra-t-butyl-1,3,2,4-dithiadisiletane [40].



(18a)

The compounds *(18)* are thermodynamically [38] unstable and rearrange to form hexaorgano-1,3,5,2,4,6-trithiatrisilin. In the case of the methyl derivative, this rearrangement occurs within a few days, even at room temperature, whereas the ethyl and propyl compounds trimerize at an appreciable rate only above 150 °C. The dimer can be regenerated from the trimer by quenching the vapor.

[36] *W. Fink*, Angew. Chem. *73*, 736 (1961); Chem. Ber. *96*, 1071 (1963).

[37] *G. Champetiere, Y. Etienne*, and *R. Kullmann*, C. R. hebd. Séances Acad. Sci. *234*, 1985 (1952); *Y. Etienne, ibid. 235*, 966 (1952).

[38] *C. Dathe*, Diploma Thesis, Universität München, 1955.

[39] *M. Schmeisser* and *H. Müller*, Angew. Chem. *69*, 781 (1957).

[40] *R. Piekos* and *W. Wojnowsky*, Z. anorg. allg. Chem. *318*, 212 (1962).

Table 2. Tetraorgano-1,3,2,4-dithiadisiletanes, $R_2SiS_2SiR_2$.

R	M.p. [°C]	B.p. [°C/mm]	
CH_3	113	172–73/38 [42]	colorless crystals $\mu = 0$ Debye
C_2H_5	20–21	60–62/0.2	
C_3H_7	29–29.5	90–91/0.2	thin, wax-like platelets
2 C_3H_7; 2 Cl [a]		261–63/760	
C_4H_9O	121–123.5		colorless crystals insoluble in petroleum ether
C_2H_5S		296/0.1	
C_6H_5	145–147		

[a] Compound *(19)*.

f) Hexaalkyl-1,3,5,2,4,6-trithiatrisilin

In addition to the preparation described above, involving the rearrangement of 1,3,2,4-dithiadisiletanes, the trimer $[(CH_3)_3SiS]_3$ has also been prepared by *Nomura, Yokoi,* and *Yamasaki*[41] by the reaction of $(CH_3)_2SiCl_2$ with hydrogen sulfide at 20 °C (in contradiction of *Etienne*'s findings[37]). On heating for several hours in a current of H_2S, however, it rearranged to the dimer $[(CH_3)_3SiS]_2$.

Physical properties:

$[(CH_3)_2SiS]_3$: b.p. 151.5–153.5 °C/38 mm, 76–78 °C/0.6 mm; m.p. 17–18 °C; dipole moment[42] 1.03 Debye.

$[C_2H_5)_2SiS]_3$: b.p. 111–115 °C/0.2 mm; colorless oil.

$[(n\text{-}C_3H_7)_2SiS]_3$: b.p. 176–180 °C/0.8 mm, 145–148 °C/0.2 mm.

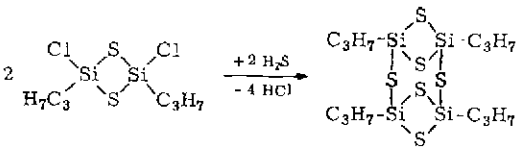
Electron diffraction measurements[43] gave Si-S distances of 2.18 ± 0.03 Å and 2.15 ± 0.3 Å. Assuming a C–S–C angle of 110 °, the following values were found for the bond angles:

	Dimer	Trimer
Si–S–Si	75 °	110 °
S–Si–S	105 °	115 °

In agreement with the results of dipole moment measurements, therefore, the trimer is not planar; instead, like the corresponding oxygen compound, it has a chair structure.

g) 2,4,6,8-Diepithiotetraorgano-1,3,5,7,2,4,6,8-tetrathiatetrasilocanes $(RSiS_{1.5})_4$

The reactions of trichloroorganosilanes with H_2S in the presence of a tertiary amine do not yield high polymers, but only tetramers. *Etienne*[44] obtained methyl, ethyl, and phenyl derivatives in benzene solution. The propyl compound *(20)*[37b] was prepared in a similar manner from *(19)*, so providing chemical evidence for the structure of this compound.



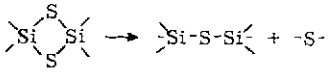
(19) *(20)*

Physical properties:

$(CH_3SiS_{1.5})_4$: m.p. 275 °C;
$(C_2H_5SiS_{1.5})_4$: m.p. 140 °C;
$(C_3H_7SiS_{1.5})_4$: m.p. 86 °C, b.p. 210–215 °C/0.2 mm;
$(C_6H_5SiS_{1.5})_4$: m.p. 216 °C.

4. Disilyl Sulfides

The "desulfurization" of *(2)* formally leads to a new class of compounds, the so-called "disilthianes". These can be produced on the preparative scale by four principal methods:



(2) *(21)*

1. By the reaction of iodosilanes[45–47] with mercury sulfide or silver sulfide, or by the reaction of chlorosilanes with anhydrous sodium sulfide[48] at 250 °C and at a high pressure (60 atm):

$$2\ R_3SiI + HgS\ (Ag_2S) \rightarrow R_3Si\text{-}S\text{-}SiR_3 + HgI_2\ (2\ AgI) \quad (n)$$

$$2\ R_3SiCl + Na_2S \xrightarrow[\text{pressure}]{250\ ^\circ C} R_3Si\text{–}S\text{–}SiR_3 + 2\ NaCl \quad (o)$$

2. By the reaction of chlorosilanes with H_2S in the presence of pyridine[37a]:

$$2\ R_3SiCl + H_2S + 2\ C_5H_5N \rightarrow R_3Si\text{–}S\text{–}SiR_3 + 2\ C_5H_5N\cdot HCl \quad (p)$$

3. A more widely used method is that described by *Larson* and *Marin*[49], who treated trialkylsilylamines with hydrogen sulfide in organic solvents and obtained good yields of disilyl sulfides:

$$R_3SiNHR' + H_2S \rightarrow R_3Si\text{–}S\text{–}SiR_3 + R'NH_2 \quad (q)$$

4. Hexachlorodisilyl sulfide[50,51] was obtained from silicon tetrachloride and hydrogen sulfide at 700 to

[41] *T. Nomura, M. Yokoi,* and *K. Yamasaki,* Proc. Japan Acad. *29,* 342 (1954); Chem. Abstr. *1955,* 12274.

[42] *Y. Kurita* and *M. Kondo,* Bull. chem. Soc. Japan *27,* 160 (1954); Chem. Abstr. *1955,* 8580.

[43] *M. Yokoi, T. Nomura,* and *K. Yamasakai,* J. Amer. chem. Soc. *77,* 4484 (1955).

[44] *M. Y. Etienne,* Bull. Soc. chim. France *1953,* 791.

[45] *H. J. Emeleus, A. G. MacDiarmid,* and *A. G. Maddock,* J. inorg. nuclear Chem. *1,* 194 (1955); *H. J. Emeleus, M. Onyszchuk,* and *W. Kuchen,* Z. anorg. allg. Chem. *283,* 74 (1956).

[46] *L. G. L. Ward* and *A. G. MacDiarmid,* J. inorg. nuclear Chem. *21,* 287 (1962).

[47] *C. Eaborn,* J. chem. Soc. (London) *1950,* 3077; Nature (London) *165,* 685 (1950).

[48] *E. W. Abel,* J. chem. Soc. (London) *1961,* 4933.

[48a] *M. Fild, W. Sundermeyer,* and *O. Glemser,* Chem. Ber. *79,* 620 (1964).

[49] *E. Larson* and *R. Marin,* Acta chem. scand. *5,* 964 (1951).

[50] *W. C. Schumb* and *W. J. Bernard,* J. Amer. chem. Soc. *77,* 862 (1953).

[51] *D. J. Panckhurst, C. J. Wilkins,* and *P. W. Craighead,* J. chem. Soc. (London) *1955,* 3395.

1100 °C, in accordance with Equation (r), or from Cl_3SiI and Ag_2S at 250 °C [50].

$$SiCl_4 + H_2S \xrightarrow{700-1100\,^\circ C} Cl_3Si-S-SiCl_3 \qquad (r)$$

Chemical properties: Of the compounds listed in Table 3, $H_5Si_2-S-Si_2H_5$ [46] is thermally the least stable. It decomposes at 157 °C into disilane, hydrogen, and a white, non-volatile substance which has not been identified. Unlike thioethers, the disilyl sulfides do not form sulfonium compounds. They are degraded by iodine and hydrogen iodide to iodosilanes and sulfur or H_2S:

$$R_3Si-S-SiR_3 + I_2\,(HI) \rightarrow 2\,R_3SiI + S\,(H_2S) \qquad (s)$$

Table 3. Disilyl sulfides $R^2R^1_2Si-S-SiR^1_2R^2$.

R	M.p. [°C]	B.p. [°C/mm]	Method of preparation	Yield [%]	Reactions
$R^1=R^2=H$	− 70	58.8/760	1)	93	$+S \rightarrow H_3Si-S-S-SiH_3$
$R^1=H$; $R^2=SiH_3$	− 70.4	144/760	1)	87	
$R^1=H$; $R^2=CH_3$	−120	105/760	1)	90	
$R^1=R^2=Cl$ [a]	− 45	100–100.5/50	1) 4)		200 °C, 3 h → $SiCl_4 + SiS_2$
$R^1=R^2=CH_3$		163–164/760	1) 3)	73	$+ ROH \rightarrow 2(CH_3)_3SiOR + H_2S$ $+ RSH \rightarrow 2(CH_3)_3SiSR + H_2S$ $+ 2\,RR'NH \rightarrow 2\,RR'NSi(CH_3)_3 + H_2S$ $+ 2\,RX \rightarrow 2(CH_3)_3SiX + R_2S$; X=Br, I $+ Br(CH_2)_4Br \rightarrow 2(CH_3)_3SiBr + (CH_2)_4S$
$R^1=R^2=C_2H_5$	− 75	277–279/760	1) 3)	45	
$R^1=R^2=C_3H_7$		168/7	3)	*ca.* 50	

[a] $(CH_3)_3Si-S-Si(CH_3)_3$ has also been obtained by passing $(CH_3)_3SiCl$ into a melt of $K_2S/LiCl/KCl$ at 400 °C [48a].

The alcoholysis, thioalcoholysis, and aminolysis of bis(trimethylsilyl) sulfide, as well as its reactions with alkyl halides, have been studied [48] (cf. Table 3). $(CH_3)_3Si-S-Si(CH_3)_3$ and $(C_2H_5)_3Si-S-Si(C_2H_5)_3$ react with the silver compounds AgX (X = Cl, Br, NCS) to form $(CH_3)_3SiX$ and $(C_2H_5)_3SiX$ together with silver sulfide, in accordance with *Eaborn*'s conversion series [41]. "Disilthianes" were converted by mercury oxide into disiloxanes. These disilyl sulfides are surprisingly stable to water and to alkaline solutions.

5. Silanethiols

Silanes containing an Si–SH group are generally more stable than the corresponding oxygen compounds, which condense fairly readily to form disiloxanes. Nevertheless, only a few silanethiols have so far been prepared, since the known methods of preparation are not generally applicable. The simplest compound of this class, silanethiol, has not yet been unambiguously identified. It is thought [52] to be formed from SiH_3Cl and H_2S in the presence of $AlCl_3$. It condenses readily to form disilyl sulfide and exists at room temperature in equilibrium with $(SiH_3)_2S$ [53]:

$$2\,H_3SiSH \rightarrow H_3Si-S-SiH_3 + H_2S \qquad (t)$$

Trichlorosilanethiol (b.p. 96 °C; m.p. −57 °C) [29, 30, 34] is much more stable thermally, and has been obtained by passing $SiCl_4$ and H_2S through red-hot porcelain tubes or by passing a mixture of $SiCl_4$ and HCl over SiS_2 at 1000 °C [34]. Trichlorosilanethiol is a colorless liquid that smells strongly of H_2S and $SiCl_4$; it is hydrolysed by water to form SiO_2, HCl, and sulfur, and it reacts with bromine in accordance with Equation (u).

$$2\,Cl_3SiSH + 3\,Br_2 \rightarrow 2\,Cl_3SiBr + S_2Br_2 + 2\,HBr \qquad (u)$$

The condensation [50] to hexachlorodisilyl sulfide [Equation (v)] occurs only at 650 to 700 °C.

$$2\,Cl_3SiSH \rightarrow Cl_3Si-S-SiCl_3 + H_2S \qquad (v)$$

Br_3SiSH [35a] occurs as an intermediate in the synthesis of *(8)*, and has been isolated by *Weiss* and *Weiss*. It forms colorless trigonal prisms, which crystallize tetragonally in the space group D^3_3d–P3ml, with a = 7.84 Å and c = 6.65 Å; m.p. 96 °C. The central silicon atom is tetrahedrally surrounded by bromine and sulfur, the interatomic distances being Si–Br = 2.25 Å and Si–S 2.28 Å. The compound is methylated to Br_3SiSCH_3 by diazomethane in benzene solution. On electrolysis, hydrogen is formed at the cathode, while yellow needles of $Br_3Si-S-S-SiBr_3$ separate out at the anode; this latter product is very unstable and is converted, *inter alia*, into *(8)* if the electrolysis is prolonged.

In addition to these carbon-free silanethiols, a number of organic derivatives have also been prepared:

1. By the reaction [49] of triorganosilylamines with H_2S:

$$R_3Si\,NHR' + H_2S \rightarrow R_3SiSH + R'NH_2 \qquad (w)$$

2. By substitution of the chlorine in organochlorosilanes with Mg, K, Na, Li, or NH_4 hydrogen sulfides in toluene or with H_2S in the presence of pyridine [37a].

3. By careful alcoholysis of SiS_2 with secondary or tertiary alcohols [40, 54].

Method 1) has been used to prepare $(CH_3)_3SiSH$ (b.p. 75–76 °C); $(C_2H_5)_3SiSH$ (b.p. 158 °C), and $(C_3H_7)_3SiSH$ (b.p. 83–84 °C/7 mm). Method 2) has been used to obtain $(CH_3)_3SiSH$ and $(C_6H_5)_3SiSH$ (m.p. 103 °C), the stability of which is comparable to that of triphenyl-

[52] *A. Stock* and *C. Somieski*, Ber. dtsch. chem. Ges. *66*, 247 (1923).

[53] *A. G. MacDiarmid*, Quart. Rev. (chem. Soc., London) *10*, 212 (1956).

[54] *W. Wojnowski* and *R. Piekos*, Z. anorg. allg. Chem. *314*, 189 (1962).

silanol. Method 3) gave $(t\text{-BuO})_3SiSH$ (b.p. 115 °/35 mm; $n_D^{20} = 1.4231$; $d_4^{20} = 0.924$), $(t\text{-AmO})_3SiSH$ (b.p. 109–110 °C/10 mm; $n_D^{20} = 1.4382$; $d_4^{20} = 0.930$); $(i\text{-PrO})_3SiSH$ (b.p. 188 °C; $n_D^{20} = 1.4075$; $d_4^{20} = 0.919$), and $(s\text{-BuO})_3SiSH$ (b.p. 231–233 °C; $n_D^{20} = 1.4200$; $d_4^{20} = 0.916$).

Alcoholysis of $(SiS_2)_n$ was assumed to yield dithiols and trithiols, $R_2Si(SH)_2$ and $RSi(SH)_3$, but attempts to isolate substances of this kind were unsuccessful.

6. Organothiosilanes $R_nSi(SR')_{4-n}$

Organothiosilanes are formally derived from the silanethiols by replacement of the hydrogen attached to the sulfur by alkyl or aryl groups. The number of theoretically possible organothiosilanes is therefore very large; only a few, however, have so far become known. They can be prepared by the following methods:

1. By the reaction of chlorosilanes with lead [39,55], mercury [56], or sodium mercaptides [57, 61–64], *e.g.*:

$$R_nSiCl_{4-n} + n/2\ Pb(SR')_2 \rightarrow R_nSi(SR')_{4-n} + n/2\ PbCl_2 \quad (x)$$

2. By the reaction [39] of chloroorganothiosilanes with lithium aluminum hydride:

$$Cl_nSi(SR)_{4-n} \xrightarrow{LiAlH} H_nSi(SR)_{4-n} \quad (y)$$

3. By the method of *Larson* [49] described above for the preparation of disilyl sulfides, if mercaptans are used instead of H_2S:

$$R_3Si{-}NR_2 + R'SH \rightarrow R_3Si{-}SR' + R_2NH \quad (z)$$

4. By the reaction [59] of triphenylsilyl-lithium with sulfur followed by coupling with organic chlorides:

$$(C_6H_5)_3SiLi + S \rightarrow (C_6H_5)_3Si{-}SLi \xrightarrow[-LiCl]{RCl} (C_6H_5)_3Si{-}SR \quad (a')$$

5. By the reactions of tri(alkylthio)silanes with bromine at 0 to 70 °C. These reactions yield di(alkylthio)dibromosilanes, tri(alkylthio)bromosilanes, or di(alkylthio)bromosilane [58], depending on the ratio of the reactants:

$$(RS)_3SiH \xrightarrow{Br_2} (RS)_3SiBr + (RS)_2SiBr_2 + (RS)_2SiHBr \quad (b')$$

The Si–S bond is generally very sensitive to hydrolysis, the products being mercaptans and the corresponding Si–O compounds [48]. Alcohols react with thiosilanes to form alkoxysilanes and thioalcohols [48]:

$$R_nSi(SR)_{4-n} + n\ R'OH \rightarrow R_nSi(OR')_{4-n} + n\ RSH \quad (c')$$

In the cases of ethanol and 1-butanol, the reactions are exothermic and the yields high. 2-Propanol and t-butanol, on the other hand, react only on heating, and the yields are low [48].

Abel [48] has shown that silylamines can be prepared from thiosilanes and amines.

$$R^1R^2NH + (H_3C)_3SiSC_2H_5 \rightarrow C_2H_5SH + R^1R^2NSi(CH_3)_3$$
$$(R^1 = R^2 = C_4H_9;\ R^1 = C_4H_9,\ C_6H_5;\ R^2 = H) \quad (d')$$

Acetic anhydride has been treated with five tri(alkylthio)silanes [alkyl = CH_3, C_2H_5, C_3H_7, $CH(CH_3)C_2H_5$, $CH(CH_3)_2$] to form alkyl thioacetates and probably di(alkylthio)silyl acetates; the latter, however, lose another

$$HSi(SCH_3)_3 + (CH_3CO)_2O \rightarrow CH_3CO{-}SCH_3 + CH_3CO{-}OSiH(SCH_3)_2$$
$$\xrightarrow{-CH_3CO{-}SCH_3} \left(-O-\overset{H}{\underset{SCH_3}{Si}}- \right)_x \quad (22)$$

molecule of alkyl thioacetate to form polymers *(22)*, the exact composition of which could not be determined [64a].

Organic halides react with thiosilanes at 100 to 250 °C to form alkylhalogenosilanes and the corresponding thioethers, presumably *via* a sulfonium salt intermediate *(23)* [60].

$$(CH_3)_3Si{-}SR' + RX \rightarrow [(CH_3)_3SiSR'R]^{\oplus}X^{\ominus} \rightarrow (CH_3)_3SiX + RSR' \quad (23)$$

The butylmethyltrimethylsilylsulfonium iodide *(24)* has actually been isolated; it is insoluble in petroleum ether

$$(CH_3)_3Si\ SC_4H_9 + CH_3I \rightarrow [(CH_3)_3Si{-}SC_4H_9(CH_3)]^{\oplus}I^{\ominus} \quad (24)$$

and extremely sensitive to hydrolysis. Attempts to prepare sulfones by the oxidation of the Si–S bond have so far been unsuccessful [55]. The Si–S bond always broke to form disulfides and the corresponding Si–O compounds [55]:

$$R_nSi(SR)_{4-n} \xrightarrow{oxid.} R_nSiO_{(4-n)/2} + n/2\ RSSR \quad (e')$$

[55] *M. Schmeisser* and *A. Haas*, unpublished work; *A. Haas*, Dissertation, Technische Hochschule Aachen, 1960.

[56] *E. V. A. Ebsworth* and *A. J. Downs*, J. chem. Soc. (London) *1960*, 3516.

[57] *S. H. Langer, S. Connell*, and *J. Wender*, J. org. Chemistry *23*, 50 (1958).

[58] *L. Wolinski, H. Tieckelmann*, and *H. W. Post*, J. org. Chemistry *16*, 1138 (1951).

[59] *H. Gilman* and *G. D. Lichtenwalter*, J. org. Chemistry *25*, 1064 (1960).

[60] *E. W. Abel, D. A. Armitage*, and *R. P. Bush*, J. chem. Soc. (London) *1964*, 2455; *E. W. Abel, ibid. 1960*, 4406.

[61] *L. Wolinski, H. Tieckelmann*, and *H. W. Post*, J. org. Chemistry *16*, 395 (1951).

[62] *H. Gilman* and *R. Smart*, J. org. Chemistry *16*, 424 (1951).

[63] *R. S. Schreiber*, US.-Pat. 2465339 (1949), E. I. du Pont de Nemours; Chem. Abstr. *1949*, 6220b.

[64] *H. J. Backer* and *H. A. Clasens*, Recueil Trav. chim. Pas-Bays. *61*, 500 (1942); *H. J. Backer* and *F. Stienstra, ibid. 51*, 1297 (1932); *52*, 912 (1933); *54*, 607 (1935).

[64a] *L. Wolinski, H. Tieckelmann*, and *H. W. Post*, J. org. Chemistry *16*, 1134 (1951).

The only evidence for the existence of silyl sulfones was provided by *Wittenberger*, *Wu*, and *Gilman*[65], who detected a phenyl triphenylsilyl sulfone as an intermediate in the reaction of triphenylsilyl-lithium *(25)* with diphenyl sulfone; however, the intermediate reacted immediately to form tetraphenylsilane and lithium phenylsulfinate.

$$(C_6H_5)_3SiLi \xrightarrow{C_6H_5-SO_2-C_6H_5} (C_6H_5)_3Si-SO_2-C_6H_5 + C_6H_5Li$$
$$\rightarrow (C_6H_5)_4Si + C_6H_5SO_2Li \qquad (25)$$

When lead diphenyl disulfide was used instead of lead mercaptide, or when the reaction was carried out at room temperature, complete substitution of the halogen could not be achieved.

A product with the composition $Si_2(SC_2H_5)_6$ was obtained by the reaction of Si_2Cl_6 with $Pb(SC_2H_5)_2$, but this also tended to undergo rearrangement in accordance with reaction (f').

The existence of both forms, *(26a)* and *(26b)*, is also indicated by infrared measurements. Both forms are thermally unstable and decompose into $Si(SC_2H_5)_4$ and $(SiSC_2H_5)_x$.

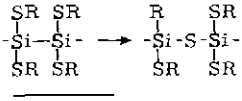
Table 4. Organothiosilanes $R_nSi(SR')_{4-n}$.

Compound	M.p. [°C] (B.p. [°C/mm])	Method of preparation	Yield [%]	Reactions
H_3SiSCF_3	−127; (13.6/760)	1)	50	+ HI → SiH_3I + CF_3SH + $(CH_3)_3N$ → $SiH_3F{\cdot}N(CH_3)_3$ + $(CSF_2{\cdot}N(CH_3)_3)_x$
$Cl_3SiSC_2H_5$	(31/0.1; 42/12)	1)	50	N_2O_4/−20 °C → $(ClSiO_{1.5})$ + NOCl + $C_2H_5SSC_2H_5$
$Cl_3SiSnC_4H_9$	174—177	1)		
$Cl_3SiSC_6H_5$	(113/117)	[a], 1)	72	$Br_2(I_2)$ → $Cl_3SiBr(I)$ + $H_5C_6SSC_6H_5$
$F_2Si(SC_2H_5)_2$ [64]	163—164	1)		
$Cl_2Si(SC_2H_5)_2$	236; (76/0.1)	1)	45	250 °C → + $H_5C_2SSC_2H_5$
$Cl_2Si(SnC_4H_9)_2$	(133.5—135/13)	1)		
$Cl_2Si(SC_6H_5)_2$	(211/15)	1)	46	$Br_2(I_2)$ → $Cl_2SiBr_2(I)_2$ + $H_5C_6SSC_6H_5$
$Br_2Si(SC_2H_5)_2$	(115—115.5/2.5)	5)	24	
$Br_2Si(SiC_4H_9)_2$	(76—79/3.5)	5)	6	
$FSi(C_2H_5)_3$	(114—115/10)	1)		$SiCl_2F_2$ + $NaS(CH_2)_6SNa$ → yellow oil; polymeric $F_2SiS_2(CH_2)_6$
$ClSi(SC_2H_5)_3$	(97/0.1)	1)		
$ClSi(SC_4H_9)_3$	71	1)		+ NaOH → $(C_4H_9S)_3SiOSi(SnC_4H_9)_3$
$ClSi[SCH(CH_3)_2]_3$	71—71.5	1)	12	
$ClSi(SC_6H_5)_3$	(255/2)	1)	30	wax-like at 20 °C
$BrSi(SCH_3)_3$	(80—81/1)	5)	46.5	
$BrSi(SC_2H_5)_3$	(155—58/2.5)	5)	23	
$BrSi(SnC_3H_7)_3$	(136—38/1.5)	5)	61	
$BrSi(SiC_3H_7)_3$	(132—34/2.5)	5)	59	
$BrSi(SiC_4H_9)_3$	(143—44/1)	5)	71	
$(CH_3)Cl_2SiSC_2H_5$	(50—51/18)	1)	10	N_2O_4/−20 °C→$(CH_3SiO_{1.5})_x$ + NOCl + $C_2H_5SSC_2H_5$
$(CH_3)Cl_2SiSC_6H_5$	(84—85/3—4)	1)	10	N_2O_4/−20 °C→$(CH_3SiO_{1.5})_x$ + NOCl + $C_6H_5SSC_6H_5$
$(CH_3)ClSi(SC_2H_5)_2$	(111—113/28)	1)	40	N_2O_4/−20 °C→$(CH_3SiO_{1.5})_x$ + NOCl + $C_2H_5SSC_2H_5$
$(CH_3)ClSi(SC_6H_5)_2$	(192—94/5)	1)	30	N_2O_4/−20 °C→$(CH_3SiO_{1.5})_x$
$(CH_3)_3SiSC_2H_5$	130; (27/12)	1)	50	N_2O_4/−20 °C→$(CH_3)_3SiOSi(CH_3)_3$ + $C_2H_5SSC_2H_5$ +H_2O→$(CH_3)_3SiOSi(CH_3)_3$ + C_2H_5SH +R'SH(ROH)→$(CH_3)_3SiSR'(OR)$ + C_2H_5SH +RCOOH→$(CH_3)_3SiO-CO-R$ + C_2H_5SH +RR'NH→$(CH_3)_3SiNHR$ + C_2H_5SR' +RI→[$(CH_3)_3SiSC_2H_5{\cdot}RI$]→$(CH_3)_3SiI$ + C_2H_5SR
$(CH_3)_3SiSC_6H_5$	(71/3)	1)	80	N_2O_4→$(CH_3)_3SiOSi(CH_3)_3$ + $C_6H_5SSC_6H_5$
$(C_3H_7)_3SiSC_6H_5$	(149—150/10)	3)		With $KMnO_4$ no sulfone can be isolated.
$(CH_3)_2Si(SC_2H_5)_2$	(81/10)	1)	83	N_2O_4/−20 °C→$[(CH_3)_2SiO]_x$ + $C_2H_5SSC_2H_5$
$(C_2H_5)_2Si(SC_2H_5)_2$	(81—82/0.1)	1)		350 °C →
(*o*-Tolyl)$_2$Si(S-*p*-Tolyl)$_2$	112—113	1)		With $KMnO_4$ no sulfone can be isolated.

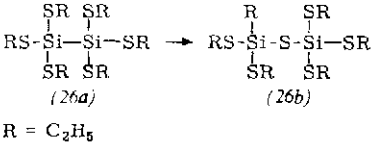
[a] Obtained in 12% yield from $SiCl_4$ and C_6H_5SH [66].

7. Silicon Dimercaptides $[(RS)_2Si]_n$

Attempts to prepare silicon dimercaptides[66a] having the general formula $[Si(SR)_2]_n$ have met with only limited success. $(SiBr_2)_x$ reacts with lead mercaptide at 80 °C complete substitution and subsequent rearrangement:



(f')



(26a) *(26b)*

R = C_2H_5

8. Spectroscopic Investigations

On the basis of infrared and Raman spectroscopic measurements on silanethiols, disilyl sulfides, and 1,3,2,4-dithiadisiletanes, *Goubeau* and *Hirsemann*[67]

[65] *D. Wittenberger*, *T. C. Wu*, and *H. Gilman*, J. org. Chemistry *23*, 1898 (1958).

[66] *H. Jorg* and *J. Stetter*, J. prakt. Chem. [2] *117*, 305 (1927).

[66a] *J. Lugauer*, Dissertation, Technische Hochschule Aachen, 1960.

[67] *J. Goubeau* and *W. D. Hirsemann*, Z. anorg. allg. Chem. *290*, 292 (1957).

found the force constant of the Si–S bond to be k_{Si-S} = 2.28 mdyne/Å, and the absorption region of the Si–S bond (see also [56] and [60]) was found to be from 520 to 400 cm^{-1}. The force constant was determined for Cl_3SiSH with the aid of the value of k_{Si-Cl} = 2.46 mdyne/Å calculated by *Siebert* [68] for $(CH_3)_3SiSCl$. It was concluded from the close resemblance of the spectra that k_{Si-S} = 2.28 mdyne/Å is valid for all silicon-sulfur compounds, any deviations being only slight. This value agrees closely with the theoretical value of 2.22 mdyne/Å calculated by *Siebert* [69] for the Si-S single bond, showing that Si–S bonds possess no appreciable double-bond character. These results were fully corroborated by subsequent investigations [70–73].

The Si–S distance as found by electron diffraction measurements [74] on Cl_3SiSH is 2.14 ± 0.02 Å, compared with the sum of the covalent radii of 2.338 Å given by *Pauling*. This contraction, however, is not attributed to any double-bond character of the Si–S bond, but to the polarity of the σ-bond. Thus, in agreement with the force constants, p_π–d_π bonds play only a minor part in the chemistry of silicon-sulfur compounds, which is in contrast with the chemistry of silicon-oxygen and silicon-nitrogen compounds. It is still uncertain, however, why the Si–S bond, unlike the C–S bond, cannot form adducts (*e.g.* $[(H_5C_2)_3S]^+I^-$).

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Translated by Express Translation Service, London

[68] *H. Siebert*, Z. anorg. allg. Chem. *268*, 177 (1952).

[69] *H. Siebert*, Z. anorg. allg. Chem. *273*, 170 (1953).

[70] *H. R. Linton* and *E. R. Nixon*, J. chem. Physics *29*, 921 (1958).

[71] *E. A. V. Ebsworth*, *R. Taylor*, and *L. A. Woodward*, Trans. Faraday Soc. *55*, 211 (1959).

[72] *H. Kriegsmann*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *61*, 1088 (1957).

[73] *H. Kriegsmann* and *H. Clauss*, Z. anorg. allg. Chem. *300*, 210 (1959).

[74] *C. J. W. Wilkins* and *L. F. Sutton*, Trans. Faraday Soc. *50*, 783 (1954).

Heterocycles Containing Phosphorus

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The preparation of heterocycles containing phosphorus is described. The chemical behavior of ring systems containing trivalent phosphorus is mainly determined by their phosphine character; heterocyclic behavior in the ordinary sense is shown by rings containing functional groups. Syntheses and reactions of cyclic compounds of pentavalent and hexavalent phosphorus are particularly interesting.

Introduction

A. General Methods of Preparation

B. Heterocycles Containing One Phosphorus Atom
   1. Phosphacylopropanes and Phosphacyclobutanes
   2. Five-Membered Rings (phospholanes, phospholenes, phospholes, five-membered rings containing pentavalent phosphorus, phosphindolines, isophosphindolines, phosphofluorenes, phosphafluorenes containing pentavalent and hexavalent phosphorus, spiro compounds)
   3. Six-Membered Rings (phosphorinanes, 1,1-diphenyl-1-phosphabenzene, 1,1-diphenyl-1-phosphanaphthalene, tetrahydrophosphinoline, tetrahydroisophosphinoline, spirophosphonium salts, phospha-anthracene and phosphaphenanthrene)
   4. Seven- and Eight-Membered Rings

C. Heterocycles Containing Two or More Phosphorus Atoms
   1. 1,3-Diphosphacyclohexane. Cyclic Phosphacyanins
   2. 1,4-Diphosphacyclohexane. 9,10-Dihydrophosphanthrene
   3. 1,4-Diphosphabicyclo[2.2.2]octane
   4. 1,2-Diphosphacycles and 1,2,3-Triphosphacycles

D. Phosphorus Heterocycles that also Contain Oxygen or Nitrogen Atoms in the Ring
   1. 1-Oxa-3-phosphacyclopentanes
   2. 1,3-Dioxa-5-phosphacyclohexanes
   3. 9-Phosphaxanthene and 9,10-Dihydrophenophosphazine
   4. 1-Aza-4-phosphacyclohexane and 1,2-Diaza-4-phosphacyclohexane

Introduction

Almost 98 % of all papers dealing with heterocycles containing phosphorus were published within the last fifteen years, and more than 80 % since 1959. This development is the result of the rapid progress made in the organic chemistry of phosphorus, which ceased to be a specialized field with the discovery of the phosphorylide olefinations.

What quantitative or qualitative differences should we expect to find between the heterocyclic systems of nitrogen and of phosphorus? The single-bond covalent

radius[1] of phosphorus (1.1 Å) is 0.4 Å greater than that of nitrogen. The greater bulk of the phosphorus atom is shown by the P–C distances of 1.83 to 1.94 Å (as compared with an N–C distance of 1.47 Å in tertiary amines) found by electron-diffraction and X-ray measurements[2] on tertiary phosphines. The C–N–C valence angle in tertiary amines (107 to 108 °) is close to the terahedral angle, whereas the phosphorus atom in tertiary phosphines (valence angle 98.9 to 99.1 °) is situated at the apex of a much more acute trigonal pyramid[2]. The fact that, in contrast to nitrogen, the phosphine pyramid inverts only at bigh temperatures (activation energy 29 to 31 kcal/mole), as is shown by *Horner*'s isolation and racemization of optically active phosphines[3], must have stereochemical consequences for cyclic phosphines. The electronic configurations of nitrogen and phosphorus are $2s^22p^3$ and $3s^23p^3$, respectively. Experimental evidence shows that trivalent phosphorus does not form double bonds either with itself ($3p_\pi-3p_\pi$) or with carbon ($3p_\pi-2p_\pi$) or nitrogen[4].

Thus we cannot to find a branch of phosphorus chemistry corresponding to that of the aromatic N-heterocycles.

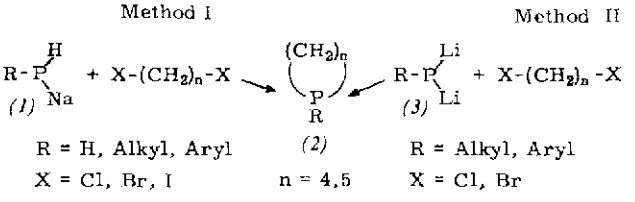
The unique ability of phosphorus to expand its valence shell to include 3d orbitals, *i.e.* to form pentaorganophosphorus compounds, promises new chemical results. In heterocycles in which the phosphorus has five covalent $sd_\sigma-2p_\sigma$ single bonds, it should be possible to observe stereochemical variation, depending on the d-orbitals involved in the hybridization[5]. Finally, ring systems containing pentavalent phosphorus with $3d_\pi-2p_\pi$ double bonds should be obtainable in the form of cyclic methylenephosphoranes.

The difficulties encountered in the nomenclature of organic phosphorus compounds, which have been discussed by *Sasse*[6], are particularly serious in the case of the heterocycles.

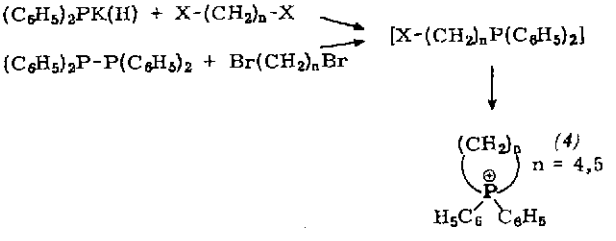
A. General Methods of Preparation

Method I. The monosodium phosphides *(1)*, which result from the reaction of primary phosphines or PH_3 witb sodium (in liquid ammonia[7] or organic solvents[8]), react with dihalogenoalkanes to form cyclic phosphines *(2)*[7,9]. The reaction also (or in some cases even exclusively[9]) yields ω,ω′-diphosphinoalkanes $RHP-(CH_2)_n-PHR$, which can be easily separated by distillation.

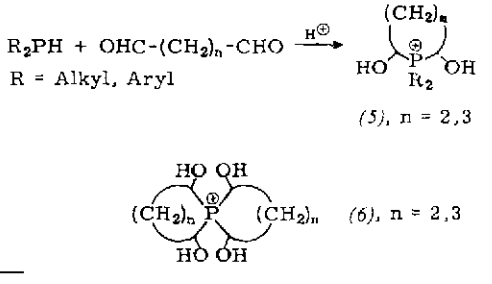
Method II. Dilithium phosphides *(3)*, which can be readily obtained by the introduction of the metal into primary phosphines, also react with dihalogenoalkanes (applying the Ruggli-Ziegler dilution principle) to form *(2)*[10]. Even the primary phosphines themselves react slowly at 80 to 130 °C[11].



Method III. Secondary aliphatic phosphines react with dihalogenoalkanes to form bis(dialkylphosphino)alkanes $R_2P-(CH_2)_n-PR_2$[11]. Potassium diphenylphosphide[13], and even diphenylphosphine itself under forcing conditions[11,12], form the cyclic phosphonium salts *(4)*. The reaction of tetraphenyldiphosphine with dihalogenoalkanes[14] is particularly simple.



Method IV. The acid-catalysed nucleophilic addition of secondary phosphines or PH_3 to dialdehydes provides an elegant synthesis of the α,α′-dihydroxyphosphonium salts *(5)*[15a,15b] and spirophosphonium salts *(6)*[15b–16b], respectively.



[1] *L. Pauling*: The Nature of the Chemical Bond. 2nd ed., Cornell University Press, Ithaca 1948, p. 164–167.

[2] *L. Maier*, Progr. inorg. Chem. *5*, 136 (1963); *J. J. Daly*, J. chem. Soc. (London) *1964*, 3799.

[3] *L. Horner, H. Winkler, A. Rapp, A. Mentrup, H. Hoffmann* and *P. Beck*, Tetrahedron Letters *1961*, 161; *L. Horner* and *H. Winkler, ibid. 1964*, 461; *L. Horner, P. Schedlbauer*, and *P. Beck, ibid. 1964*, 1421.

[4] See, however, *K. Dimroth* and *P. Hoffmann*, Angew. Chem. *76*, 433 (1964); Angew. Chem. internat. Edit. *3*, 384 (1964).

[5] *R. F. Hudson* and *M. Green*, Angew. Chem. *75*, 47 (1963); Angew. Chem. internat. Edit. *2*, 11 (1963).

[6] *K. Sasse* in Houben-Weyl: Methoden der organischen Chemie. Georg Thieme, Stuttgart 1963, Vol. 12, I.

[7] US.-Pat. 3086053 (Apr. 16th, 1963), inventor: *R. I. Wagner*, Chem. Abstr. *59*, 10124 (1963); US.-Pat. 3086056; Chem. Abstr. *60*, 559 (1964).

[8] *F. Pass, E. Steininger*, and *H. Schindlbauer*, Mh. Chem. *90*, 148, 792 (1959).

[9] *K. Issleib* and *D. Jakob*, Chem. Ber. *94*, 107 (1961); *K. Issleib* and *F. Krech, ibid. 94*, 2656 (1961).

[10] *K. Issleib* and *S. Häusler*, Chem. Ber. *94*, 113 (1961).

[11] *K. Issleib, K. Krech*, and *K. Gruber*, Chem. Ber. *96*, 2186 (1963).

[12] *S. O. Grim* and *R. Schaaff*, Angew. Chem. *75*, 669 (1963); Angew. Chem. internat. Edit. *2*, 436 (1963).

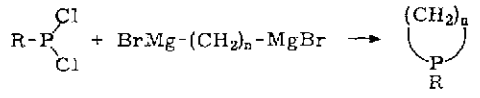
[13] *G. Märkl*, Angew. Chem. *75*, 669 (1963); Angew. Chem. internat. Edit. *2*, 479 (1963).

[14] *G. Märkl*, Angew. Chem. *75*, 859 (1963); Angew. Chem. internat. Edit. *2*, 620 (1963).

[15a] *Sh. A. Buckler* and *M. Epstein*, J. org. Chemistry *27*, 1090 (1962); Tetrahedron *18*, 1231 (1962); French. Pat. 1348669; Chem. Abstr. *60*, 15912 (1964).

[15b] *M. Grayson*, Chem. Engn. News No. 49, *40*, 90 (1962).

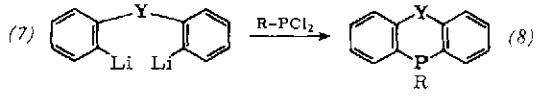
Method V. Reactions of bifunctional Grignard compounds with halogenophosphines (a reversal of Methods I and II) were used by *Grüttner* [17] in the first synthesis of cyclic phosphines. Contrary to earlier belief [20],



R = Alkyl[18], Aryl[17], $N(CH_3)_2$[19] *(2)*, n = 4,5

ring closure evidently does not take place with phosphonic chlorides $R-POCl_2$ [R = $N(C_2H_5)_2$, C_6H_5] or phosphites [21].

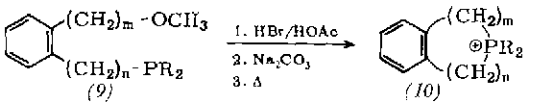
Method VI. The use of bifunctional lithium compounds in reactions corresponding to method V is restricted to the 2,2-dilitbiumdiphenyl derivatives *(7)*, which can be readily obtained by reaction of the 2,2'-dibromides with lithium. This method can, however, be adapted for the synthesis of a very wide range of ring systems *(8)* by variation of the bridging group Y.



Y = -[22a–22c], $(CH_2)_2$[23], PR[24], NR[25a,25b], O[26]; R = Alkyl, Aryl

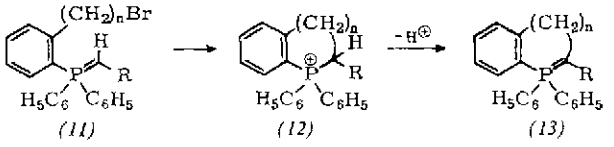
Method VII. Intramolecular formation of quaternary salts *(10)* from ω-bromoalkylphosphines, which are readily available from tertiary phosphines *(9)* containing an ω-alkoxy side chain by cleavage of the ether linkage.

Method VIII. Formation of *(12)* by intramolecular *C*-alkylation of the ylides *(11)* derived from the phosphonium salts, using the ω-bromoalkyl side chain in



n = 0, m = 2,3[27-29]; n=m = 1[30,31]; n = 2, m = 1[32]
R = C_2H_5, C_6H_5

the *o*-position as the alkylating agent [33]. With 2 moles of base, the cyclic methylenephosphoranes *(13)* are formed directly from the open-chain salts.

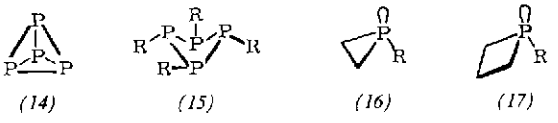


R = C_6H_5, $COOCH_3$; n = 1, 2, 3

B. Heterocycles Containing One Phosphorus Atom

1. Phosphacyclopropanes and Phosphacyclobutanes

As is shown by the examples of the tetrahedral P_4 *(14)* (valence angle 60°) and the cyclotetraphosphines *(15)*, phosphorus forms very stable small rings with itself. The ring strain may be reduced by spd hybridization [34], and stabilization of *(15)* by p_π-d_π double bonds between the phosphorus atoms has been suggested [35].



Small phosphorus-carbon rings are difficult to prepare. 1-Substituted phosphacyclopropanes *(16)* (R = H, CH_3) and unsubstituted phosphacyclobutane *(17)*, R = H, can be synthesized by Method I (for n = 3 and R = alkyl or aryl, only the open-chain phosphines are obtained [7]).

Formation of the four-membered ring is also suppressed in Methods II, III, and VII in favor of polymer formation [10,14] or cyclodimerization [12,29]. An unusual cycloaddition of PCl_3 (as $PCl_2^{\oplus}/AlCl_4^{\ominus}$) to 1,4,4-trimethylpent-2-ene yields the phosphinic acid *(18)* [36].

[16a] *Sh. A. Buckler* and *V. P. Wystrach*, J. Amer. chem. Soc. *80*, 6454 (1958); *83*, 168 (1961).

[16b] US.-Pat. 2969398 (Jan. 24th, 1961), inventor: *Sh. A. Buckler*; Chem. Abstr. *55*, 17660 (1961); *Sh. A. Buckler* and *M. Epstein*, Tetrahedron *18*, 1211 (1962).

[17] *G. Grüttner* and *M. Wiernik*, Ber. dtsch. chem. Ges. *48*, 1473 (1915); *G. Grüttner* and *E. Krause*, *ibid. 49*, 437 (1916).

[18] US.-Pat. 2853518 (Sept. 23rd, 1958), inventor: *W. J. Balon*; Chem. Abstr. *53*, 5202 (1959).

[19] *A. B. Burg* and *P. J. Slota Jr.*, J. Amer. chem. Soc. *82*, 2148 (1960).

[20] *G. M. Kosolapoff* and *R. F. Struck*, J. chem. Soc. (London) *1957*, 3739.

[21] *G. Hilgetag*, *H.-G. Henning*, and *D. Gloyna*, Z. Chem. *4*, 347 (1964).

[22a] *G. Wittig* and *G. Geissler*, Liebigs Ann. Chem. *580*, 44 (1953).

[22b] *G. Wittig* and *A. Maerker*, Chem. Ber. *97*, 747 (1964).

[22c] *A. F. Bedford*, *D. M. Heinekey*, *J. T. Millar*, and *C. Mortimer*, J. chem. Soc. (London) *1962*, 2932.

[23] *F. G. Mann*, *I. T. Millar*, and *B. B. Smith*, J. chem. Soc. (London) *1953*, 1130.

[24] *M. Davis* and *F. G. Mann*, Chem. and Ind. *1962*, 1539; J. chem. Soc. (London) *1964*, 3770.

[25a] *E. R. H. Jones* and *F. G. Mann*, J. chem. Soc. (London) *1956*, 786.

[25b] *G. Baum*, *H. A. Lloyd*, and *C. Tamborski*, J. org. Chemistry *29*, 3410 (1964).

[26] *F. G. Mann* and *I. T. Millar*, J. chem. Soc. (London) *1953*, 3746.

[27] *F. G. Mann* and *I. T. Millar*, J. chem. Soc. (London) *1951*, 2205.

[28] *M. H. Beeby* and *F. G. Mann*, J. chem. Soc. (London) *1951*, 411.

[29] *G. Märkl*, Angew. Chem. *75*, 168 (1963); Angew. Chem. internat. Edit. *2*, 153 (1963).

[30] *F. G. Mann*, *I. T. Millar*, and *F. H. C. Stewart*, J. chem. Soc. (London) *1954*, 2832.

[31] *F. G. Mann*, *I. T. Millar*, and *H. R. Watson*, J. chem. Soc. (London) *1958*, 2516.

[32] *F. G. Holliman* and *F. G. Mann*, J. chem. Soc. (London) *1947* 1634.

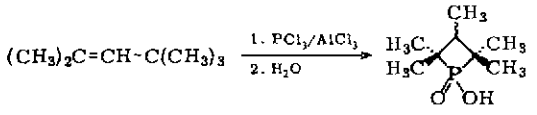
[33] *G. Märkl*, Z. Naturforsch. *18b*, 84 (1963).

[34] *L. Pauling* and *Simonetta*, J. chem. Physics *20*, 29 (1952).

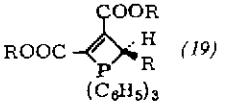
[35] *W. Mahler* and *A. B. Burg*, J. Amer. chem. Soc. *79*, 251 (1957); *80*, 6161 (1958).

[36] *J. J. McBride Jr.*, *E. Jungermann*, *J. V. Killheffer*, and *R. J. Clutter*, J. org. Chemistry *27*, 1833 (1962); see also [20].

The four-membered ring is not opened even under extreme conditions (*e.g.* boiling conc. HNO_3 or boiling aqueous conc. NaOH), indicating that there is no internal strain.



(18)



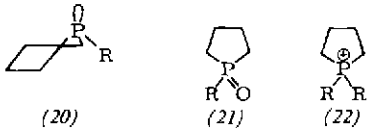
(19)

On the basis of considerations regarding the reaction mechanism, the reaction of alkylidenetriphenylphosphoranes with esters of acetylenedicarboxylic acid [37] or with arynes [38] must proceed *via* 1,1,1-triphenylphosphacyclobut-2-enes *(19)*.

2. Five-Membered Rings

a) Phospholanes

Phospholanes *(20)* have been prepared by Methods I, II, and V. Another interesting preparation is the reduction of dimethylamide *(20)* [R = $N(CH_3)_2$] to 1*H*-phospholane *(20')* by the pyrolysis of the BH_3 adduct *(23)* [19,39].



(20) *(21)* *(22)*

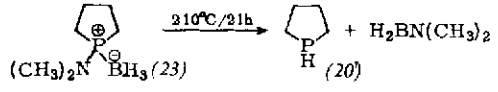


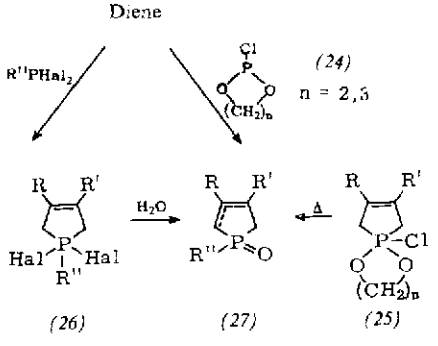
Table 1. Comparison of phospholanes *(20)* with the analogous pyrrolidines *(20a)*.

R	*(20)* b.p. [°C/mm]	*(20a)* b.p. [°C/mm]
C_2H_5	145—147/760	107/760
C_6H_5	97/3	124/14

The phospholanes are mostly oily, distillable, unassociated liquids (cf. Table 1) having the characteristic phosphine odor. They are oxidized to the oxides *(21)* by atmospheric oxygen, but the reaction is much slower than that of open-chain phosphines. Like all tertiary phosphines [40], they are strongly nucleophilic and react with alkyl halides, sometimes in an exothermic reaction, to form the phosphonium salts *(22)* (R = alkyl) by an S_N2 mechanism. In accordance with *Ingold*'s rule [41], diaryl-substituted salts (which can be prepared by Method III) are degraded by aqueous alkali to the oxide *(21)* (R = aryl) without suffering ring cleavage.

b) Phospholenes

McCormack [42] discovered in 1955 that, in the presence of polymerization inhibitors (*e.g.* Cu stearate), aryldihalogenophosphines add onto dienes in a quasi-Diels-Alder reaction to form 1-aryl-1,1-dibalogenophospholenes *(26)*, which are readily hydrolysed to 1-arylphospholene oxides *(27)*. Modifications of this synthesis were achieved by the use of PCl_3, PBr_3 [43a–44], and



(26) *(27)* *(25)*

$RO-PHal_2$ [45]. Diene = butadiene, isoprene, 2,3-dimethylbutadiene, chloroprene, dicyclohexylidene, *etc.*; R″ = phenyl, *p*-tolyl, mesityl, CH_3, C_2H_5, OC_2H_5, OC_6H_5, Cl, Br, *etc.*

The diene component must be able to assume a *cisoid* conformation (1,1-disubstituted dienes do not react) and 1-substituted dienes must be in the *trans* form. Phosphorus bromides are more reactive than the chlorides. The average reaction time (1 to 10 days at 25 °C) is increased by bulky and electronegative substituents in the diene. The ring closure probably starts with the nucleophilic addition of the phosphine to the 1-position of the diene.

The use of a dihalide $R''PHal_2$ is not absolutely necessary, as is shown by the addition of cyclic monochlorophosphites *(24)* to dienes to form the spiro intermediates *(25)*, which then undergo rearrangement to *(27)*,

[37] *S. T. D. Gough* and *S. Trippett*, Proc. chem. Soc. (London) *1961*, 302; *J. B. Hendrickson*, J. Amer. chem. Soc. *83*, 2018 (1961); *J. B. Hendrickson, R. Rees, J. F. Templeton*, *ibid.* *86*, 107 (1964); *H. J. Bestmann* and *O. Rothe*, Angew. Chem. *76*, 569 (1964); Angew. Chem. internat. Edit. *3*, 512 (1964); *G. W. Brown, R. C. Cookson*, and *I. D. Stevens*, Tetrahedron Letters *1964*, 1263.

[38] *E. Zbiral*, Tetrahedron Letters *1964*, 3963.

[39] US.-Pat. 3025326 (March 12th, 1962), inventors: *A. B. Burg* and *R. I. Wagner*; Chem. Abstr. *57*, 8619 (1962).

[40] *W. A. Henderson* and *Sh. A. Buckler*, J. Amer. chem. Soc. *82*, 5794 (1960).

[41] *G. W. Fenton* and *C. K. Ingold*, J. chem. Soc. (London) *1929*, 2342.

[42] *W. B. McCormack*: US.-Pat. 2663736 (Dec. 22nd, 1953), and 2663737 (Dec. 22nd, 1953); Chem. Abstr. *49*, 7601 (1955); US.-Pat. 2663738 (Dec. 22nd, 1953); Chem. Abstr. *49*, 7602 (1955).

[43a] *U. Hasserodt, K. Hunger*, and *F. Korte*, Tetrahedron *19*, 1563 (1963).

[43b] *K. Hunger, U. Hasserodt*, and *F. Korte*, Tetrahedron *20*, 1593 (1964)

[43c] Belg. Pat. 631416 (Nov. 18th, 1963); Chem. Abstr. *61*, 688 (1964).

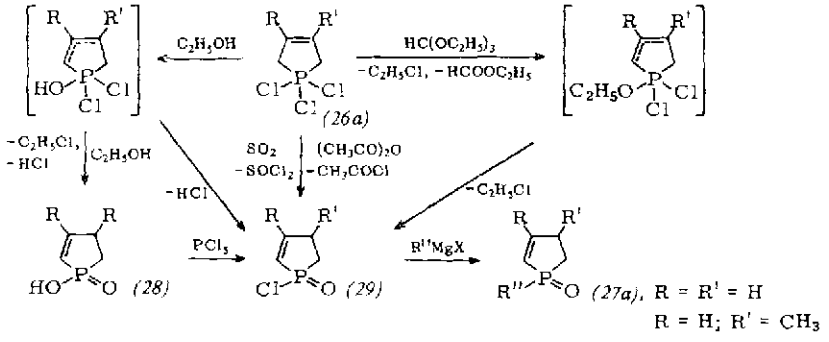
[44] *B. A. Arbuzov* and *A. O. Vizel*, Dokl. Akad. Nauk U.S.S.R. *158* (5), 1105 (1964); Chem. Abstr. *62*, 2791 (1965).

[45] *B. A. Arbuzov* and *L. A. Shapshinskaya*, Izv. Akad. Nauk U.S.S.R., Otdel. khim. Nauk *1962*, 65; Chem. Abstr. *57*, 13791 (1962).

[46] *N. A. Razumova* and *A. A. Petrov*, Zh. obshch. Khim. *31*, 3144 (1961); *33*, 783 (1963); *33*, 3858 (1963); *34*, 1886 (1964); Chem. Abstr. *56*, 12720 (1962); *59*, 8738 (1963); *60*, 10711 (1964); *61*, 8336 (1964).

R″ = $O-(CH_2)_2Cl$, $O-(CH_2)_3Cl$, by an intramolecular Michaelis-Arbusow reaction[46,47].

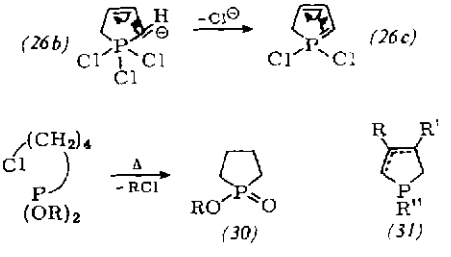
Korte[43b] recognized that the hydrolysis of the primary adduct *(26)* to yield *(27)* may be accompanied by migration of the double bond to the 2-position. The two possible products can be distinguished on the basis of ultraviolet, infrared, and NMR data[48]. The PCl_3 adducts *(26a)* (R = H; R′ = H, CH_3) undergo complete rearrangement in all their reactions, whereas a mixture of both isomers is formed in the case of R = R′ = CH_3. The reactivity of the adducts *(26a)* is similar to that of



PCl_5. Thus alcohols are chlorinated by *(26a)*, which is itself converted into the phosphinic acid *(28)* and the acid chloride *(29)*. Reactions with SO_2, acetic anhydride, and above all, orthoesters of carbocylic acids[49] permit the direct preparation of the acid chlorides *(29)*, which can then be converted into esters, thioesters, amides, and (by reaction with Grignard reagents) tertiary phospholene oxides *(27a)* (R″ = alkyl, aryl). The double bond never migrates in the PBr_3[43b] and CH_3PCl_2 adducts[50].

The tendency of the double bond to migrate is increased by a high concentration of strongly electronegative substituents on the phosphorus, and decreased by the presence of CH_3 groups in positions 3 and 4 (stabilization by hyperconjugation). The first step of the rearrangement is probably the removal of a strongly acidic α-proton to form a carbanion *(26b)* or an ylide *(26c)*.

Partial interconversion of the Δ^2- and Δ^3-phospholene oxides *(27)* occurs on heating at 200 to 300 °C or in the presence of strong bases such as $KOC(CH_3)_3$[43b,50,51].

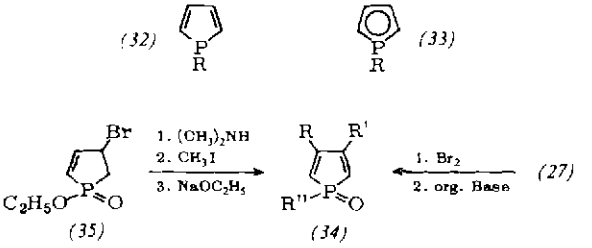


Oxophospholanes can be obtained by catalytic hydrogenation of the double bond in *(27)* with Raney nickel, Adams' catalyst, or noble metal catalysts[42,43c]. *Helferich*[52] achieved an independent synthesis of 1-alkoxy-1-oxophospholane *(30)* by an intramolecular Michaelis-Arbuzov reaction [R = C_2H_5, $(CH_2)_3CH_3$; yield = 75 %].

The primary adducts *(26)* are dehalogenated by Mg turnings in tetrahydrofuran[53] or by $LiAlH_4$[18,53] to 1-substituted phospholenes *(31)*, [R = R′ = H, CH_3; R″ = CH_3, C_6H_5; yield = 20–40 %], with retention of the double bond (the position of which, however, must be checked). The phosphinic acids and their esters *(27)* [R″ = OH, $O(CH_2)_2Cl$] are reduced to *(31)* by $LiAlH_4$[54].

c) Phospholes

The reason for the great interest shown in the phosphole ring system is the question whether it behaves like pyrrole, *i.e.* whether the phosphorus atom in *(32)* makes its lone electron pair available for the formation of an aromatic system of 6 π-electrons *(33)*. Phosphole oxides *(34)* were obtained by *Howard*[55] (R = R′ = H, CH_3; R = H, R′ = CH_3; R″ = C_6H_5) by dehydrobromination of the bromine adducts of *(27)* with organic bases, and by *Westheimer*[56] (R = R′ = H; R″ = OC_2H_5) from the allyl bromide *(35)* or by Hofmann degradation of the methylphosphonium iodide prepared from *(35)*. As expected, the phosphole oxides *(34)* behave as cyclic



[47] *B. A. Arbuzov, L. A. Shapshinskaya,* and *V. M. Erokhina,* Izv. Akad. Nauk U.S.S.R., Otdel. khim. Nauk *1962*, 2074; Chem. Abstr. *58*, 11396 (1963); *B. A. Arbuzov* and *L. A. Shapshinskaya,* Izv. Akad. Nauk U.S.S.R., Otdel. khim. Nauk *1964*, 581; Chem. Abstr. *60*, 15903 (1964).

[48] *H. Weitkamp* and *F. Korte,* Z. analyt. Chem. *204*, 245 (1964).

[49] *K. Hunger* and *F. Korte,* Tetrahedron Letters *1964*, 2855.

[50] *L. D. Quinn* and *J. A. Peters,* Tetrahedron Letters *1964*, 3689.

[51] *E. W. Müller* and *F. Korte,* Tetrahedron Letters *1964*, 3039.

[52] *B. Helferich* and *E. Autderhaar,* Liebigs Ann. Chem. *658*, 100 (1962).

[53] *L. D. Quinn* and *D. A. Mathews,* J. org. Chemistry *29*, 836 (1964); Dissertat. Abstr. *24*, (3) 997 (1963).

[54] *G. M. Bogolyubov, N. A. Razumova,* and *A. A. Petrov,* Zh. obshch. Khim. *33*, 2419 (1963); Chem. Abstr. *59*, 1408 (1963).

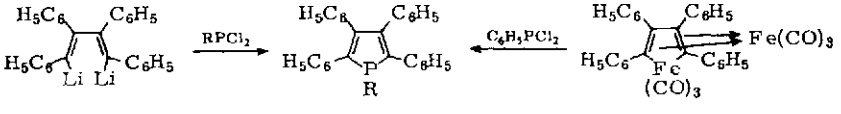
[55] *E. Howard Jr.* and *R. E. Donadio,* Abstr. Papers, Amer. chem. Soc. *1959*, 100-P.

[56] *D. A. Usher* and *F. Westheimer,* J. Amer. chem. Soc. *86*, 4732 (1964).

dienes. They form crystalline dimers (for R″ = C_6H_5) on standing at room temperature. The tendency to dimerize is so great in the case of 1-ethoxyphosphole oxide that this compound can only be detected by ultraviolet spectroscopy or by interception as the Diels-Alder adduct.

The phospholes themselves are obtained by a number of syntheses that are both simple and elegant. *Campbell*[57] prepared 1,3,5-triphenylphosphole [yellow needles, m.p. 186.5–187.5 °C] in a single step by the cycloaddition of $C_6H_5PCl_2$ to 1,4-diphenylbutadiene at 226 to 230 °C (thermal dehydrochlorination after migration of the halogen in *(26)* from the phosphorus to the double bond?).

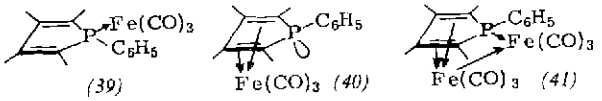
Hübel and *Braye*[58] and *Leavitt*[59] discovered about simultaneously that 1,4-dilithio-1,2,3,4-tetraphenylbuta-1,3-diene *(36)*[60], which is readily obtainable by the dimerization of diphenylacetylene with lithium, is a useful starting material for the synthesis of phospholes. It reacts with dihalogenophosphines to form *P*-alkyl- or *P*-aryl-2,3,4,5-tetraphenylphospholes *(37)*, [R = C_6H_5: light yellow needles; m.p. 255–256 °C; UV: λ_{max} (log ε) = 357.5 mμ (3.945), 320 mμ (3.94), 247.5 mμ (4.51); strong fluorescence with maximum at 480 mμ], while the phosphole oxide is obtained directly by the reaction of *(36)* with $C_6H_5P(O)Cl_2$.



(36) *(37)* R = C_6H_5, CH_3, $C_6H_5CH_2$ *(38)*

Related to this in principle is a second synthesis described by *Hübel*[58]: The $Fe(CO)_3$ complex *(38)* of butadiene[61], which is obtained by the reaction of $[Fe(CO)_4]_3$ with diphenylacetylene in boiling petroleum ether, reacts with $C_6H_5PCl_2$ at 140 °C to form pentaphenylphosphole.

The stability of triphenylphosphole and pentaphenylphosphole towards oxygen is the same as that of tertiary aromatic phosphines; benzylphosphole and methylphosphole are more liable to autoxidation. The diene character of pentaphenylphosphole oxide is shown by the formation of an adduct with maleic anhydride (yield = 67 %); the pentaphenylphosphole itself, on the other hand, gives only a 3 % yield of this adduct, so that prior oxidation appears to be possible and essential. Diethyl acetylenedicarboxylate, however, forces even 1,3,5-triphenylphosphole and *(37)* (R = C_6H_5) into diene reactions, which result in the loss of the C_6H_5P group and formation of the phthalate esters. The availability of the lone electron pair on the phosphorus becomes obvious with the quantitative formation of the σ-complex *(39)* with $Fe(CO)_5$; reaction with $[Fe(CO)_4]_3$ in addition yields the π-complexes *(40)* characteristic of conjugated dienes and *(41)*.



(39) *(40)* *(41)*

Pentaphenylphosphole oxide forms a π-complex corresponding to *(40)*, whereas the sulfide, surprisingly, yields the complex *(39)*. The tendency of the P=S bond to undergo cleavage is observed even in the reaction of *(36)* with $C_6H_5P(S)Cl_2$, which yields 45 % of pentaphenylphosphole together with 1 % of the sulfide.

Using the LCAO and SCFMO methods, respectively, *Brown*[62] calculated conjugation energies of 1.37 and 1.49 β for pyrrole and for the unsubstituted phosphole. The ease of oxidation of 1,3,5-triphenylphosphole and *(37)*, in comparison with pyrrole, can be explained by the fact that the PO bond energy is 70–90 kcal/mole greater than the NO bond energy, so that the loss of conjugation energy is more than compensated.

As is shown by a comparison of the experimental P=O dissociation energies[22a] (Table 2), the conjugation energy in the phosphole, as compared with the corresponding oxide, is much greater than in all other phosphines. The decrease in the D_{PO} value has been explained by increasing participation of the 3pπ-orbital in the conjugation.

Table 2. Dissociation energies of the P–O bonds in some phosphine oxides.

Phosphine oxide	$D_{P=O}$ [kcal/mole]
Pentaphenylphosphole oxide	100.4 ± 9.5
9-Phenyl-9-phosphafluorene oxide	126.0 ± 9.0
Triphenylphosphine oxide	128.4 ± 5.5
Trimethylphosphine oxide	139.3 ± 3.0

Since the D_{PS} values are about 50 kcal/mole lower than the D_{PO} values[2], the formation of the phosphole from the sulfide could also be "financed" by the gain in conjugation energy. The difference of 39 ± 13 kcal/mole in comparison with trimethylphosphine oxide is regarded as a measure of the conjugation energy of the phosphole[22a]. The discussion of the bonding system in the phospholes is not yet closed.

d) Five-Membered Rings Containing Pentavalent Phosphorus

Triphenylphosphine reacts with esters of acetylenedicarboxylic acid at −50 °C to form an unstable yellow 1:2 adduct, which undergoes rearrangement to *(43)*

[57] *I. M. Campbell, R. C. Cookson,* and *M. B. Hocking,* Chem. and Ind. *1962,* 359.

[58] *E. H. Braye* and *W. Hübel,* Chem. and Ind. *1959,* 1250; *E. H. Braye, W. Hübel,* and *I. Capier,* J. Amer. chem. Soc. *83,* 4406 (1961).

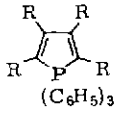
[59] *F. C. Leavitt, T. A. Manuel,* and *F. Johnson,* J. Amer. chem. Soc. *81,* 3163 (1959); *F. C. Leavitt, T. A. Manuel, F. Johnson, L. U. Matternas,* and *D. S. Lehmann, ibid. 82,* 5099 (1960).

[60] *L. I. Smith* and *H. H. Hoehn,* J. Amer. chem. Soc. *63,* 1184 (1941).

[61] *W. Hübel* and *E. H. Braye,* J. inorg. nuclear Chem. *10,* 250 (1959).

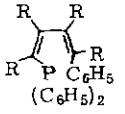
[62] *D. A. Brown,* J. chem. Soc. (London) *1962,* 929.

even at room temperature[63]. On the basis of PMR measurements and the observation that the migration of the phenyl group is catalysed by $H^{\oplus}$, the primary adduct is assumed by *Hendrickson*[64] to possess the structure *(42a)*, in which the phosphorus forms five covalent $3p_\sigma-2p_\sigma$ bonds. The red acetylenedicarbonitrile adduct, for which structure *(42b)* has been postulated by *Reddy* and *Weis*[65], is unusually stable (dec. point 245 °C) in comparison with *(42a)*, as is the 1,1,1-triphenyloctacyanophosphole *(44)* (dec. point 230 °C) obtained in an exothermic reaction with tetracyanoethylene.



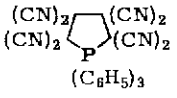
$(C_6H_5)_3$

(42a), R = $COOCH_3$
(42b), R = CN



$(C_6H_5)_2$

(43), R = $COOCH_3$

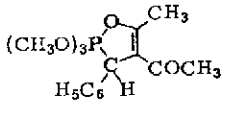
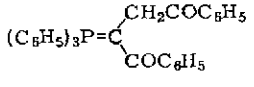


$(C_6H_5)_3$

(44)

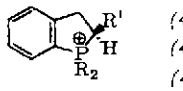
The ^{31}P–NMR spectrum of *(44)* shows a chemical shift δ of −22 ppm[65]. Since according to recent NMR studies, δ-^{31}P values of +25 to +100 ppm are to be expected for compounds of pentavalent phosphorus (phosphoranes) (see Table 3), at least the structure of *(44)* appears uncertain.

Table 3. Chemical shifts of ^{31}P–NMR signals for compounds containing pentavalent phosphorus, based on 85 % H_3PO_4 as external standard.

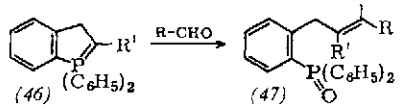
Compound	σ [ppm]	Ref.
(63a)	+97 ± 2	[67]
(63d)	+85 ± 2	[67]
$P(OC_2H_5)_5$	+70.9	[66a]
	+27.9	[66b]
	−16.9	[66b]
$[(C_6H_5)_4P]^{\oplus}Br^{\ominus}$	−22	[65]

e) Phosphindolines and Isophosphindolines

The phosphindolinium salts *(45)* are readily obtainable by methods VII[27,29] and VII[33]. Cyclic ylides *(46)* prepared by the reaction of *(45b)* and *(45c)* with potassium t-butoxide [or directly from *(11)*, n = 1] react with aldehydes in normal Wittig olefinations, with ring cleavage, to form the olefins *(47)*[33].

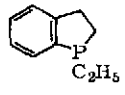
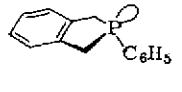


(45a), R' = H; R = C_2H_5
(45b), R' = H; R = C_6H_5
(45c), R = R' = C_6H_5



(46) *(47)*

As expected[68], 1-ethylphosphindoline *(48)* (b.p. 102 to 104 °C/13 mm) is formed on pyrolysis of *(45a)* at 350 to 375 °C (yield 75 %); 2-phenylisophosphindoline *(49)* is obtained in a similar manner[31]. The phosphine *(49)* possesses the unusual ability to form stable complexes having abnormal coordination numbers with transition metals of group VIII. Whereas the complexes

(48)   *(49)*

formed by aliphatic and aromatic phosphines, as well as by *(48)*, are normal *(50)*, covalent or ionic (depending on the solvent) complexes *(51)* with the coordination number 5 are also formed from *(49)*[69].

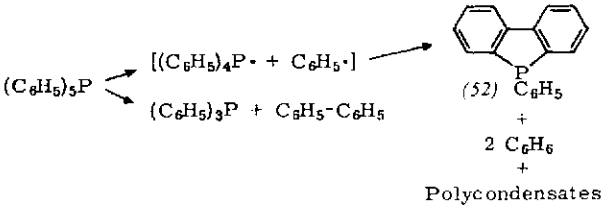
$[(Phosphine)_2PdCl_2]$ *(50)* $[A_3MX_2] \rightleftharpoons [A_3MX]^{\oplus}X^{\ominus}$ *(51)*

A = *(49)*; M = Pd, Pt, Ni, Co; X = Cl, Br, I, SCN

The explanation for this is probably the combination of favorable steric (quinuclidine character) and electronic factors (favorable relationship between optimum $P \rightarrow M$ σ-bonding and π-back donation).

f) 9-Phosphafluorenes

Of theoretical interest is the formation of 9-phenyl-9-phosphafluorene *(52)* on thermal decomposition of pentaphenylphosphorane either in the melt or in boiling benzene[22b,70,71]. The ring closure may be initiated by the removal of hydrogen atoms from the *o*-position by phenyl radicals. According to *Razuvaev*[71], the yield of 9-phospha-



(52) C_6H_5
+
2 C_6H_6
+
Polycondensates

[63] *A. W. Johnson* and *J. C. Tebby*, J. chem. Soc. (London) *1961*, 2126.

[64] *J. B. Hendrickson*, *R. E. Spenger*, and *J. J. Sims*, Tetrahedron Letters *1961*, 447; Tetrahedron 9, 707 (1963).

[65] *G. R. Reddy*, and *C. D. Weis*, J. org. Chemistry *28*, 1822 (1963).

[66a] *D. B. Denney* and *S. T. D. Gough*, J. Amer. chem. Soc. *87*, 138 (1965).

[66b] *F. Ramirez*, *A. V. Patwardhan*, and *S. R. Heller*, J. Amer. chem. Soc. *86*, 519 (1964); *F. Ramirez*, *O. P. Madan*, and *C. P. Smith*, Tetrahedron Letters *1965*, 201.

[67] *D. Hellwinkel*, Chem. Ber., in the press; personal communication.

[68] *G. F. Fenton*, *L. Hey*, and *C. K. Ingold*, J. chem. Soc. (London) *1933*, 989.

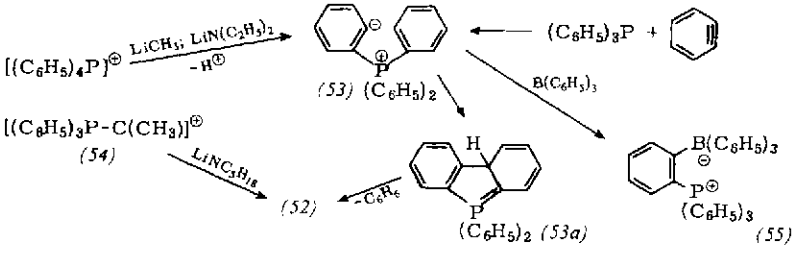
[69] *J. W. Collier*, *F. G. Mann*, *D. G. Watson*, and *H. R. Watson*, J. chem. Soc. (London) *1964*, 1803; *J. W. Collier* and *F. G. Mann*, *ibid. 1964*, 1815; *J. W. Collier*, *A. R. Fox*, *I. G. Hinton*, and *F. G. Mann*, *ibid. 1964*, 1819.

[70] *G. Wittig* and *M. Rieber*, Liebigs Ann. Chem. *562*, 187 (1949).

[71] *G. A. Razuvaev* and *N. A. Osanova*, Dokl. Akad. Nauk U.S.S.R. *104*, 552 (1955); Chem. Abstr. *50*, 11268c (1956); Zh. obshch. Khim. *26*, 2531 (1956); Chem. Abstr. *51*, 1875 (1957); Zh. obsheh. Khim. *27*, 1466 (1957); Chem. Abstr. *52*, 3715 (1958).

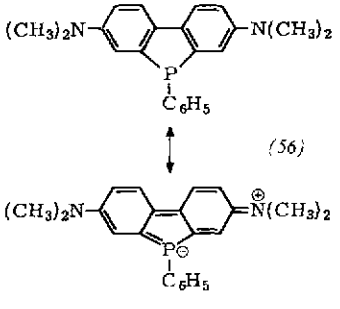
fluorene increases to 60 % if the reaction is carried out in pyridine at room temperature (150 hours) (see also [22b]).

The tetraphenylphosphonium cation reacts with methyl-lithium [22b, 73] or lithium diethylamide (yield 60 %) [72] to form *(52)*. The cyclization, which is facilitated by the inductive and mesomeric effects of the cation, is preceded by the introduction of the metal into the *o*-position to form *(53)*; the ylide *(53a)* then loses benzene to form *(52)*.



The fact that, even in *(54)*, the *o*-attack by the metal is preferred to attack on the β-hydrogen atoms of the t-butyl group is shown by the formation of *(52)* [42 %, together with 8 % of $(C_6H_5)_3P$] on reaction of *(54)* with lithium piperidide [73]. A second route to *(52)* *via* the intermediate *(53)* is the addition of benzene to triphenylphosphine, discovered by *Wittig* and *Benz* [74]; *(53)* was intercepted as the $B(C_6H_5)_3$ adduct *(55)*. This reaction became preparatively important as a result of *Zbiral*'s work [75]. The surprising formation of *(52)* (yield 10 %) from $(C_6H_5)_3P$ and phenylsodium [70] undoubtedly proceeds by an *o*-deprotonation, although this reaction is not favored.

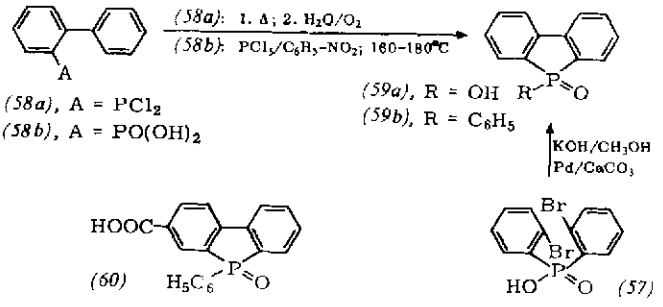
The conventional Method VI [22a–22c] was found to be particularly useful for the synthesis of *(56)* and of 9-(*p*-dimethylaminophenyl)-9-phosphafluorene. The bright



yellow phosphine *(56)* and its orange-red methylphosphonium salt clearly indicate that the phosphorus participates in the conjugation of the biphenyl system.

Many derivatives, particularly containing substituents in the nucleus, have been obtained by the intramolecular electrophilic substitution of substituted biphenyl derivatives *(58a)* and *(58b)* [prepared from the diazonium fluoroborates by reaction with PCl_3 and $C_6H_5P(O)Cl_2$] [76a, 76b, 77]. 2-Carboxy-9-phosphafluorene 9-oxide *(60)* [m.p. 250–251 °C; $[\alpha]_D^{20} = \pm 126 \pm 2°$), which is prepared from the 2-methyl derivative of *(59b)*, has been resolved into its optical antipodes by *Campbell* [77], using the amide of (+)- or (−)-α-phenylethylamine; both antipodes are fully racemized to the phosphine on reduction with $LiAlH_4$.

Finally, another variant is the application of *Busch*'s [78] biphenyl synthesis to phosphinic acids such as *(57)*, particularly for derivatives of the phosphinic acid *(59a)* [79].



g) 9-Phosphafluorenes Containing Pentavalent and Hexavalent Phosphorus. Spiro Compounds

This field was pioneered by *Wittig* and his school. In an adaptation of the synthesis of $(C_6H_5)_5P$ to 9-phosphafluorenes, the salts *(62)* of the latter are treated with phenyl-lithium. For example, 9,9,9-triphenyl-9-phosphafluorene *(61)* [m.p. 155.5–156.5 °C; yield 84 %] is obtained by the addition of phenyl-lithium and displacement (S_N2 reaction) of the methylaniline residue by a second mole of phenyl-lithium; the reaction with 2,2′-dilithiobiphenyl leads to the spiro compound *(63a)* [m.p. 201.5–202.5 °C; yield 68 %], and that with 2,2′-dilithio-4,4′-bis(dimethylamino)biphenyl to *(63b)* [80]. The tosylimines of the 9-phosphafluorenes, too, are suitable starting materials for the synthesis of *(63)* [*(63a)–(63c)* from 9-(*p*-dimethylaminophenyl)-9-phosphafluorene] and are more readily obtainable than

[72] *H. Hoffmann*, Chem. Ber. *95*, 2563 (1962).

[73] *D. Seyferth*, *M. A. Eisert*, and *J. K. Heeren*, J. organomet. Chemistry *2*, 101 (1964).

[74] *G. Wittig* and *E. Benz*, Chem. Ber. *92*, 1999 (1959).

[75] *E. Zbiral*, Tetrahedron Letters *1964*, 1649.

[76a] *G. O. Doak*, *L. D. Freedman*, and *J. B. Levy*, J. org. Chemistry *29*, 2382 (1964).

[76b] *L. D. Freedman*, *G. O. Doak*, and *I. R. Edmisten*, J. org. Chemistry *26*, 284 (1961).

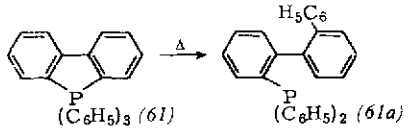
[77] *I. G. M. Campbell* and *J. K. Way*, J. chem. Soc. (London) *1961*, 2133.

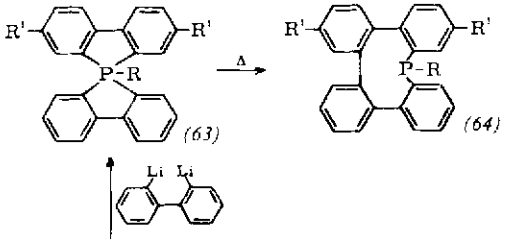
[78] *M. Busch* and *W. Weber*, J. prakt. Chem. *146*, 1 (1936).

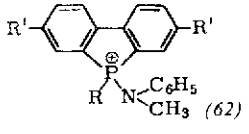
[79] *L. D. Freedman* and *G. O. Doak*, J. org. Chemistry *21*, 238 (1956); *24*, 638 (1959).

[80] *G. Wittig* and *E. Kochendoerfer*, Chem. Ber. *97*, 741 (1964).

(62)[22b]. Corresponding to the behavior of the phosphole *(42a)*, compound *(61)* rearranges to the tertiary phosphine *(61a)* with migration of the phenyl group, but only at temperatures above the melting point [*i.e.* 250 °C higher than in the case of *(42a)*]. The analogous rearrangement of *(63)* yields derivatives of the 1-substituted phosphacyclononatetraene *(64)*. The stereochemical behavior of *(61)* and *(63)* must be interpreted in accordance with the trigonal-bipyramid arrangement of the phenyl groups in $(C_6H_5)_5P$[81].



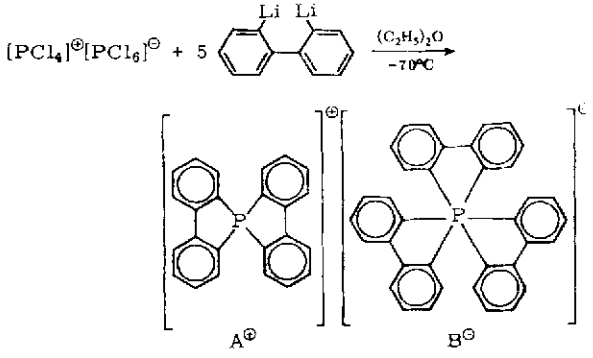


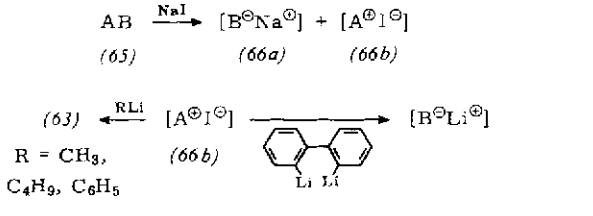


(a): R' = H; R = C_6H_5
(b): R' = $N(CH_3)_2$; R = C_6H_5
(c): R' = H; R = p-$(CH_3)_2N$-C_6H_4
(d): R' = H; R = CH_3
(e): R' = H; R = C_4H_9

Heterocycles containing hexavalent phosphorus were first prepared by *Hellwinkel*[67]. The reaction of 2,2'-dilithiobiphenyl with PCl_5 leads directly to the onium-ate complex $A^{\oplus}B^{\ominus}$ *(65)*, which crystallizes as yellow needles.

The ^{31}P–NMR values are δ = −26.5 ppm for $A^{\oplus}$ (in agreement with the values for other phosphonium salts, cf. Table 3) and δ = +186.5 ppm for $B^{\ominus}$, as compared with +118 ppm and +305 ppm for $PF_6^{\ominus}$ and $PCl_6^{\ominus}$, respectively.





[81] *P. J. Wheatley*, J. chem. Soc. (London) *1964*, 2206.

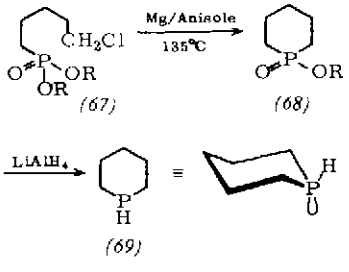
Compound *(65)*, which is stable in boiling ethanol or water, is decomposed by NaI into the sparingly soluble phosphonium iodide *(66b)* and sodium trisbiphenylylenephosphate *(66a)*. The octahedral structure of the anion $B^{\ominus}$ is clearly demonstrated by the resolution of potassium trisbiphenylylenephosphate ($[\alpha]_{578}^{24.5}$ = 1920 ± 30 °).

The iodide *(66b)*, which is directly obtainable (yield 87 %) by the action of 2,2'-dilithiobiphenyl on triphenyl phosphate, is a valuable starting material for the synthesis of the phosphoranes *(63)* and (with dilithiobiphenyl) of the ate-complex itself. Compound *(63)* (R = 2-biphenylyl) is formed by acid cleavage and *(64)* (R = 2-biphenylyl, R = H) by pyrolysis (270 °C) of lithium trisbiphenylylenephosphate.

3. Six-Membered Rings

a) Phosphorinanes

Phosphorinanes (phosphacyclohexanes) and their phosphonium salts, which are synthesized by Methods I, II, III, and V, present no new features in comparison with the phospholanes. The parent compound *(69)* is a readily oxidizable liquid (b.p. 110 °C; m.p. 19 °C) and was prepared by *Howard*[82] by the reduction of *(68)*, which is obtained by an intramolecular Grignard reaction with a phosphonate *(67)*.



Two simple and valuable syntheses of 1-substituted phosphorinan-4-ones were developed by *Welcher*. The bis-(2-cyanoethyl)phosphines *(70)*, which are obtained in good yields by the thermal[83a] or base-catalysed[83b] addition of primary phosphines to acrylonitrile, can be cyclized by the Thorpe-Ziegler method to *(71)* (the enamine structure is confirmed by infrared and PMR spectra); the hydrolysis of *(71)* leads directly to *(72)*[84,85].

After numerous unsuccessful attempts to prepare 1-phenyl-1-phospha-4-tetralone *(73)* by intramolecular

[82] *E. Howard Jr.* and *M. Braid*, Abstr. Papers, 140th ACS-Meeting, *1961*, 40Q; Dissertat. Abstr. *23*, 434 (1962).

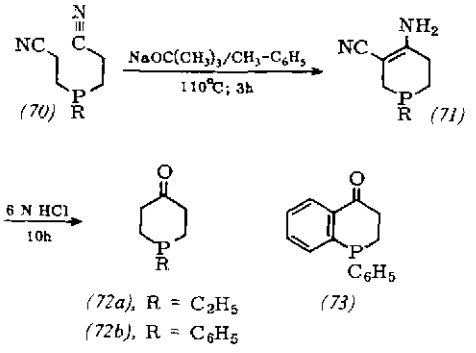
[83a] *F. G. Mann* and *I. T. Millar*, J. chem. Soc. (London) *1952*, 4453.

[83b] *M. M. Rauhut*, *G. B. Borowitz*, and *H. C. Gillham*, J. Amer. chem. Soc. *81*, 1103 (1959).

[84] *R. P. Welcher*, *G. A. Johnson*, and *V. P. Wystrach*, J. Amer. chem. Soc. *82*, 4437 (1960); German Pat. 1162840 (Febr. 13th, 1964), inventors: *R. P. Welcher*, *G. A. Johnson*, and *V. P. Wystrach*; Chem. Abstr. *60*, P 14542a (1964).

[85] *M. J. Gallagher* and *F. G. Mann*, J. chem. Soc. (London) *1962*, 5110.

acylation on the benzene nucleus [86], *Mann* succeeded in preparing this compound from the benzonitrile derivative corresponding to *(70)*, which is difficult to obtain [87a]. The formation of phosphonium salts and

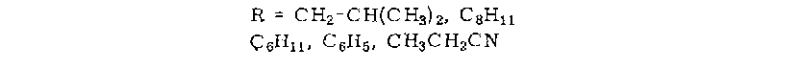


(70) *(71)* *(72a)*, R = C_2H_5 *(72b)*, R = C_6H_5 *(73)*

normal carbonyl derivatives and the position of the C=O band [1695 and 1680 cm^{-1} for *(72b)* and *(73)*, respectively] indicate that there is no interaction between the carbonyl group and the phosphine part of the molecule.

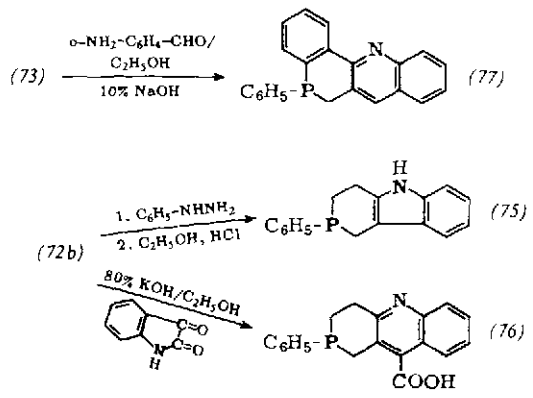
PH_3 and primary and secondary phosphines add onto olefins by a free-radical mechanism; however, the addition can also be catalysed by $H^{\oplus}$ ions or, in the case of strongly polar double bonds, by $OH^{\ominus}$ ions [88]. The possibility of cycloadditions was proved by the preparation of the phosphorinanones *(74)* from primary phosphines and phorone $[(CH_3)_2C{=}CH]_2CO$, dibenzalacetone, *etc.* [89]. In some cases the initial products are open-chain or macrocyclic polymers, which form *(74)* on thermal decomposition (sublimation at 220 °C/0.1 mm).

Reduction of *(74)* with $LiAlH_4$ yields the cyclic alcohols, whereas *Wolff-Kishner* reduction leads to the phosphorinanes. Chemical reactions at the ring became possible for the first time with the phosphorinanones [85, 87a, 87b]. The *Fischer* indole synthesis when applied to the phenylhydrazone of *(72a)* leads to the indole derivative *(75)*; compound *(73)* reacts similarly, in contrast to the formation of the yellow, conjugated Ψ-indoles [*] from the tetralones. The Pfitzinger condensation of *(72b)* yields *(76)*, and the Friedländer condensation of *(73)* yields *(77)*.



(74a) *(74b)*

R = $CH_2{-}CH(CH_3)_2$, C_8H_{11}, C_6H_{11}, C_6H_5, CH_3CH_2CN

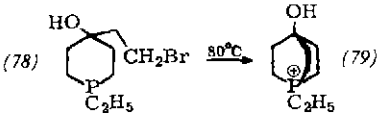


(73) *(77)* *(72b)* *(75)* *(76)*

The yellow color of the hydrochloride of the colorless compound *(77)* has been interpreted by *Mann* as being due to a small contribution by the limiting structure in which phosphorus forms a $p_{\pi}{-}p_{\pi}$ double bond:

$$\overset{\cdot\cdot}{>}P{-}C{=}C{-}CH{=}\overset{\oplus}{N}H{-} \;\leftrightarrow\; \overset{\oplus}{>}P{=}C{-}C{=}CH{-}\overset{\cdot\cdot}{N}H{-}$$

In the corresponding N series, these salts are deep red [87b], owing to the formation of a delocalized π-electron system in a phenylogous trimethinecyanin.



(78) *(79)*

Compound *(72a)* was used for the synthesis of the phosphine *(78)*, which undergoes self-alkylation in boiling benzene to form 1-ethyl-4-hydroxy-1-phosphoniabicyclo[2.2.2]octane bromide *(79)* [90]. The theoretically interesting bicyclic phosphine could not be obtained from *(79)*.

b) 1,1-Diphenylphosphabenzene and 1,1-Diphenylphosphanaphthalene

The trimeric phosphonitrilic chlorides *(80)* are ring systems of pentavalent phosphorus which contain only double bonds of the $p_{\pi}{-}d_{\pi}$ type. MO calculations taking into account only the d_{xz} orbital of the phosphorus *(81)* led *Craig* [91] to postulate the existence of a new type of aromatic system (4n π-rule). *Dewar* [92], on the other hand, believes that each phosphorus atom uses two orthogonal d orbitals, $d_{\pi a}$ and $d\pi b$, *(81)* (from a linear combination of d_{yz} and d_{yz}) in localized three-center π-honds.

[86] *F. G. Mann* and *I. T. Millar*, J. chem. Soc. (London) *1952*, 4453; *R. C. Hinton*, *F. G. Mann*, and *D. Todd*, *ibid. 1961*, 5454.

[87a] *M. J. Gallagher*, *E. C. Kirby*, and *F. G. Mann*, J. chem. Soc. (London) *1963*, 4846.

[87b] *M. J. Gallagher* and *F. G. Mann*, J. chem. Soc. (London) *1963*, 4855.

[88] See [6], p. 25.

[89] *R. P. Welcher* and *N. E. Day*, J. org. Chemistry *27*, 1824 (1962); US.-Pat. 3105096 (Sept. 24th, 1963), inventor: *R. P. Welcher*, Chem. Abstr. *60*, 5553d (1964).

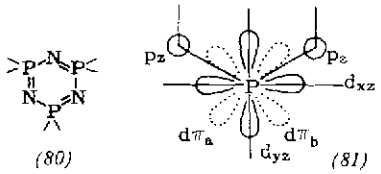
[*] Ψ-Indoles are conjugated, yellow products which are formed on dehydrogenation of indoles.

[90] *L. D. Quin* and *D. A. Mathews*, Chem. and Ind. *1963*, 210; *D. A. Mathews*, Dissertat. Abstr. *24*, (3) 977 (1963); *G. A. Wiley*, Abstr. Papers, 145th ACS-Meeting, *1961*, 40Q; *W. E. McEwen*, *et al.*, *ibid.* 96Q.

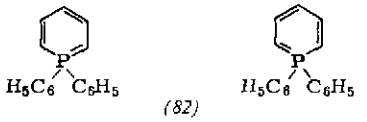
[91] *D. P. Craig* and *N. L. Paddock*, J. chem. Soc. (London) *1962*, 4118.

[92] *M. J. S. Dewar*, *E. A. C. Lucken*, and *M. A. Whitehead*, J. chem. Soc. (London) *1960*, 2423.

The question of the consequence of replacing one $2p_\pi-2p_\pi$ double bond in benzene with a $2p_\pi-3d_\pi$ double bond led to the synthesis of 1,1-diphenylphosphabenzene *(82)* [29,93]. This compound possesses the structural characteristics of a methylenephosphorane, for which two Kekulé structures can formally be written.

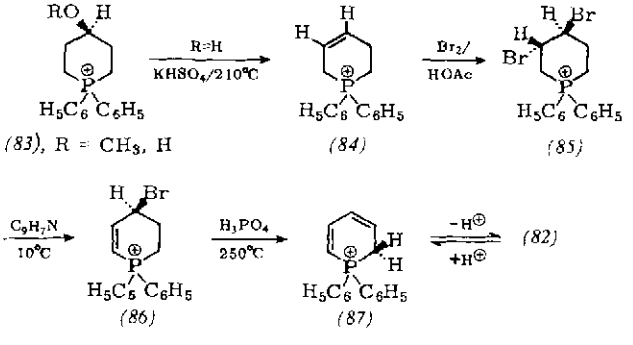


(80) *(81)*



(82)

The ether linkage of 1,1-diphenyl-4-methoxy-1-phosphoniacyclohexane bromide *(83)* (prepared by Method III [13]) can be cleaved to form the alcohol; this is then dehydrated to obtain *(84)*, the double bond being formed in the 3,4-position [$\nu_{C=C}$ = 1637 cm^{-1}]. Intermediate ylide formation permits the ready dehydrobromination of the Br_2 adduct *(85)* to the vinylphosphonium salts *(86)* [$\nu_{C=C}$ = 1596 cm^{-1}]. Since *(86)* is a vinylogous α-bromophosphonium salt [94], both the hydrogen and the bromine at position 4 are active ($H^\oplus$, $Br^\ominus$), and since it is also an allyl bromide, it also possesses S_N1 reactivity. The introduction of the second double bond to form a 1,1-diphenyl-1-phosphoniacyclohexa-2,4-diene salt *(87)* (perchlorate: m.p. 117–119 °C; $\nu_{C=C}$ = 1626, 1572, 1550 cm^{-1}) is possible only with the catalytic action of hot H_3PO_4.



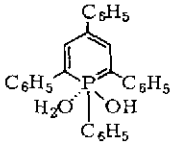
(83), R = CH_3, H *(84)* *(85)*

(86) *(87)* *(82)*

The cation *(87)* is deprotonated by dilute alkalis even in aqueous solution. Compound *(82)* is formed as a yellow (λ_{max} = 409 mμ in ether), non-crystalline precipitate which is stable in water; *(87)* is re-formed in acidic solution. Similar open-chain phosphonium salts, as well as *(84)*, form ylides only with strong bases, and these ylides are extremely readily hydrolysed.

The question of whether this stabilization of *(82)* is due to the formation of a delocalized π-electron system (through conjugation at the phosphorus atom) or to resonance stabilization as postulated by *Dewar* (the phosphorus atom acts as an "insulator" owing to the orthogonality of the d-orbitals) has not yet been settled (see also [95]).

Price [96,97] adapted the classic synthesis of pyridine from pyrilium salts to the preparation of phosphorus heterocycles. $C_6H_5PH_2$ reacts with 2,4,6-triphenylpyrylium fluoroborate in boiling pyridine to form two compounds, one being amorphous and the other crystalline (m.p. 257 °C, colorless). The structure *(88)* has been assigned to the former on the basis of infrared, PMR and ^{31}P–NMR measurements; no protonation of the "quasi-ylide" corresponding to *(82)* ⇌ *(87)* can be observed.



(88)

The deep red ylides of the 3,4-dihydro-1,1-diphenyl-1-phosphanaphthalenes *(90)* [29,33] are formed from the salts *(89)* (obtained by Methods VII and VIII) on treatment with strong bases in aprotic solvents. With these ylides, as with compounds *(46)*, normal Wittig reactions can be carried out. Moreover, *(90)*, R = H, can be methylated or acylated to the stable α-acylylide *(91)*. The bromination of *(89)* to *(92)* with *N*-bromosuccinimide, followed by H_3PO_4-catalysed dehydrobromination, leads to almost quantitative yields of the diene salts *(93)* (perchlorates: R = H, m.p. 173 °C; R = CH_3, m.p. 197–199 °C; R = C_6H_5, m.p. 182–183 °C). In agreement with the structure *(82)*, the ylides *(94)* can be deposited from the aqueous solutions of their salts (R = H; λ_{max} = 439 mμ; strong infrared band at 1550 cm^{-1}; PMR doublet at 4.46 τ, J = 9 c/s, 1 proton; complex spectrum from 2.3 to 3.3 τ). Attempted Wittig olefinations have so far been unsuccessful. Thus *(94)* cannot form betaines with the carbonyl component (by participation of the free electron pair on the ylide carbon atom in a resonance system), but it exhibits nucleophilic behavior towards stronger electrophiles. *(94)*, R = H, is methylated at position 4 (according to infrared and PMR measurements) to give *(95)*; with R = CH_3 or C_6H_5 it couples with diazonium salts to form 4-azo compounds *(96)* and, in the case of R = H, the 2,4-bisazo compounds *(96)*, R = –N–N–R′, is obtained; the cation *(95)* forms the isomeric 2-azo compound [98].

The phosphanaphthalenes with R = H, CH_3 and phosphabenzene *(82)* are extremely susceptible to autoxidation. A mixture of high-molecular weight colored salts (λ_{max} = 460–600 mμ), which are vinylogues of the simplest phosphacyanin $(C_6H_5)_3P{=}CH{-}P(C_6H_5)_3$ [99], are formed, probably *via* free-radical cations such as *(97)*. The ease of formation of *(98)* also indicates a

[93] *G. Märkl*, Habilitation Thesis, Universität Würzburg, 1963.

[94] *D. Seyferth, J. K. Herren*, and *S. O. Grimm*, J. org. Chemistry *26*, 4783 (1961).

[95] *G. Märkl*, Angew. Chem. *75*, 1121 (1963).

[96] *Ch. C. Price*, Chem. and chem. Ind. (Japan) *16*, 109 (1963).

[97] *Ch. C. Price, T. Parasaran*, and *T. Lakshminarayan*, Abstr. Papers, 148th ACS-Meeting 1964.

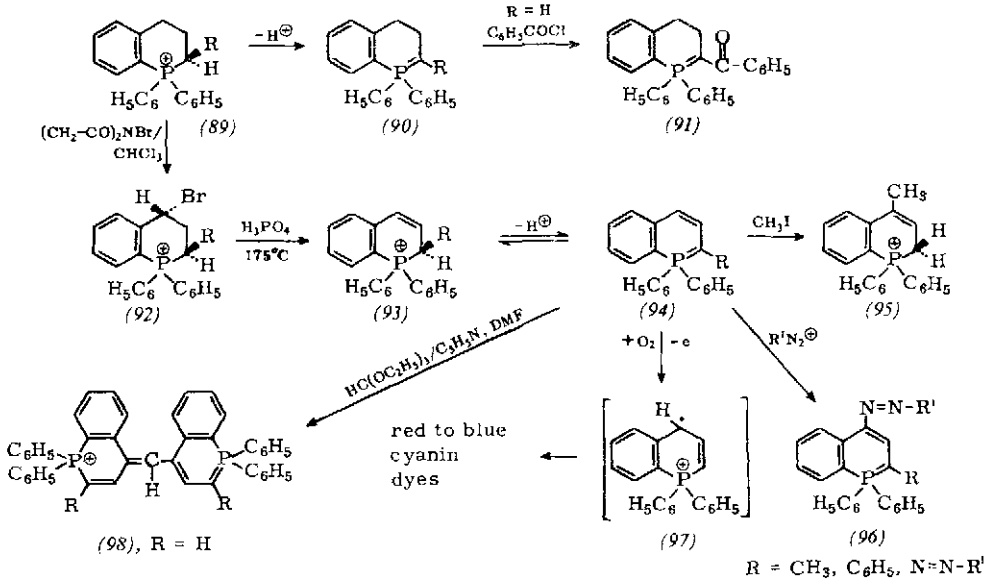
[98] See also *G. Märkl*, Tetrahedron Letters *1961*, 807; Z. Naturforsch. *17b*, 782 (1962).

[99] *F. Ramirez, N. B. Desai, B. Hansen*, and *N. Mc Kelvie*, J. Amer. chem. Soc. *83*, 3539 (1961).

considerable gain in π-electron delocalization energy in the transition from the phosphanaphthalene to a phosphacyanin system[13,93].

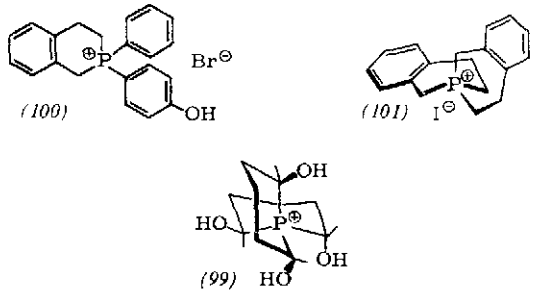
9,9-Diphenyl-9-phosphaphenanthrene[100] is obtained in the same way as *(82)* and *(94)*, from the corresponding phosphonium salt (prepared by Method VII) in aqueous solution. Once again, no Wittig reactions have been observed.

1,5,7,11-Tetrahydroxy-6-phosphoniaspiro[5,5]undecane salts *(99)* and the spiro compound *(6)*, n = 2, with five-membered rings are formed in a single step by Method IV[15b, 16b]. In the paddle-wheel arrangement of the OH groups which is postulated for steric reasons, the molecule has the *meso* structure[103].



c) Tetrahydrophosphinoline, Tetrahydroisophosphinoline, and Spirophosphonium Salts

P-Ethyltetrahydrophosphinoline and *P*-ethyltetrahydroisophosphinoline, like the phosphines *(48)* and *(49)*, can be obtained in good yields as oils which are relatively stable in air, by thermolysis of the diethylphosphonium salts (obtained by Method VII)[28,32,101]. The first optically active phosphonium salt was prepared by *Mann*[32] by the resolution of the camphorsulfonate of the asymmetrically substituted isophosphinolinium salt *(100)* (m.p. 268–270 °C, $[M]_D$ = +32.9 °).



The phosphonium iodide *(101)*[102], which is obtained by twofold intramolecular salt formation (Method VII) exhibits molecular asymmetry, and has been resolved into its optical antipodes by means of the (−)-menthyl acetate (iodide: m.p. 246–248 °C, $[M]_D$ = −65 ° and +66 ° in $CHCl_3$).

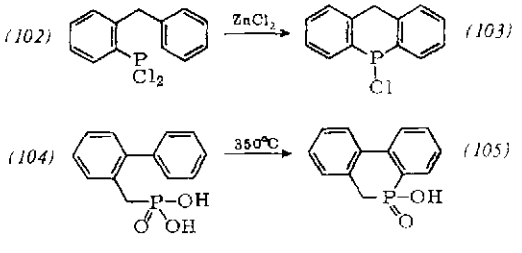
[100] *P. C. Crofts*, personal communication.

[101] See also *F. G. Holliman* and *F. G. Mann*, J. chem. Soc. (London) *1943*, 547, 550.

[102] *F. A. Hart* and *F. G. Mann*, J. chem. Soc. (London) *1955*, 4107

d) Phospha-anthracene and Phosphaphenanthrene

The dichlorophosphine *(102)*, which is prepared in the same way as *(58a)*, undergoes ring closure in the presence of $ZnCl_2$ to form 9-chloro-9-phospha-anthracene *(103)*, which is converted by hydrolysis and oxidation into the phosphinic acid[76]. The acid *(104)*, which can be obtained from 2-bromomethylbiphenyl by an Arbuzov reaction, cannot be cyclized by the usual methods (with P_2O_5, PCl_5, $AlCl_3$); it is, however, cyclized to 9-hydroxy-9-oxo-9-phosphaphenanthrene *(105)* simply on heating at 350 °C[104].



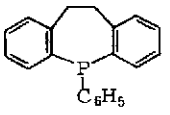
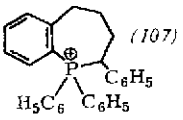
4. Seven- and Eight-Membered Rings

1-Benzyl-1-phosphacycloheptane and 1-phenyl-1-phosphacyclooctane have been synthesized by Method I[7]. Attempted syntheses by other methods led only to polymeric products. The phosphacycloheptadiene *(106)*

[103] *McCashland* and *S. Proskow*, J. Amer. chem. Soc. *77*, 4688 (1956).

[104] *E. R. Lynch*, J. chem. Soc. (London) *1952*, 3729; Brit. Pat. 933800 (Aug. 14th, 1963); Chem. Abstr. *60*, 1796 (1964).

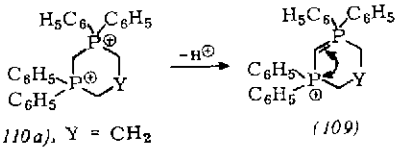
(m.p. 75–75.5 °C) is practically identical to $(C_6H_5)_3P$ in its chemical behavior and in its ultraviolet spectrum[105]. The phosphonium salt *(107)* has been obtained by intramolecular ylide alkylation in accordance with Method VIII[33].

(106)  *(107)* 

C. Heterocycles Containing Two or More Phosphorus Atoms

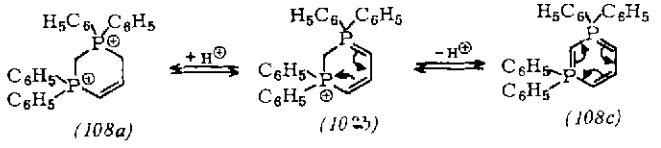
1. 1,3-Diphosphacyclohexane and Cyclic Phosphacyanins

Bisphosphonium salts containing the ring system *(110)* can be readily obtained by the reaction of bis(diphenylphosphino)methane[107] with 1,3-dihalogeno compounds[106]. The salts *(110)* lose a proton in aqueous sodium carbonate solution to give a quantitative yield of the resonance-stabilized phospha-amidinium salts *(109)*. A double bond can be introduced by the dehydration of the alcohol *(110c)* with polyphosphoric acid. The resulting compound *(108)*, like *(110)*, is deprotonated to the resonance-stabilized cyclic trimethinephosphacyanin *(108b)* [perchlorate: m.p. 236–237 °C, $\nu_{C=C}$ = 1620 cm^{-1}, λ_{max} (log ε) = 268 mμ (3.954), 274 mμ (3.967), 340 mμ (4.086)]. A second proton is removed by stronger bases such as aqueous sodium hydroxide, and 1,1,3,3-tetraphenyl-1,3-diphosphabenzene *(108c)* separates out from aqueous solution as a bulky, yellow, non-crystalline precipitate (λ_{max} = 281 and 384 mμ).



(110a), Y = CH_2
(110b), Y = CO
(110c), Y = CHOH

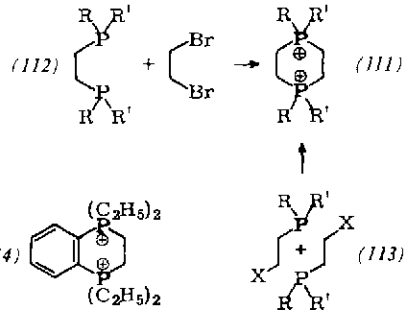
(109)



(108a) *(108b)* *(108c)*

2. 1,4-Diphosphacyclohexane and 9,10-Dihydrophosphanthrene

The bis-quaternary salts *(111)* are again very easy to prepare. One method is by salt formation between 1,2-bis(phosphino)ethanes *(112)*[107] with 1,2-dibromoethane[93, 108–111]; 1,2-bis(diethylphosphino)benzene reacts to form *(114)*. 1,3-Dibromopropane and *o*-bis(bromomethyl)benzene react to form seven- and eight-membered bisphosphonium salts, respectively[112, 113]. A second method is by the free-radical addition of secondary phosphines to vinyl acetate or vinyl bromide at 80 °C. This leads to the phosphines *(113)*. With R = R′ = CH_2CH_2CN and X = OAc, Br, these dimerize even during the preparation to form *(111)*. Temperatures between 120 and 150 °C are required for the dimerization when R = R′ = butyl, isobutyl, or C_6H_{11} (yield = 21–59 %)[109]; linear polymers are first formed at 80 to 120 °C, and these then rearrange at higher temperatures to form *(111)*.



(112) *(111)* *(114)* *(113)*

R = R′ = C_6H_5, $CH_2C_6H_5$, CH_2CH_2CN;
R = C_6H_5, R′ = C_2H_5, $CH_2C_6H_5$

Diphenylvinylphosphine dimerizes quantitatively to *(111)*, R = R′ = C_6H_5, in the presence of proton donors [HOAc, $(C_2H_5)_3NH^{\oplus}Cl^{\ominus}$, α-halogenohydrins]; besides the protonated phosphine, another possible intermediate is the cyclic bis-ylide[114]. On thermolysis of *(111)* (R = C_2H_5, R′ = C_6H_5), ethylene is split off to reform the original phosphine *(112)*.

The reductive debenzylation of phosphonium salts with $LiAlH_4$ was found to be an excellent method of preparing 1,4-diphosphacyclohexanes *(116a)* (m.p. 90–92 °C) and *(116b)* (m.p. 128–130 °C)[108b]. The availability of secondary bis(phosphino)ethanes and their lithium salts *(115)* enabled *Issleib*[115] to develop a direct synthesis of the compound *(116)* without first forming the phosphonium salts. The remarkable octafluoro derivative *(117)* (m.p. 73–73.5 °C, yellowish crystals) is formed, together with a little phospholane *(118)*, in the reaction

[105] *F. G. Mann, I. T. Millar,* and *B. B. Smith,* J. chem. Soc. (London) *1953*, 1130.

[106] *G. Märkl,* Z. Naturforsch. *18b*, 1136 (1963).

[107] *K. Issleib* and *F. Krech,* Chem. Ber. *94*, 2656 (1961).

[108a] *C. H. Hitchcock* and *F. G. Mann,* J. chem. Soc. (London), *1958*, 2081.

[108b] *R. C. Hinton* and *F. G. Mann,* J. chem. Soc. (London), *1959*, 2835.

[109] *R. C. Hinton* and *F. G. Mann,* J. chem. Soc. (London) *1959*, 2835.

[110] *M. M. Rauhut, G. B. Borowitz,* and *H. C. Gillham,* J. org. Chemistry *28*, 2565 (1963); Brit. Pat. 898759 (June 14th, 1962); Chem. Abstr. *57*, 12539 (1962).

[111] *A. M. Aguiar, H. Aguiar,* and *D. Daigle,* J. Amer. chem. Soc. *87*, 671 (1965).

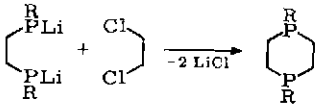
[112] *F. A. Hart* and *F. G. Mann,* Chem. and Ind. *1956*, 574, J. chem. Soc. (London) *1957*, 3939.

[113] *E. R. H. Jones* and *F. G. Mann,* J. chem. Soc. (London) *1955*, 4472.

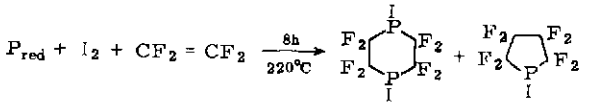
[114] *G. Märkl,* unpublished work.

[115] *K. Issleib* and *G. Döll,* Chem. Ber. *96*, 1544 (1963).

of tetrafluoroethylene with elementary red phosphorus(!) in the presence of stoichiometric quantities of iodine [116].

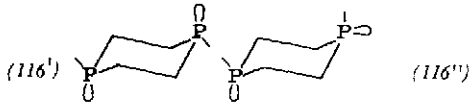


(115) (116a), R = C_6H_5
(116b), R = $CH_2C_6H_5$

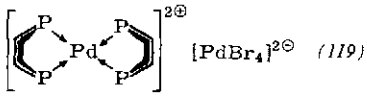


(117) (118)

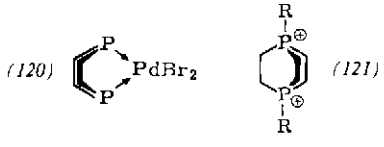
The stability of the phosphines against inversion, as discussed in the Introduction, suggests that *(116)* should exist in two stereoisomeric forms *(116')* and *(116'')*. Compounds *(116a)* and *(116b)* have sharp melting points; they form the complexes *(119)* and *(120)* with $K_2[PdCl_4]$, give bicyclic salts *(121)* with dibromoethane, and form uniform oxides on oxidation [109]. The existence of the *cis* structure *(116'')* thus appears to be certain. On the other hand, the oily product with R = C_6H_5 which was obtained by *Issleib* [115] by distillation at 300 to 310 °C/7 mm was probably the isomer mixture of *(116)*. This also holds for the products with R = C_2H_5, $CH_2C_6H_5$, and cyclo-C_6H_{11}. Since the uptake of oxygen



(116') (116'')



(119)



(120) (121)

or sulfur is not accompanied by inversion of the configuration [117], the formation of two isomeric sulfides and of oxides with very indistinct melting points supports this belief.

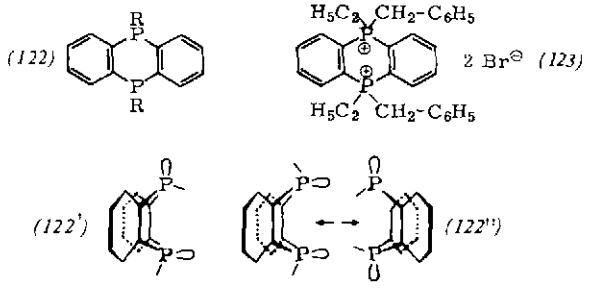
The 9,10-diethyl-9,10-dihydrophosphanthrene *(122)* with R = C_2H_5, which was prepared by *Mann* [118] using Method VI, fulfils these stereochemical expectations. The compound is separated from the reaction mixture by precipitation as the bisbenzylphosphonium bromide *(123)*; the expected salts *(123a)* [m.p. 346 °C] and *(123b)* [m.p. 319 °C] with *cis-trans* isomerism about the tetrahedral phosphorus atom were found.

[116] *C. G. Krespan* and *C. M. Langkammerer*, J. org. Chemistry *27*, 3584 (1962); US.-Pat. 2931803 (Apr. 5th, 1960), inventor: *C. G. Krespan*; Chem. Abstr. *55*, 12436 (1961).

[117] *L. Horner* and *H. Winkler*, Tetrahedron Letters *1964*, 175.

[118] *M. Davis* and *F. G. Mann*, Chem. and Ind. *1962*, 1539; J. chem. Soc. (London) *1964*, 3770.

The debenzylation of *(123a)* gives rise to two phosphanthrenes, *i.e.* *(122a)* [m.p. 52–53 °C] and a little *(122b)* [m.p. 96–97 °C]; the isomerism of these compounds is due to the stable *cis* and *trans* arrangements of the substituents R in the molecule, which is folded about the P–P axis [*(122')* and *(122'')*]. This "butterfly conformation" permits a synchronous oscillation of



(122) (123)

(122') (122'')

the benzene rings about the P–P aixs without loss of isomerism [cf. Formula *(122'')*]. Since *(122a)* readily reacts with dibromoethane and *o*-bis(bromomethyl)-benzene to form bicyclic phosphonium salts, and forms a 1:1 complex with $K_2[PdCl_4]$, for which only a bimolecular *cis* structure is possible, this is probably the *cis* isomer *(122'')*.

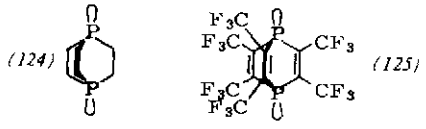
Compound *(122)* with R = C_6H_5 as well as 9,10-diphenyl-9-phospha-10-arsaphenanthrene form only one of the two possible stereoisomers, probably because of the greater bulk of the phenyl group [118].

3. 1,4-Diphosphabicyclo[2.2.2]octane

The first phosphine with the phosphorus in a bridgehead position, *i.e.* 1,4-diphosphabicyclo[2.2.2]octane *(124)* (colorless needles, m.p. 252 °C), was prepared by *Mann* [108b] by the debenzylation of *(121)* (R = $CH_2C_6H_5$) with $LiAlH_4$. Even in boiling benzene, *(124)* is not oxidized by atmospheric oxygen, and quaternization with CH_3I occurs only on heating. The ease of sublimation of this compound is reminiscent of the behavior of quinuclidine and triethylenediamine.

The low nucleophilicity of this compound as compared with normal phosphines may be due to the resistance of the phosphine *(124)* to the widening of the valence angle associated with the change from sp^2 to sp^3 hybridization.

The unexpected formation of the 1,4-diphosphabicyclo-[2.2.2]octatriene derivative *(125)* from hexafluorobut-2-yne and elementary red phosphorus (200 °C, 8 hours, I_2 as catalyst) again shows the special position occupied by perfluorinated compounds, even in the chemistry of phosphorus [119]. The evidence for the structure of the colorless and, like *(124)*, readily sublimable product *(125)* (m.p. 119–120 °C) is based mainly on infrared and ^{19}F–NMR measurements.



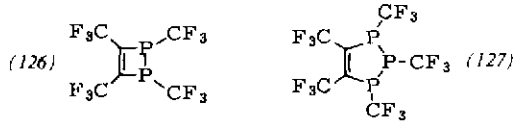
(124) (125)

[119] *C. G. Krespan, B. C. McKusick*, and *T. L. Cairus*, J. Amer. chem. Soc. *82*, 1515 (1960); *C. G. Krespan, ibid. 83*, 3432 (1961); US.-Pat. 2996527 (Aug. 15th, 1961); Chem. Abstr. *56*, 1483 (1962).

The decrease in the basicity and nucleophilicity is even more pronounced in *(125)* than in *(124)*: compound *(125)* is insoluble in concentrated H_2SO_4, does not react with CH_3I or benzyl bromide, and does not add on Br_2. Beside the change in the valence angle, there are other factors that contribute to the decrease in basicity, *i.e.* steric hindrance by the CF_3 groups, electron deficiency on the phosphorus owing to the attraction of electrons by the CF_3 and vinyl groups, and possible stabilization of the trivalent phosphorus by $d_\pi - p_\pi$ overlap with the adjacent double bonds.

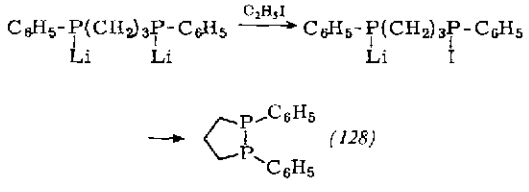
4. 1,2-Diphosphacycles and 1,2,3-Triphosphacycles

Interaction of the d-orbital of the phosphorus with the p_π-orbitals of adjacent double bonds is also indicated by ultraviolet measurements on the 1,2-diphosphacyclobutene and 1,2,3-triphosphacyclopentene derivatives *(126)* and *(127)*, which are formed from hexafluorobut-2-yne and the cyclopolyphosphines $[P(CF_3)]_n$ (n = 4,5)[120]. These phosphines, which are stable in a nitrogen atmosphere, ignite spontaneously on contact with



(126) *(127)*

air. The structurally related 1,2-diphenyl-1,2-diphosphacyclopentane *(128)* (b.p. 184–190 °C) is formed by an exchange reaction[121,122]:

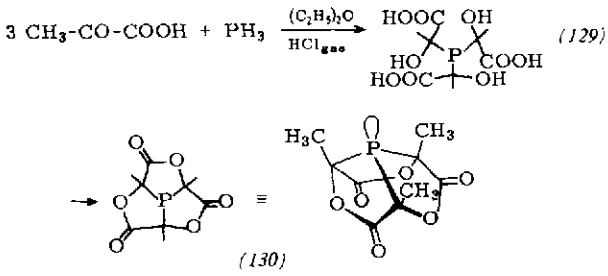


(128)

D. Phosphorus Heterocycles which also Contain Oxygen or Nitrogen as Ring Atoms

1. 1-Oxa-3-phosphacyclopentanes

Unusual phosphorus heterocycles have been obtained by unexpected reactions. An example is the reaction between PH_3 and pyruvic acid, which was carried out as early as 1888[123], and which was shown by *Buckler*[124a–124c] to yield the product *(134)*. The $H^\oplus$ catalysed nucleophilic addition of PH_3 to the C=O groups to form *(129)* is followed by closure of the γ-lactone ring to form *(130)*.

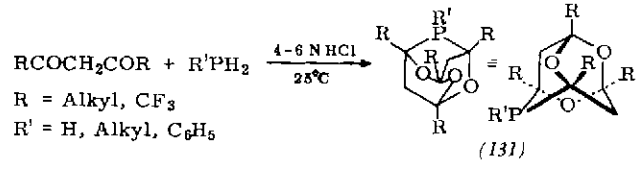


(129)

(130)

Compound *(130)*, which like *(124)* is a tertiary phosphine with a bridgehead phosphorus atom, cannot be protonated even in $HClO_4$/nitromethane, and does not react with CH_3I, H_2O_2, or sulfur. Therefore, the rigid polycyclic system appears to be incapable of tolerating a tetrahedral phosphorus atom at the bridgehead.

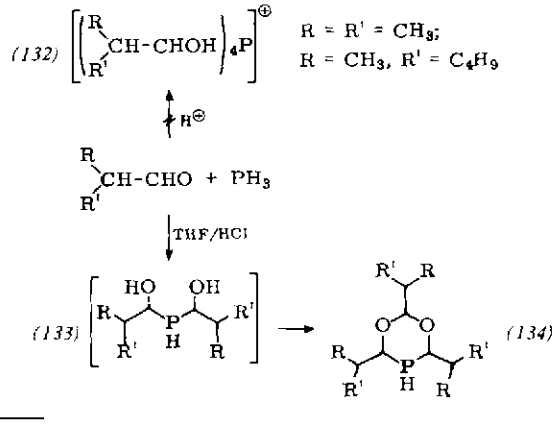
The reaction of acetylacetone with PH_3 has also been known for a long time[123]. *Epstein* and *Buckler* found that the product (as well as the products obtained with other 1,3-diketones and secondary phosphines) has the phospha-adamantane structure *(131)*. These compounds behave as normal phosphines[125].



(131)

2. 1,3-Dioxa-5-phosphacyclohexane

The nucleophilic addition of PH_3 to α-branched aldehydes leads to 2,4,6-trialkyl-1,3-dioxa-5-phosphacyclohexanes[124b,127], and not to the expected[126] phosphonium salts *(132)*. For steric reasons, only the 1:2 adduct *(133)* is formed, and this is then cycloacetalized to *(124)*. The accumulation of bulky substituents favors both the ring closure and the stability of *(134)*, which is



(132) R = R' = CH_3; R = CH_3, R' = C_4H_9

(133) *(134)*

[120] *W. Mahler*, J. Amer. chem. Soc. *86*, 2306 (1964).

[121] *K. Issleib* and *F. Krech*, Chem. Ber. *94*, 2656 (1961).

[122] *K. Issleib* and *D. Jakob*, Chem. Ber. *94*, 107 (1961).

[123] *J. Messinger* and *C. Engels*, Ber. dtsch. chem. Ges. *21*, 326, 2919 (1888).

[124a] *Sh. A. Buckler*, J. Amer. chem. Soc. *82*, 4215 (1960).

[124b] *Sh. A. Buckler* and *M. Epstein*, Tetrahedron *18*, 1211 (1962).

[124c] US.-Pat. 2845454 (July 29th, 1958), inventors: *Sh. A. Buckler* and *V. P. Wystrach*; Chem. Abstr. *53*, 3061 (1959).

[125] *M. Epstein* and *Sh. A. Buckler*, J. Amer. chem. Soc. *83*, 3279 (1961); US.-Pat. 3050531 (Aug. 21st, 1962); Chem. Abstr. *57*, 16659c (1962).

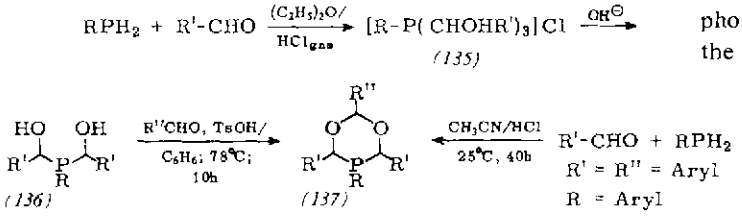
[126] *H. Hellmann*, *J. Bader*, *H. Birkner*, and *O. Schumacher*, Liebigs Ann. Chem. *659*, 49 (1962).

[127] *Sh. A. Buckler* and *V. P. Wystrach*, J. Amer. chem. Soc. *80*, 6454 (1958); *83*, 168 (1961); US.-Pat. 2984683 (May 16th, 1961), inventor *Sh. A. Buckler*; Chem. Abstr. *55*, 22347 (1961).

not decomposed even in boiling concentrated HCl. The similarity to normal secondary phosphines is only slight. The 1,3-dioxa-5-phosphacyclohexanes have a mild, not unpleasant odor (!), and are more stable towards oxygen than other secondary phosphines.

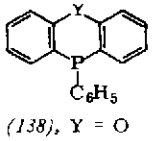
The generally lower sensitivity to oxygen of cyclic as compared with open-chain phosphines indicates that autoxidation is probably hindered by the conformational change accompanying the P → PO transition, as well as by steric shielding of the σ-orbital of the phosphorus.

The α-hydroxyalkylphosphonium salts *(135)* obtained from primary phosphines (R = alkyl, aryl) and aliphatic aldehydes can be readily degraded by bases to the α,α'-dihydroxyphosphines *(136)*, the acetalization of which with any aldehyde (R'' = alkyl, aryl) also leads to cyclic compounds *(137)* [128]. Aromatic aldehydes also react directly with aryl-substituted secondary phosphines (benzaldehyde even reacts with PH_3 [124b, 130]) to give *(137)* (R' = R'') [129].

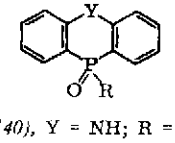


3. 9-Phosphaxanthene and 9,10-Dihydrophenophosphazine

9-Phenyl-9-phosphaxanthene *(138)* (m.p. 94–94.5 °C) has been prepared from 2,2'-dibromodiphenyl ether by Method VI [26]. 2,2'-Dibromodiphenylamine, which is difficult to prepare, gives only polymerization products, owing to metalation of the NH group [25a]. The alkylation of the amine *via* the Li compound [131] led to *(139)* [R = CH_3: pale yellow crystals, m.p. 154 to 157 °C] [25b]. Compounds *(138)* and *(139)* are almost identical in their chemical behavior and in their ultraviolet spectra to $(C_6H_5)_3P$. The valence angles (C–O–C: 116 ± 4 °; C–N–C: 107 °) indicate a folded structure, as in *(122)*.



(138), Y = O
(139), Y = NR



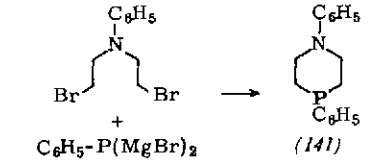
(140), Y = NH; R = H
(140a), Y = O; R = OH

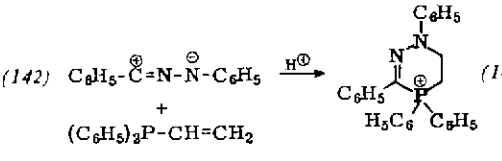
Michaelis and *Schenk* [132] reported a phenophosphazine derivative, *i.e.* the secondary phosphine oxide *(140)* (m.p. 214–216 °C, yield 40 %), which they had prepared by the reaction of diphenylamine with $PCl_3/ZnCl_2$ (in a sealed tube) followed by hydrolysis. This was later confirmed, in particular by *Häring* [133]. Compound *(140)* is oxidized to the phosphinic acid by atmospheric oxygen, whereas the reaction with bromine surprisingly leads to a dibrominated product in which no attack on the phosphorus has taken place. Whereas di-*p*-tolyl ether reacts in a similar manner with ring closure [76b], the unsubstituted phosphinic acid *(140a)* is obtainable only by the cyclization of dichloro-*o*-phenoxyphenylphosphine, which proceeds on heating [76a].

4. 1-Aza-4-phosphacyclohexane

The applicability of Method II in cases in which the dibromoalkane chains also contain heteroatoms is shown by the synthesis of 1,4-diphenyl-1-aza-4-phosphacyclohexane *(141)* (colorless crystals; m.p. 89 to 90 °C) [134]. CH_3Br and C_2H_5Br attack only on the phosphorus atom, due to the greater nucleophilicity of the phosphine; a bis-salt of *(141)*, which is thermally very unstable, is formed only in boiling methyl iodide. Compound *(141)* is stable towards oxygen at room temperature, *i.e.* substantial deactivation has taken place in comparison with 1-phenylphosphorinane, owing to the presence of the nitrogen atom in the ring.

Cycloadditions onto vinylphosphines promise interesting methods for the preparation of phosphorus heterocycles. The 1,3-dipolar nitrilimine *(142)* adds onto triphenylphosphine to form the azophosphorus ylide; with diphenylvinylphosphine, on the other hand, *(142)* undergoes ring closure to the 1,3,4,4-tetraphenyl-1,2-diaza-4-phosphoniacyclohex-2-ene cation *(143)* [114].





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Translated by Express Translation Service, London

[128] US.-Pat. 30050201 (March 3rd, 1959), inventor: *Sh. A. Buckler*; Chem. Abstr. *56*, 6002 (1962).

[129] Franz. Pat. 1333818 (Aug. 2nd, 1963), inventors: *M. Grayson* and *P. T. Keough*; Chem. Abstr. *60*, 3013 (1964); *Sh. A. Buckler* and *M. Epstein*, Tetrahedron *18*, 1231 (1962).

[130] *V. Ettel* and *J. Horák*, Collect. czechoslov. chem. Commun. *25*, 2192 (1960).

[131] *H. Gilman* and *E. A. Zuech*, Chem. and Ind. *1958*, 1227.

[132] *A. Michaelis* and *A. Schenk*, Liebigs Ann. Chem. *260*, 1 (1890).

[133] *M. Häring*, Helv. chim. Acta *43*, 1826 (1960).

[134] *F. G. Mann* and *I. T. Millar*, J. chem. Soc. (London) *1952*, 3039.

Electronic Structure and Properties of Non-Alternant Hydrocarbons [*]

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The present paper is concerned mainly with studies on the electronic structure of non-alternant hydrocarbons by quantum-chemical methods. The references to original publications are by no means exhaustive, but an attempt has been made to cover the entire field. (Analogues and derivatives of non-alternant hydrocarbons are only touched.) The intention is to outline the present situation with regard to quantum-mechanical studies on non-alternant hydrocarbons, and to indicate to the chemist the use of the theoretical characteristics obtained by various approximations of the MO-LCAO method [**].

I. The Classification of Non-Alternant Hydrocarbons

The terms "alternant" and "non-alternant" hydrocarbons were coined by *Coulson* and *Rushbrooke* [1]. A conjugated unsaturated hydrocarbon is non-alternant if the carbon atoms cannot be divided into two groups such that all the atoms of the first group have only atoms of the second group as immediate neighbors, and *vice versa*. Thus all fully conjugated hydrocarbons that contain rings with an uneven number of carbon atoms are non-alternant. There is no simple relationship between the energies and the orbital coefficients of the bonding and antibonding molecular orbitals in non-alternant hydrocarbons, as there is in the case of alternant hydrocarbons.

The results of studies on non-alternant hydrocarbons by *B.* and *A. Pullman*, *Berthier*, *Bergmann*, *Fischer*, *Ginsburg*, *Mayot*, and *Pontis* are discussed in a monograph [1a]. Considerable attention is paid to non-alternant hydrocarbons in a book by *Ginsburg* [2] and in a monograph by *Streitwieser* [3] (see also [4,5]). HMO data for a few dozen hydrocarbons are given in tables published by *Coulson* and *Daudel* [6], which also contain many references (for numerical data see also [1a,7,7a]). The reader is also referred to early papers [8–15]; the reviews [16,17] concentrate mainly on experimental aspects.

The present review makes use of a classification [18] which takes into account the number of condensed rings in a carbon skeleton (benzenoid rings with even numbers of carbon atoms and sharing only two atoms with non-alternant rings are not counted). Non-alternant hydrocarbons have also been classified on the bases of rings with even and odd numbers of carbon atoms and of rings containing only odd numbers of carbon atoms [19].

Thus we regard the tropylium cation *(1)* and the fluorenyl anion *(2)*, for example, as monocyclic compounds, whereas s-indacene *(3)* is tricyclic, and indeno[2,1-*a*]-

[*] Based on a lecture delivered to a colloquium in the Organic Chemistry Laboratory of the ETH Zurich (Switzerland) on October 26th, 1964.

[**] The simplest modification of the MO–LCAO method is the Hückel approximation (HMO), in which the molecular orbitals ψ_i are expressed as linear combinations of the atomic orbitals φ_j; in the π-electron approximation only the $2p_z$ atomic orbitals are considered. For the interaction of n orbitals we have:

$$\psi_i = \sum_{j=1}^{n} c_{ij}\,\varphi_j \qquad (a)$$

The π-electron densities and the bond orders can be calculated from the coefficients c_{ij} of the molecular orbitals. The energies E_i of the molecular orbitals are found by solving the determinantal equation; the n permitted levels are given by:

$$E_i = \alpha + k_i\beta, \qquad (b)$$

where α is the Coulomb integral of the $2p_z$ orbital of carbon and β is the resonance integral of the C–C π-bond (and also the unit of energy in the HMO theory). The occupied molecular orbital with the highest energy is denoted by k_1 (normal state), and the unoccupied level with the lowest energy by k_{-1} (valence state). The transfer of an electron from k_1 to k_{-1} is called $N \rightarrow V_1$ excitation.

The main difference between the HMO method and the more accurate MO–LCAO methods is that electronic interactions are explicitly taken into account in the latter; these methods are *Pople*'s SCF (self-consistent field) method and *Pariser* and *Parr*'s LCI (limited configuration interaction) method.

[1] *C. A. Coulson* and *G. S. Rushbrooke*, Proc. Cambridge philos. Soc. *36*, 193 (1940).

[1a] *B. Pullman* and *A. Pullman*: Les Théories Electroniques de la Chimie Organique, Masson, Paris 1952.

[2] *D. Ginsburg*: Non-benzenoid Aromatic Compounds. Interscience, New York 1959.

[3] *A. Streitwieser Jr.*: Molecular Orbital Theory for Organic Chemists. Wiley, New York 1961.

[4] *R. Daudel*, *R. Lefebvre*, and *C. Moser*: Quantum Chemistry. Interscience, New York 1959.

[5] *A. Julg*, Chimie Théorique. Dunod, Paris 1964.

[6] *C. A. Coulson* and *R. Daudel*: Dictionary of Values of Molecular Constants. Mathematical Inst., Oxford and Paris 1955, Vol. I–III.

[7] *R. Zahradnik*, *J. Michl*, and *J. Koutecký*, Collect. czechoslov. chem. Commun. *29*, 1932 (1964).

[7a] *R. Zahradnik* and *J. Michl*, *ibid.*, in press.

[8] *C. A. Coulson* and *H. C. Longuet-Higgins*, Rev. sci. *1947*, 929.

[9] *R. D. Brown*, Trans. Faraday Soc. *44*, 984 (1948); *45*, 296 (1949); *46*, 146 (1950).

[10] *R. D. Brown*, J. chem. Soc. (London) *1951*, 2391.

[11] *C. Sándorfy*, C. R. hebd. Séances Acad. Sci. *226*, 1611 (1948); *229*, 653 (1949).

[12] *G. W. Wheland* and *D. E. Mann*, J. chem. Physics *17*, 264 (1949).

[13] *F. H. Burkitt*, *C. A. Coulson*, and *H. C. Longuet-Higgins*, Trans. Faraday Soc. *47*, 553 (1951).

[14] *J. I. F. Alonso* and *J. S. Lucas*, An. Real Soc. españ. Fisica Quim., Ser B *50*, 143 (1954).

[15] *J. I. F. Alonso* and *J. Mira*, An. Real Soc. españ. Fisica Quim., Ser. B *50*, 146 (1954).

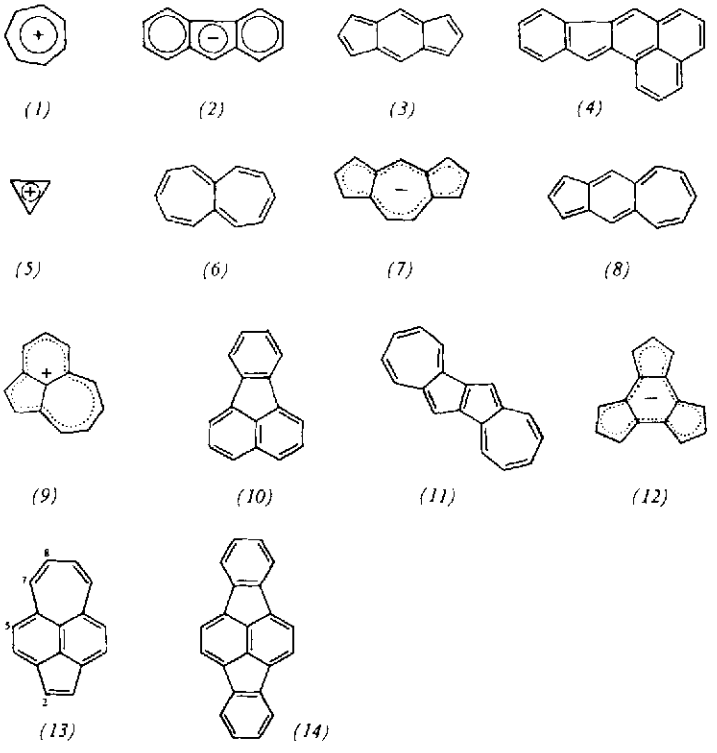
[16] *K. Hafner*, Angew. Chem. *75*, 1041 (1963); Angew. Chem. internat. Edit. *3*, 165 (1964).

[17] *M. E. Volpin*, Usp. Khim. *29*, 298 (1960).

[18] *R. Zahradnik* and *J. Michl*, Collect. czechoslov. chem. Commun. *30*, 515 (1965).

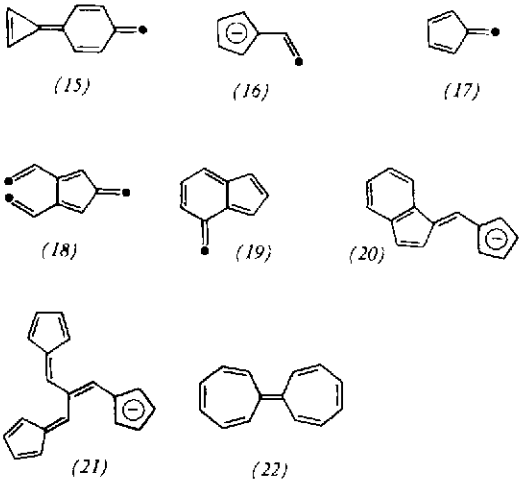
[19] *E. Heilbronner* in [2], p. 171.

phenalene *(4)* (in which one benzene ring is not counted) is tetracyclic. In the conjugated system phenalene, which has an odd number of carbon atoms, the benzene rings cannot be disregarded.



We distinguish between the basic types of skeletons shown in Figure 1 [examples are given in formulae *(1)* to *(14)*]. This formal classification is important to a systematic treatment, and can be readily applied to larger systems. Skeletons of Group A contain an uneven number of carbon atoms, those of Group B are even, while those of Groups C and D are subdivided into even and odd.

The basic skeletons contain no exocyclic bonds. Skeletons such as *(16)* to *(19)* are derived by the introduction of one or more polyene chains or residues such as *(15)*; furthermore, several basic skeletons may be linked by a polyene chain as in *(20)* and *(21)*, or directly, as in *(22)*.



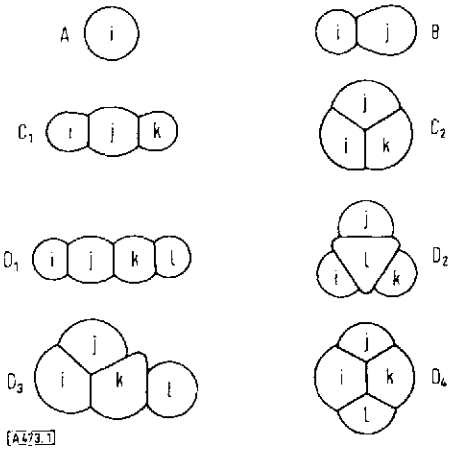


Fig. 1. Basic skeletons of conjugated unsaturated hydrocarbons. i, j, k, and l denote the numbers of carbon atoms in the rings. Each number may be even or odd, unless otherwise indicated. Each skeleton must contain at least one odd ring.

A: monocyclic, i = odd [*e.g. (5)*]
B: bicyclic, i, j = odd [*e.g. (6)*]
C_1: tricyclic, kata-fused, i, j, k = odd [*e.g. (7)*]
j = even, indenoid [*e.g. (8)*]
C_2: tricyclic, peri-fused [*e.g. (9)*]. Benz[*a*]acenaphthylene (= fluoranthene) *(10)* and its benzo derivatives form an independent sub-group: fluoranthenoid hydrocarbons.
D_1,D_2: tetracyclic, kata-fused, i, l = odd or i, j, k = odd [*e.g. (11)* or *(12)*].
D_3: tetracyclic, kata-peri-fused, l = odd.
D_4: tetracyclic, peri-fused [*e.g. (13)*]. Dibenzo[*a*,*g*]pyracylene *(14)* and its benzo derivatives are regarded as fluoranthenoid hydrocarbons.

II. Physical Properties of Non-Alternant Hydrocarbons

1. Electronic and Charge-Transfer Spectra

Electronic spectrocscopy is an important tool for the study of the electronic structures of conjugated organic compounds. The energies corresponding to the maxima of the various absorption bands (electronic bands) are the energies required to raise the molecule from the ground state to the various excited singlet or triplet states.

The spectra of non-alternant hydrocarbons, unlike those of alternant hydrocarbons (particularly benzenoid), cannot be classified empirically. In order to be able to interpret or predict these spectra, it is therefore necessary to use the LCI method. Only in special cases (vinylogous series, ions) is it possible to correlate the energies of the maxima of the intense longest-wavelength bands with the energies of the $N \rightarrow V_1$ transitions, which are calculated by the HMO method.

Various authors [20–23] have used the LCI method in the theoretical treatment of the electronic spectra of non-alternant hydrocarbons; it was only recently, however, that systematic studies have been undertaken [24,25].

[20] *R. Pariser*, J. chem. Physics *25*, 1112 (1956).

[21] *J. N. Murrell* and *H. C. Longuet-Higgins*, J. chem. Physics *23*, 2347 (1955).

[22] *A. Julg* and *B. Pullman*, J. Chim. physique *52*, 481 (1955).

[23] *H. C. Longuet-Higgins* and *K. L. McEwen*, J. chem. Physics *26*, 719 (1957).

[24] *E. Heilbronner* and *J. N. Murrell*, Molecular Physics *6*, 1 (1963).

[25] *J. Koutecký*, *P. Hochman*, and *J. Michl*, J. chem. Physics *40*, 2439 (1964).

Satisfactory agreement has been found between the calculated and experimental values of the singlet excitation energies of 45 hydrocarbons (cf. *e.g.* Fig. 2, in which calculated values for the absorption maxima were plotted together with the absorption curves). The advantage of comparing the experimental and theoretical values as in Figure 2 [24] is that it is not necessary therefore, that series of non-alternant hydrocarbons and their derivatives have been found in which the longest-wavelength bands lead to a satisfactory correlation between the HMO energies and the experimental excitation energies (see Table 1 and Fig. 3). The values for the ions lie on a regression line which is different from that for neutral hydrocarbons.

Table 1. Regression coefficients (a,b) and correlation coefficients (r) for the relationship between the experimental wavenumbers $\tilde{\nu}$ of the longest-wavelength bands and the theoretical values $E(N \rightarrow V_1)$.
(N: normal spectra; CT: charge-transfer spectra; n: number of compounds that belong to one type.)

N: $\tilde{\nu}\,[cm^{-1}\cdot 10^{-3}] = a\cdot E\,(N \rightarrow V_1)\,[\beta] + b$
CT: $\tilde{\nu}\,[cm^{-1}\cdot 10^{-3}] = a\cdot k_1(_{-1})\,[\beta] + b$

Compound	Spectrum	n	a	b	r	Ref.
Tropylium cations	N	7	19.90	2.83	0.996	[27, 28]
Cyclopentadienyl anions	N	5	20	3	—	[29]
Hydrocarbons of the fluoranthene type	N	28	22.58	5.80	0.957	[30]
(40)	N	9	14.45	7.13	0.962	[31, 32, 33]
(39)	N	12	27.3	14.7	—	[34, 35]
ω-Phenylpolymethinetropylium cations	N	5	14.5	8.5	—	[36, 37]
ω,ω-Diphenylpolymethinetropylium cations	N	4	16.4	7.8	—	[36, 37]
(β-Arylvinyl)tropylium cations	N	6	19.3	5.7		[37, 38]
Hydrocarbons of the fluoranthene type + trinitrofluorenone	CT	6	29.57	4.91	0.934	[30, 39]
Benzenoid hydrocarbons + tropylium cation	CT	5	22.45	8.37	0.997	[40, 41]

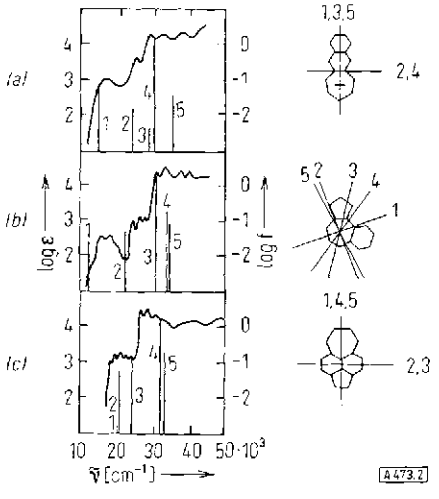


Fig. 2. Comparison of experimental and calculated electronic spectra of non-alternant hydrocarbons [25] for the five longest-wavelength transitions. The theoretical polarization directions are shown in the formulae (f = oscillator strength).

to select that band in the spectrum which corresponds to a vertical electronic excitation (the geometry remains unchanged), since this can be particularly difficult in the case of non-alternant hydrocarbons. It was found [25] that nearly all the hydrocarbons studied have an excited state in which the configuration $\chi_{1\rightarrow -1}$ predominates as a result of the excitation of the electron from k_1 to k_{-1}; the contribution of this configuration, in fact, is frequently about 90 %. The transition in question is evidently similar to *Clar*'s p-transition in benzenoid hydrocarbons [26]. Thus within the various classes (*e.g.* tropylium and its benzo or naphtho derivatives), there is a relationship between these LCI excitation energies for the first transitions and the HMO energies of the $N \rightarrow V_1$ transitions. It is not surprising,

A perturbation calculation [42] within the framework of the simple HMO method shows that the replacement of a carbon atom j in the skeleton by a hetero-atom causes a change in the excitation energy δE_j which is given by

$$\delta E_j = \left(c^2_{-1,j} - c_{1,j}\right)\delta\alpha_j \qquad (c)$$

[$c_{1,j}$ and $c_{-1,j}$ are the orbital coefficients of φ_j in the k_1 and k_{-1} orbitals, and α_j is the Coulomb integral of the hetero-atom (in β units)]. If $\delta\alpha_j$ is positive, a positive value of the expression in brackets corresponds to a bathochromic shift of the first band.

This method has been used in particular in the study of alkyl-substituted azulenes, in which only an inductive effect of the alkyl groups was considered. In many systems containing one hetero-atom, it was found that

[26] *E. Clar*: Aromatische Kohlenwasserstoffe. 2nd ed. Springer, Berlin-Göttingen-Heidelberg 1952.

[27] *G. Naville, H. Strauss*, and *E. Heilbronner*, Helv. chim. Acta *43*, 1221 (1960).

[28] *G. Naville, H. Strauss*, and *E. Heilbronner*, Helv. chim. Acta *43*, 1243 (1960).

[29] *A. Streitwieser Jr.* and *J. I. Brauman*, J. Amer. chem. Soc. *85*, 2633 (1963).

[30] *R. Zahradnik, J. Michl*, and *J. Koutecký*, J. chem. Soc. (London) *1963*, 4998.

[31] *R. Kuhn*, Angew. Chem. *74*, 721 (1962); *75*, 174 (1963); Angew. Chem. internat. Edit. *1*, 602 (1962); *2*, 163 (1963).

[32] *Ch. Jutz* and *H. Amschler*, Angew. Chem. *73*, 806 (1961).

[33] *R. Zahradnik* and *J. Michl*, Collect. czechoslov. chem. Commun. *30*, 1060 (1965).

[34] *Ch. Jutz*, Ber., in the press.

[35] *R. Zahradnik, J. Michl*, and *Ch. Jutz*, Collect. czechoslov. chem. Commun. *30*, 3227 (1965).

[36] *Ch. Jutz* and *F. Voithenleitner*, Chem. Ber. *97*, 1590 (1964).

[37] *R. Zahradnik* and *J. Michl*, unpublished work.

[38] *Ch. Jutz*, Chem. Ber. *97*, 1349 (1964).

[39] *A. R. Lepley*, J. Amer. chem. Soc. *84*, 3577 (1962).

[40] *M. Feldman* and *S. Winstein*, J. Amer. chem. Soc. *83*, 3338 (1961).

[41] *M. Nepraš* and *R. Zahradnik*, Collect. czechoslov. chem. Commun. *29*, 1545 (1964).

[42] *C. A. Coulson*, Proc. physic. Soc. (London) A *65*, 933 (1952).

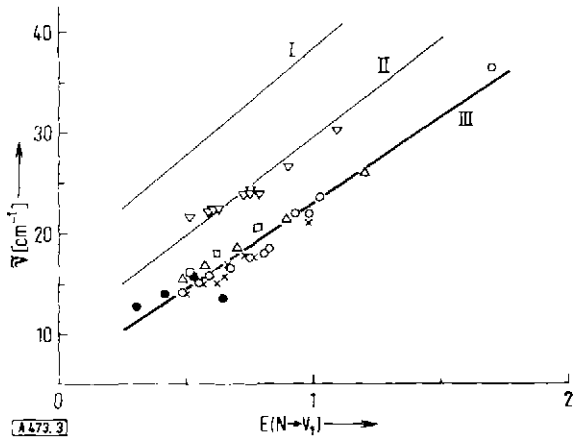


Fig. 3. Relationship between the excitation energies of the maxima of the first bands and the calculated energies of the $N \rightarrow V_1$ transitions. ○ = tropylium cations; ● = cyclopentadienylium cations (anti-Hückel systems); × = anions of the type *(40)*; △ = ω-phenyl- and □ ω,ω-diphenylpolymethinetropylium cations; ▽ = compounds of the type *(39)* (cf. Table 1).
I, II, and III: regression lines for polyenes, benzenoid hydrocarbons, and ions respectively.

there is a close relationship between the quantities δE_i found by perturbation calculations and the energies of the $N \rightarrow V_1$ transitions, which were obtained by solving the secular equations.

The charge-transfer spectra of many complexes containing non-alternant hydrocarbons have been studied. Neutral hydrocarbons and in particular anions act as π-electron donors, and cations as acceptors. It was found that the excitation energies of the charge-transfer bands of complexes of the tropylium cation with benzenoid hydrocarbons and of fluoranthenes with trinitrofluorenone can be correlated with the HMO energies of the corresponding frontier orbitals [*] (see Table 1).

2. Polarographic Behavior

Attempts (see *e.g.* [3]) to correlate the half-wave potentials for the reduction of conjugated unsaturated hydrocarbons have so far been based on the assumption that the process determining the potential of the first step is the reversible uptake of an electron; unfortunately, however, there is no convincing experimental proof. The reduction to the free radical may be preceded or followed by interfering reactions (preceded by molecular association, the formation of solvated complexes, *etc.*, or followed by dimerization, free-radical reactions, *etc.*). Interference with the establishment of the polarographic potential is least likely to occur in aprotic solvents. A remarkably good agreement has been found between the cathodic and anodic half-wave potentials and energies of the k_1 and k_{-1} levels in the case of alternant hydrocarbons and their derivatives [42a]. The only unsubstituted non-alternant hydrocarbons that have been systematically studied are fluoranthene and its benzo, naphtho *etc.* derivatives [43]. It was found that their half-wave potentials lie almost on the same regression line as the values for benzenoid hydrocarbons [30]. The data for α-(2,2′-biphenylylene)polyenes and for α,ω-bis(biphenylylene)polyenes also correspond to this regression line [44].

The half-wave potential of azulene, on the other hand, does not fall on the line. A perturbation calculation leads only to an explanation of the increasing difficulty of reduction as we pass from azulene to monomethylazulene and dimethylazulene. The HMO theory cannot explain the order of the cathodic half-wave potentials of azulene, benz[*a*]azulene and benz[*b*]azulene, just as it cannot explain the order of the excitation energies of the absorption bands in the visible region [19].

The polarographic half-wave potentials of the esters of fluoranthenecarboxylic acid are related to the energies of the k_{-1} orbitals in exactly the same way as those of the esters derived from alternant hydrocarbons [45].

3. Possibilities of Radio-Frequency Spectroscopy

In NMR spectroscopy [46], the linear relationship between the chemical shift and the π-electron densities on the carbon atoms in the cyclopentadienyl anion, benzene, and the tropylium cation can be used to estimate the π-electron densities in other systems. ESR spectroscopy, on the other hand, gives the distribution of the unpaired electrons in the k_1 or k_{-1} orbital in the radical cation or radical anion. The agreement of the HMO theory with experiment regarding the hyperfine structure constants is remarkably good.

III. Chemical Properties of Non-Alternant Hydrocarbons

1. Aromaticity

The concept of "aromaticity" has undergone a far-reaching change, and the use of the term is by no means uniform [47]. It is more convenient, therefore, to speak of chemical stability, and to base the estimation of this stability on the theoretical values of the specific delocalization energy and on the theoretical reactivity indices (atom and ortho-localization energies or superdelocalizability [*]). It is also important to characterize the ability of the molecule as a whole to give up or accept a π-electron (energies of the frontier orbitals k_1 and k_{-1}).

At the moment, only the relative stabilities of substances can be given, on the basis of a comparison with struc-

[*] The frontier orbitals are the highest occupied (k_1) and the lowest unoccupied (k_{-1}) molecular orbitals.

[42a] *R. Zahradnik* and *C. Párkányi*, Analytica chim. Acta, in the press.

[43] *I. Bergmann*, Trans. Faraday Soc. *52*, 690 (1956).

[44] *G. J. Hoijtink*, Recueil Trav. chim. Pays-Bas *74*, 1525 (1955).

[45] *G. Klopman* and *J. Nasielski*, Bull. Soc. chim. Belgique *70*, 490 (1961).

[46] *T. Schaefer* and *W. G. Schneider*, Canad. J. Chem. *41*, 966, (1963); *E. de Boer* and *S. I. Weissman*, J. Amer. chem. Soc. *80* 4549 (1958).

[47] *D. P. Craig* in [2], p. 1.

[*] For a definition of the superdelocalizability S, see *K. Fukui, T. Yonezawa*, and *C. Nagata*, Bull. chem. Soc. Japan *27*, 423 (1954). – This reactivity index is obtained by a simple perturbation calculation using the model of the activated state. *Fukui et al.* assume that the substituting group forms a weak π-bond with the atom of the substituted system, such that this system remains unperturbed.

turally related substances whose properties have been determined experimentally and theoretically (keeping in mind that the medium also has some effect)[48].

The specific delocalization energy $E_{d,s}$ is defined as the ratio of the HMO delocalization energy to the number m of C–C σ-bonds in a conjugated system, m also being a measure of the size of the conjugated system. Only in the case of polyacenes is $E_{d,s}$ almost independent of m; in polyenes and cyclopolyenes $E_{d,s}$ increases or decreases as the conjugated system increases in size and approaches the value of 0.273 β, which is the value for an infinitely long polyene (see Fig. 4)[48]. In

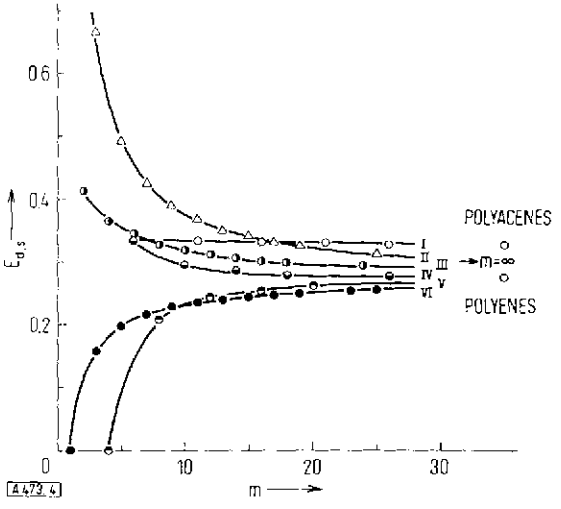


Fig. 4. Relationship between the specific delocalization energy ($E_{d,s}$) and the number m of C–C σ-bonds.
I: polyacene; II: odd cyclopolyenes (cations and anions); III: odd polyenes; IV: even cyclopolyenes with (4n − 2 π-electrons; V: even cyclopolyenes with 4n π-electrons; VI: even polyenes.

practice, the values of $E_{d,s}$ are plotted in a diagram containing the $E_{d,s}$ values for a number of substances of various types (Fig. 4), and the thermochemical stability of the compound in question is estimated by comparison. A similar method, *i.e.* comparison of the reactivity indices with those of structurally related substances, is used to predict the chemical properties of compounds that have not yet been synthesized[33, 49, 50].

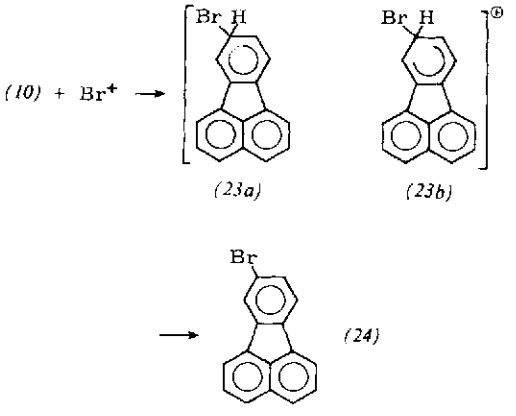
If the delocalization energies found by experiment are plotted against those obtained by the HMO method, the points for some non-alternant hydrocarbons (*e.g.* heptafulvene, fulvalene)[3] lie on a straight line whose slope is smaller than that found for other compounds (*e.g.* benzenoid hydrocarbons)[48]. The reason for this appears to be that the delocalization in compounds of the fulvalene type *(32)* is overestimated by the HMO method.

2. Chemical Reactivity

a) Kinetic Processes

The estimation of the reactivities of non-equivalent positions and bonds in conjugated hydrocarbons should at least be based on calculations of the π-electron contributions to the activation energy, assuming that there is a linear relationship between the activation energy and the entropy of activation, and that the σ-electron contribution is constant for all members of the series in question.

The π-electron contribution is easily found, *e.g.* in the 8-bromination of fluoranthene *(10)*, as the difference between the π-electron energy of the activated complex



(23a) and that of the reacting compound *(10)*. It is nearly always assumed, in fact, that the model of type *(23a)* can be replaced by a Wheland model *(23b)*. In the activated complex *(23a)* the substituted position is assumed to exhibit reduced interaction with the conjugated system, whereas in the model *(23b)* it is assumed that the substituted position is completely excluded from the conjugation. In the case of alternant hydrocarbons it was found that the reactivity is theoretically the same whether model *(23a)* or model *(23b)* is used[51]. In the case of non-alternant hydrocarbons it was shown only for the benzofluoranthenes[37] that the difference between the π-electron energies of the complex *(23b)* and of the reacting substance (*i.e.* Wheland's localization energy A_e) is linearly related to a similar quantity M_e for the complex *(23a)* (see Fig. 5). The localization energy A for electrophilic and nucleophilic reactions

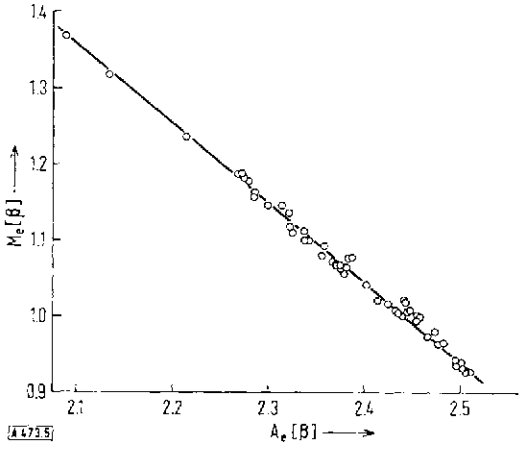


Fig. 5. Relationship between the electrophilic reactivity indices M_e of fluoranthene complexes in accordance with model *(23a)* and the localization energy A_e for model *(23b)*. The values for substituted fluoranthenes, benzo[*a*]-, -[*b*]-, -[*j*]-, and -[*k*]-fluoranthenes, are included.

[48] *R. Zahradnik*: Kvantová organická chemie. Státní pegagogické nakladatelství, Praha 1963, and unpublished work.

[49] *R. Zahradnik* and *J. Michl*, Collect. czechoslov. chem. Commun. *30*, 520 (1965).

[50] *R. Zahradnik*, *J. Michl*, and *J. Pancíř*, Collect. czechoslov. chem. Commun. *30*, 2891 (1965).

[51] *R. Zahradnik* and *J. Koutecký*, Collect. czechoslov. chem. Commun. *28*, 904 (1963).

shows a linear dependence on the superdelocalizability S, not only for the fluoranthenes, but also for other classes of non-alternant hydrocarbons (*e.g.* azulene).

Thus any of the quantities M_e, A_e, or S_e can be used for correlation with the experimental values. However, the localization energy and the π-electron density are not related; on the other hand, the dynamic (A_r, S_r) and static (F = free valence) indices of the free-radical reactivity are generally linearly related to one another. Separation was observed into three groups, depending on the nature of the substitution site; these groups are the benzene type, the α-naphthalene type, and the meso-anthracene type (corresponding to class 0, 1, and 2 positions [52]). The linear relationship between the bond order and the ortho-localization energy found in the case of benzenoid hydrocarbons [53] is also valid for fluoranthene-like hydrocarbons (Fig. 6).

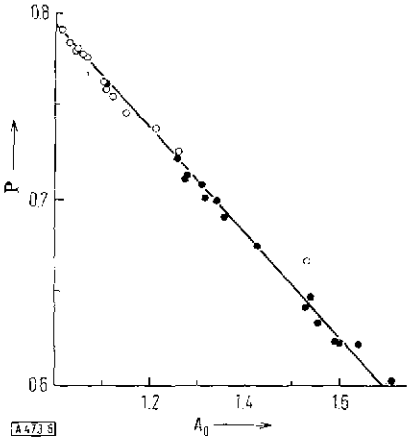


Fig. 6. Relationship between the bond orders p and the ortho-localization energy (A_0) [β units] for benzenoid (○) (benzene, naphthalene, anthracene, phenanthrene, and some benzo derivatives of these) and fluoranthenoid (●) hydrocarbons (fluoranthene *(10)* and four of its benzo derivatives: [*a*], [*b*], [*j*], and [*k*]).

The π-electron densities of the hetero-analogues of non-alternant hydrocarbons, as found by perturbation calculations from the atom-atom polarizabilities, are approximately linearly related to similar quantities calculated by the HMO method (except for positions α to the hetero-atom). However, a completely satisfactory linear relationship was found only in the case of fluoranthene [54].

The results of experimental studies are still unsatisfactory, since data on the reactivities of large groups of structurally related substances are lacking. By analogy with alternant hydrocarbons we conclude that, when the rate constants of polar substitutions are plotted against the theoretical indices (A_e, S_e), the values group themselves according to the class of the substitution site. In this respect the rate constants for the nitration of fluoranthene *(10)* [55], for example, must be regarded as inhomogeneous, since two positions that can be substituted are of class 0, while the other three are of class 1 (two of these belonging to the sterically unfavorable sub-class 1* of the 4-phenanthrene type). This may be the reason for the disagreement between the theoretical and experimental results.

[52] *J. Koutecký*, *R. Zahradnik*, and *J. Čížek*, Trans. Faraday Soc. *57*, 169 (1961).

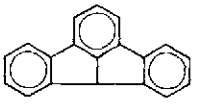
[53] *R. D. Brown*, Austral. J. sci. Res., Ser. A *2*, 564 (1949).

[54] *R. Zahradnik* and *E. Heilbronner*, unpublished work.

[55] *A. Streitwieser Jr.* and *R. C. Faley*, J. org. Chemistry *27*, 2352 (1962).

b) Equilibrium States

Acid-base equilibria have been most thoroughly studied in the case of C-acids, both in alternant and in non-alternant systems [3]. The equilibrium constants can in many cases be estimated from the contribution of the π-electrons to the dissociation energy, which is proportional to the difference in the π-electron energies of the forms occurring in the reaction. Some of the non-alternant hydrocarbon anions are extremely weak bases, so weak, in fact, that they can exist even in solutions of alkali metal hydroxides in aqueous alcohol. These include the anion derived from fluoradene *(25)* [56], as



(25)

well as a number of anions, such as *(40)*, which have been studied by *Kuhn* [31] and *Jutz* [32]; the pK values of the conjugated acids in extreme cases are about 12, whereas the acidity of a hydrocarbon such as cyclopropene or toluene is extremely low. Thus the total range covered by the pK values of these acids is of the order of several decades. Although there is a relationship between the pK values of many C-acids and the corresponding localization energies (*e.g.* [3]), points which still remain unsettled include the influence of the class of the reacting site, the difference between alternant and non-alternant hydrocarbons, and the influence of the solvent.

The situation found in the case of hetero-analogues and protonatable or ionizable derivatives is also interesting. For example, the basicity of an aromatic amine increases with the π-electron density at the position in the parent hydrocarbon to which the amino group is bound, and *vice versa*. Thus 1-aminoazulene [57] is a strong base; the pK value of 3-aminofluoranthene is 2.6 (the amino group is attached at a position for which q = 0.959), while that of the 8-isomer is 4.0 (the q value for this position in the hydrocarbon is 1.008) [58].

A satisfactory agreement between the theoretical and experimental values is also found in the case of the pseudo-basicity (loss of the OH^- group in strongly acidic media: $ROH \rightarrow R^+ + OH^-$) of the carbinols [3]; the experimental pK_{R^+} [58a] values are linearly related to the difference in the π-electron energies of the carbonium ion and of the adduct formed by the combination of OH^-

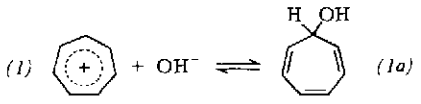
[56] *H. Rapoport* and *G. Smolinsky*, J. Amer. chem. Soc. *82*, 934 (1960).

[57] *J. Schulze* and *E. Heilbronner*, Helv. chim. Acta *41*, 1492 (1958).

[58] *J. Michl*, Dissertation, Institute of Physical Chemistry of the Czechoslovak Academy of Sciences, Prague 1964.

[58a] *N. C. Deno*, *J. J. Jaruzelski*, and *A. Schriesheim*, J. org. Chemistry *19*, 155 (1954).

with the cation, *i.e.* in the case of the tropylium cation *(1)*, to the difference between the π-electron energy of *(1)* and that of the hexatriene derivative *(1a)*.



IV. Classification of Conjugated Unsaturated Cyclic Hydrocarbons

1. Monocyclic Systems

Two groups of non-alternant monocyclic systems can be distinguished: (a) "Hückel" systems, which contain $4n+2$ π-electrons, and in which all the bonding orbitals are occupied, and (b) "anti-Hückel" systems, which contain $4n$ π-electrons, and in which not all the bonding orbitals are occupied, or antibonding orbitals are also occupied. Out of the group *(26a)* to *(30a)*, the systems *(27a)* to *(29a)* have been prepared [2,59]. The dipropyl derivative of *(26a)* is the simplest cyclopropenylium cation known [60]. Many aryl and aralkyl derivatives of the systems *(26a)* to *(29a)* have been prepared. It can be seen from curve II in Fig. 4 that $E_{d,s}$ rapidly approaches the value characteristic for polyenes, as the ring size increases. The spectra of the benzo derivatives of the anion *(27a)* [29] and of the cation *(28a)* [27,28] have been studied. The spectra and reactivities of many analogues of tropylium compounds containing sulfur, *e.g.* the thiapyrylium and dithiolium ions and their derivatives [61], have also been studied.

The "anti-Hückel" ions *(26b)* to *(30b)* are interesting. The fluorenyl cation *(31)* [62] and its four benzo-derivatives ([*a*], [*b*], [*c*], [*def*]) have been studied most thoroughly [58, 63]. These compounds absorb at the edge of

(31)

the near infrared region (*ca.* 13000 cm^{-1}). This is understandable, since the absorption is due to a $\pi \rightarrow \pi$ transition, and not to a $\pi \rightarrow \pi^*$ transition, as is the case in "Hückel" ions and in most neutral molecules. However, even if the extension of the conjugated system is taken into account, the wavelength of the first absorption band is still extremely high, even in the case of the anion. For

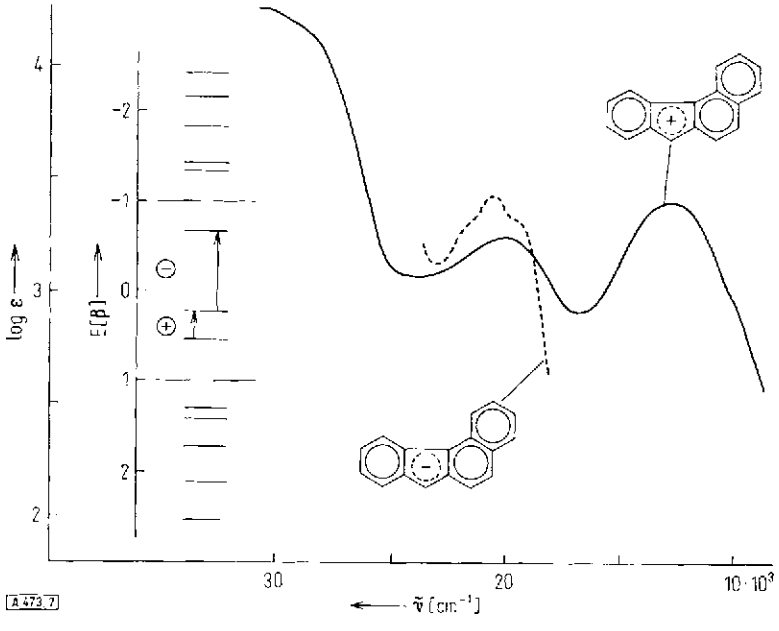
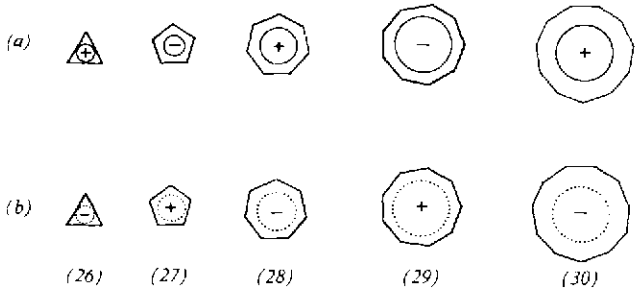


Fig. 7. Absorption curve of the benzo[*c*]fluorenylium cation [58] and the longest-wavelength absorption band of the benzo[*c*]fluorenyl anion [29], together with the HMO energy levels.

example, benz[*a*]anthracene which is isoelectronic with the benzo[*c*]fluorenyl anion (see Fig. 7), absorbs at 26000 cm^{-1}. The explanation for this behavior appears to be that, in the case of ions, the part of the total excitation energy which is due to the mutual repulsion of



[59] *T. J. Katz* and *P. J. Garratt*, J. Amer. chem. Soc. *85*, 2852 (1963); *E. A. LaLancette* and *R. E. Benson*, *ibid.* *85*, 2853 (1963).

[60] *R. Breslow*, *H. Hover*, and *Hai Won Chang*, J. Amer. chem. Soc. *84*, 3168 (1962).

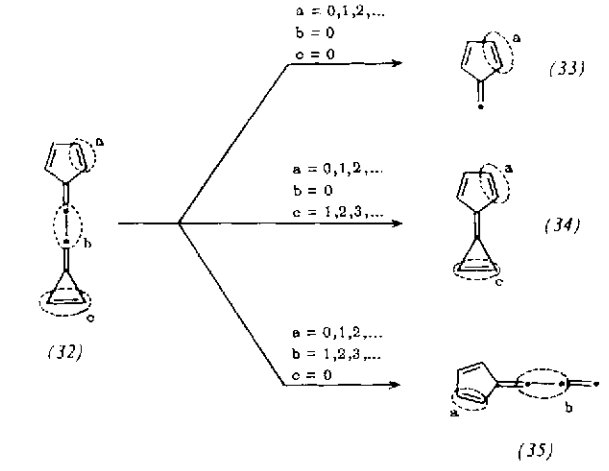
[61] *R. Zahradnik* in *A. R. Katritzky*: Advances in Heterocyclic Chemistry. Academic Press, New York 1965, Vol. 5, p. 1.

[62] *N. C. Deno*, *J. J. Jaruzelski*, and *A. Schriesheim*, J. Amer. chem. Soc. *77*, 3044 (1955).

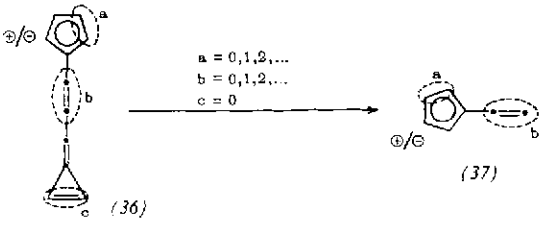
[63] *J. Michl*, *R. Zahradnik*, and *P. Hochmann*, J. physic. Chem., in the press.

the electrons, and which is not taken into account in the HMO method, is approximately 5000 cm^{-1}, *i.e.* appreciably less than in the case of conjugated neutral hydrocarbons (approximately 10000 cm^{-1})[64].

By combining rings with polyene chains, systems of the type *(32)* are obtained [special cases of which are fulvenes *(33)*, fulvalenes *(34)*, and compounds *(35)* consisting of a ring with an odd number of carbon atoms and a polyene chain with an odd number of carbon atoms], as well as compounds *(36)* and *(37)*. The systems *(32)* to *(35)* possess only one Kekulé structure, and their delocalization energies are very low[65]; in these cases, therefore, the results of the HMO method can only be regarded as rough approximations. It was only recently that fulvene *(33)*, with a = 1, has been prepared in high yields[66,66a]; heptafulvene *(33)*, with a = 2, has only been prepared in solution and is stable only at −60 °C for a short time[67].

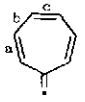


(32) *(33)* *(34)* *(35)*



(36) *(37)*

It is worth noting that the fusion of a benzene ring onto fulvene *(33)* causes a hypsochromic shift of the first band in the electronic spectrum; this shift is correctly predicted by the HMO theory[1a]. A similar increase is found in the energies of the $N \rightarrow V_1$ transitions in benzo derivatives of heptafulvene *(38)* in which the benzene ring is attached in position *a* or *c*. On the other hand, a significant bathochromic shift is to be expected if a benzene ring is fused in position *b*[7]. The exocyclic carbon atom in fulvene (heptafulvene) and its vinylogues *(35)* carries a large positive (negative) charge; the molecule should therefore be stabilized by the attachment of a substituent with a −M (+M) effect, *e.g.* an NH_2 or OH (NO_2 or CN) group to this carbon. The dimethylaminofulvenes of the type *(39)* are, in fact, relatively stable[34].



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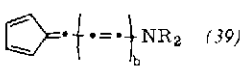
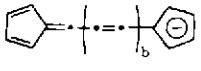


(39)

As predicted by theory, substances of the type *(39)* have been found to be strong π-bases; their ease of polarographic oxidation was to be expected[35]. 8,8-Dicyanoheptafulvene and its vinylogues are also stable for the same reasons[68–69]. It is interesting to note that the energy of the $N \rightarrow V_1$ transitions of fulvapolyenes *(32)* (a = 1; b = 0, 1, 2; c = 2) increases with increasing chain length[1a]; it should be added that these are $\pi \rightarrow \pi$ transitions, since the highest bonding molecular orbital is unoccupied.

Two compounds of the type *(34)* are known, namely fulvalene and heptafulvalene *(22)*[67,70]. Judging from MO theory[1a] it should also be possible to synthesize the sesquifulvalene *(34)* (a = 1, c = 3). The use of improved MO methods is particularly important for compounds of the type *(32)*[71]. It should be noted, that these substances are strongly olefinic in character. The spectra of fulvene and heptafulvene as calculated by the LCI method do not agree with the experimental findings[25]; the use of SCF orbitals would be desirable[72]. It is interesting to note that the energies of the $N \rightarrow V_1$ transitions as calculated by the HMO method and by a method that takes the alternation into account are linearly related[73].

Anions of the type *(40)* with a five-membered ring at each end of the odd polyene chain have been studied both experimentally and theoretically. Their dibenzo and tetrabenzo derivatives[31–33], however, show that the corresponding "anti-Hückel" cations can also be prepared[74]. The very large differences in the delocalization energies of the anion and the cation of the system



(40), b = 0,1,2

(40) with b = 0 are predicted by the theory; the difference decreases with increasing chain length and above all with ring fusion. The most remarkable property of

[64] *J. Koutecký, J. Paldus,* and *R. Zahradnik*, J. chem. Physics *36*, 3192 (1962).

[65] *M. J. S. Dewar* and *H. N. Schmeising*, Tetrahedron *11*, 96 (1960).

[66] *K. Hafner*, Angew. Chem. *76*, 862 (1964); Angew. Chem. internat. Edit. *3*, 749 (1964).

[66a] *H. Schaltegger, M. Neuenschwander,* and *D. Mencke*, Helv. chim. Acta *48*, 955 (1955).

[67] *W. v. E. Doering* and *H. Krauch*, Angew. Chem. *68*, 661 (1956).

[68] *T. Mukai, T. Nozoe, K. Osaka,* and *N. Shishido*, Bull. chem. Soc. Japan *34*, 1384 (1961).

[68a] *K. Hafner, H. W. Riedel,* and *M. Danielisz*, Angew. Chem. *75*, 344 (1963); Angew. Chem. internat. Edit. *2*, 215 (1963).

[69] *Ch. Jutz*, Chem. Ber. *97*, 2050 (1964).

[70] *J. R. Mayer*, Dissertation, Yale University, 1955.

[71] *T. Nakajima* in: Molecular Orbitals in Chemistry, Physics, and Biology. Academic Press, New York 1964, p. 451.

[72] *A. J. Silvestri, L. Goodman,* and *J. A. Dixon*, J. chem Physics *36*, 148 (1962).

[73] *J. Koutecký* and *P. Hochmann*, personal communication.

[74] *R. Kuhn, H. Fischer, F. A. Neugebauer,* and *H. Fischer*, Liebigs Ann. Chem. *654*, 64 (1962).

anions of the type *(40)* is their unusually low basicity; for this reason, their conjugate acids are called "highly acidic hydrocarbons".

2. Bicyclic Systems

Of the basic bicyclic systems two are known at present, namely azulene [20] and heptalene *(6)* [75]. Since the synthesis of other bicyclic hydrocarbons seems possible, we shall consider systems that are formally derived by the fusion of rings containing from three to eleven carbon atoms (Figure 8). System containing $4n+2$ π-electrons will be referred to as azulenoid (A) and systems

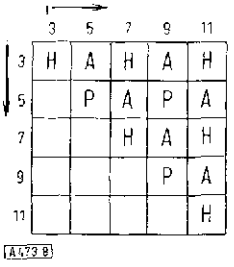
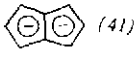


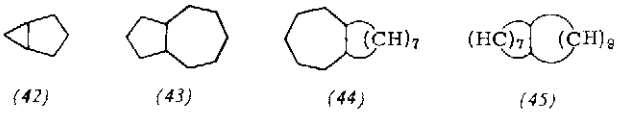
Fig. 8. Combination of monocyclic systems to give azulenoid (A), pentalenoid (P), and heptalenoid (H) bicyclic systems.

with $4n$ π-electrons as pentalenoid (P) or heptalenoid (H), depending on whether they contain an occupied (H) or unoccupied (P) non-bonding π-molecular orbital in the ground state. Pentalenoid systems should show some tendency to form dianions and heptalenoid systems to form dications, which again contain $4n+2$ π-electrons. The pentalene dianion *(41)* has in fact been prepared [76].



(41)

Energy data and extreme values of the π-electron density (q_{max}, q_{min}) of various azulenoid systems are given in Table 2. It can be concluded from these results that a system such as *(44)* consisting of a seven-membered ring and a nine-membered ring should be reasonably stable. It is found that the maximum (minimum) π-electron density always occurs on a carbon atom adjacent to the common bond, and in a ring containing $4n+1$ $(4n+3)$ carbon atoms. The probability that it will be possible to prepare substances *(42)* and *(45)* is considerably lower.



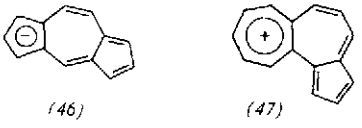
(42) *(43)* *(44)* *(45)*

The spectra, the electrochemical and other physical properties (*e.g.* infrared frequencies, thermodynamic quantities), and the reactivities of azulene and its alkyl derivatives were studied by *Heilbronner* [19]. Considerable attention was paid to pentalene and heptalene *(6)* [71, 77]. Heptalene possesses alternating bonds (olefinic character), and the same will probably also be true of pentalene, which has not yet been prepared in spite of numerous attempts. In agreement with this, it has been found [78, 79] that the pentalene and heptalene structures with an axis of symmetry (C_{2h}) are energetically more favorable than structures containing two planes of symmetry (D_{2h}).

3. Tricyclic Systems

a) Kata-Fused Systems

Of the nine odd structures that can be constructed from five-membered and seven-membered rings (Fig. 1, type C_1; i, j, k = odd), six contain a plane of symmetry. Symmetrical ions with occupied bonding orbitals are negatively or positively charged, depending on whether the outer rings are five- or seven-membered. Compound *(46)* is an example of an ion that should be relatively stable, the energies of its frontier orbitals being k_1 $0.275\,\beta$ and $k_{-1} = -0.494\,\beta$. Unsymmetrical compounds, such as *(47)* [$k_{-1} = -0.07\,\beta$] always have a molecular orbital that is almost non-bonding. This means that these unsymmetrical compounds will not be very stable;



(46) *(47)*

Table 2. Energy data of some azulenoid bicyclic hydrocarbons (in β units). W: total π-electron energy; $E_{d,s}$: specific delocalization energy; k_2, k_1, k_{-1}, k_{-2}: energies of the two highest occupied and of the two lowest unoccupied molecular orbitals; $E(N \rightarrow V_1)$: energy of the $N \rightarrow V_1$ transition; q: π-electron density.

Compound	W	$E_{d,s}$	k_2	k_1	k_{-1}	k_{-2}	$E(N \rightarrow V_1)$	q_{max}	q_{min}
(42)	8.390	0.341	1.139	0.618	−0.820	−1.618	1.438	1.215	0.700
(43)	13.364	0.306	0.887	0.477	−0.400	−0.738	0.878	1.173	0.855
(44)	18.410	0.294	0.543	0.295	−0.335	−0.618	0.630	1.110	0.877
(45)	23.477	0.288	0.474	0.258	−0.233	−0.429	0.491	1.096	0.912

it should, however, be possible to prepare both their anions and cations [137].

Kata-fused hydrocarbons of the type C_1 (i, k = odd, j = even) are characterized by the fact that they contain two non-alternant rings fused to a central alternant ring.

[75] *H. J. Dauben Jr.* and *D. J. Bertelli*, J. Amer. chem. Soc. *83*, 4656, 4657 (1961).

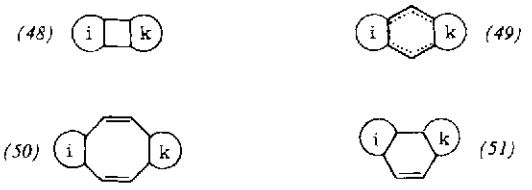
[76] *T. J. Katz* and *M. Rosenberger*, J. Amer. chem. Soc. *84*, 865 (1962).

[77] *E. D. Bergmann* in [2], p. 141.

[78] *P. C. Boer-Veenendaal, J. A. Vliegenthart*, and *D. W. W. Boer*, Tetrahedron *18*, 1325 (1962).

[79] *L. C. Snyder*, J. physic. Chem. *66*, 2299 (1962).

These hydrocarbons *(48)* to *(51)* are referred to as indacenoid. Great interest is being devoted at present



to hydrocarbons of the type *(49)*. The HMO calculations for three substances of this type (i, k = 5, 7) and for three isomeric compounds of the type *(51)* [80,81], as well as the fact that s-indacene *(3)* has been prepared [16], indicate that compounds that are formally derived from azulene will be relatively stable. According to Fig. 9,

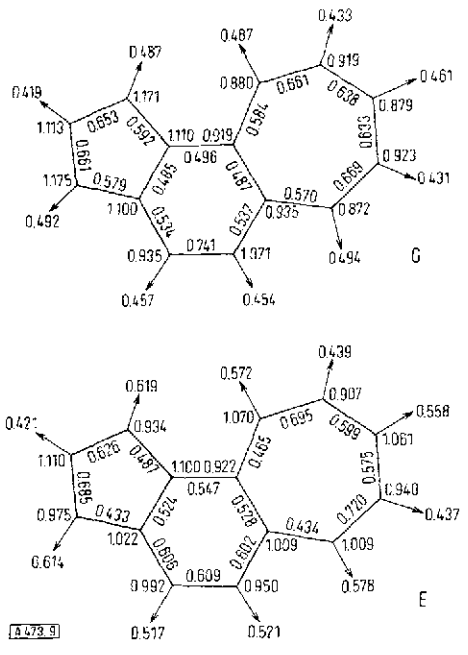
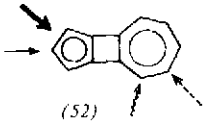


Fig. 9. Molecular diagrams of dehydrocycloheptatrieno[*e*]indene in the ground state (above) and in the excited state ($N \rightarrow V_1$) (below) [80].

the properties of the angular isomer are rather favorable. It has been found that the insertion of one or two benzene rings between the five-membered and the seven-membered rings of azulene (linear condensation) has no effect on the positions of the centers of electrophilic and nucleophilic reactivity of the latter. On the other hand, in the non-alternant isomer *(52)* of biphenylene, which has not yet been prepared, a change in the positions of these centers is to be expected [80]. (The arrows $\longrightarrow$, $\dashrightarrow$, and $\rightsquigarrow$ indicate the theoretical centers of electrophilic, nucleophilic, and free-radical reactivity; the bond which is most likely to undergo an addition is marked by a bold arrow.)



(52)

[80] *R. Zahradnik, J. Michl,* and *J. Kopecký,* Collect. czechoslov. chem. Commun., in the press.

[81] *D. Peters,* J. chem. Soc. (London) *1958,* 1028, 1039.

In the case of pentalene and heptalene derivatives, type *(49)* is theoretically more favorable than type *(51)*. This difference is so pronounced that angularly fused compounds can probably only be obtained in the form of the dianion.

b) Peri-Fused Systems

Nine non-alternant peri-fused hydrocarbons can be derived by the combination of five-membered, six-membered, and seven-membered rings, three of them being odd.

System *(9)* is an interesting case, since it contains a non-bonding molecular orbital [37,*] and should therefore be stable both as the anion and as the cation (Fig. 10).

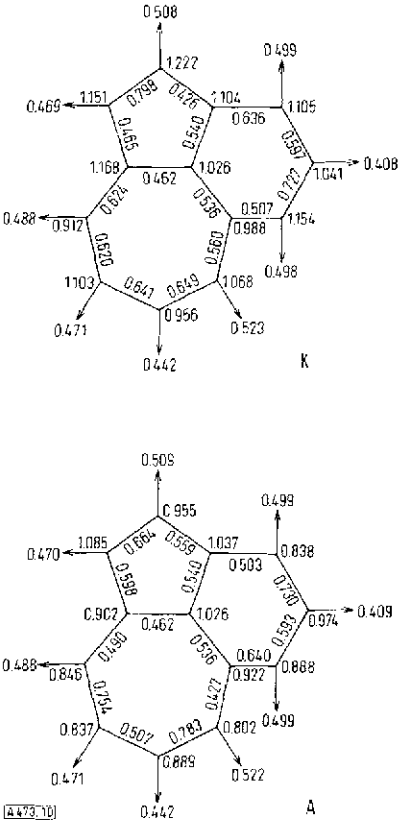


Fig. 10. Molecular diagrams of the anion (above) and the cation (below) of benz[*cd*]indene [37].

Both forms have actually been prepared as the methyl derivatives [83,84]. Dimethyl derivatives have also been prepared [84,85] of the hydrocarbons *(53)* and *(54)*, which can be derived from pentalene and heptalene. The theoretically expected centers of reactivity are marked in these formulae in the same way as in formula *(52)* [86].

[*] This is remarkable, since the system is odd and non-alternant. The absolute term in the determinantal equation is equal to zero, as can be shown by an analysis of the graphical representation of the molecule [82].

[82] *J. Čížek,* personal communication.

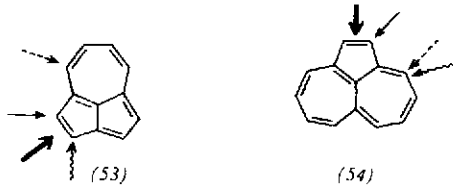
[83] *K. Hafner* and *H. Schaum,* Angew. Chem. *75,* 90 (1963); Angew. Chem. internat. Edit. *2,* 95 (1963).

[84] *K. Hafner* and *H. Schaum,* unpublished work.

[85] *K. Hafner* and *J. Schneider,* Liebigs Ann. Chem. *624,* 37 (1959).

[86] *M. A. Ali* and *C. A. Coulson,* Molecular Physics *4,* 5 (1961).

The hydrocarbon *(54)*, unlike *(53)*, possesses some aromatic character [85]. The properties of the ions *(55)*



(53) *(54)*

(55) *(56)*

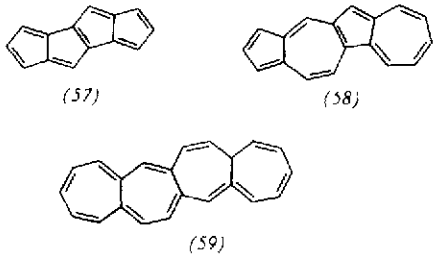
and *(56)* are theoretically promising, and the possibility of a synthesis of the anion *(55)* appears to be very good [37].

Theoretical studies have been carried out on acenaphthylenes, their hetero-analogues and derivatives [58], benz[*a*]acenaphthylene (= fluoranthene) *(10)*, and a few dozen benzo derivatives of fluoranthene, including compounds of the type *(14)* [26, 30, 58, 87]. The half-wave potentials, electronic spectra, and reactivities found can be satisfactorily explained by theory. It appears that the fluoranthenes have the character of real non-alternant hydrocarbons [87a].

4. Tetracyclic Systems

a) Kata-Fused Systems

Only a few kata-fused tetracyclic systems have been subjected to a theoretical study [37]. It appears that azulenoazulene *(58)* should be the most stable of the compounds *(57)* to *(59)*.

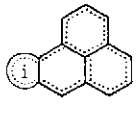


(57) *(58)*

(59)

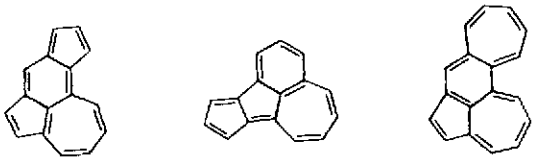
b) Kata-Peri-Fused Systems

The extremely interesting kata-peri-fused hydrocarbons include the Reid hydrocarbons [49, 88]. Reid hydrocarbons of the type *(60)* are formally analogues of azulene, which may be regarded as the "fusion products" of the cyclopentadienyl anion and the tropylium cation. Replacement of one of these structural units by phenalenyl [*], which is stable both as a cation and as an anion (presence of a non-bonding MO) leads to other interesting compounds.



(60), i = 5, 7

By definition, Reid hydrocarbons are formally derived by kata-fusion of the cyclopentadienyl anion or the tropylium cation with an oppositely charged odd peri-fused tricyclic hydrocarbon with an HMO energy of zero. This definition fits henz[*cd*]azulenyl *(9)* as well as



(61) *(62)* *(63)*

the phenalenyl system. The theoretical values indicate that, of the eight hydrocarbons studied (none of which has yet been prepared), *(61)* and *(62)* should be most stable; the hydrocarbon *(63)*, on the other hand, should be very unstable.

The agreement between the theoretical and experimental values of the excitation energy is satisfactory in the case of the benzo derivative *(60′)* of *(60)*, i = 5 (Fig. 11).

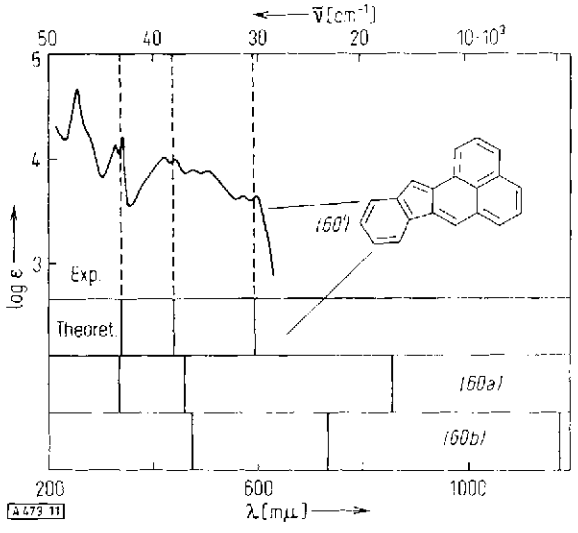


Fig. 11. Results of calculations of the absorption bands of Reid hydrocarbons and experimental curve of a compound of this type [49].

The chemistry of this hydrocarbon [88] has been interpreted in terms of the HMO theory [49]. The excitation energies of the two parent substances *(60a)* and *(60b)* [*(60)*, i = 5, 7] which have not yet been synthesized have been calculated by the LCI method; the results show that the longest-wavelength absorption bands will lie in the near infrared region. It should be pointed out that a close linear relationship has been found between the energies of the $N \rightarrow V_1$ transitions for hetero-analogues of the Reid hydrocarbons, as obtained by perturbation calculations from the data for the parent substances, and the energies obtained by accurate calculation from the secular determinants [49].

[87] *A. Pullman*, C. R. hebd. Séances Acad. Sci. *257*, 288 (1963).

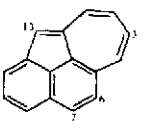
[87a] *J. Michl* and *R. Zahradnik*, Collect. czechoslov. chem. Commun., in the press.

[88] *D. H. Reid*, Tetrahedron *3*, 339 (1958).

[*] Cf. formula *(4)* for indeno[2,1-*a*]phenalene.

c) Peri-Fused Systems

Of the 35 possible hydrocarbons of this type, the neutral compounds *(13)* [89], *(64)* [90], and *(65)* [91], as well as the anion [29] and the cation [58] derived from the skeleton *(66)*, have been synthesized. The electronic spectra of *(13)*, *(64)*, and *(65)* have been successfully interpreted. The reactivity indices of the most reactive positions in these hydrocarbons are given in Table 3.



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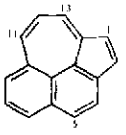

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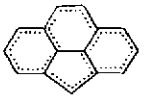

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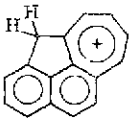

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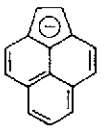

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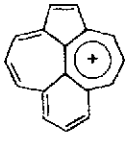

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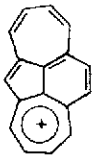

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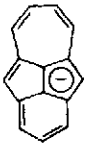


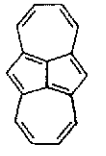
(71)

Table 3. Chemical reactivity indices of selected positions in the hydrocarbons *(13)*, *(64)*, and *(65)*. q: π-electron density; F: free valences; A_E, A_N, A_F: Wheland localization energies for electrophilic, nucleophilic, and free-radical substitution (β units).

Compound	Position	q	F	A_E	A_F	A_N
(13)	2	1.095	0.470	2.081	2.205	2.329
	5	1.055	0.449	2.164	2.323	2.482
	8	0.938	0.438	2.431	2.296	2.161
	7	0.934	0.488	2.234	2.130	2.026
(64)	1	1.113	0.465	2.065	2.200	2.336
	5	1.060	0.458	2.105	2.277	2.450
	11	0.849	0.509	2.351	2.079	1.806
	13	0.832	0.498	2.543	2.188	1.833
(65)	13	1.198	0.542	1.732	2.010	2.287
	6	1.005	0.448	2.294	2.294	2.294
	7	0.946	0.458	2.471	2.290	2.109
	3	0.924	0.437	2.443	2.289	2.135

Protonation of *(65)* apparently yields the cation *(67)*, the π-electron arrangement of which corresponds to that of the naphtho[1,2]tropylium cation; the ultraviolet spectra of both substances are in fact very similar [48].

Most of the 35 possible hydrocarbons have not yet been prepared. On the basis of the HMO charcteristics, we believe [91a,92] that the ions *(68)* to *(71)* and the hydrocarbons *(72)* to *(74)* should be reasonably stable. A methyl derivative of the hydrocarbon *(74)* has recently been synthesized [93]. Calculated absorption maxima (LCI method) [94] and experimental findings agree well. The three molecules *(75)*, *(76)*, and *(77)* appear to be very unstable. The hydrocarbon *(75)* possesses a non-bonding molecular orbital; according to Craig's rule it is non-aromatic, and its chemical reactivity indices are unfavorable. The stability of the hydrocarbon *(76)* would undoubtedly be adversely affected by ring strain; the corresponding dication, however, has a favorable π-electron distribution.



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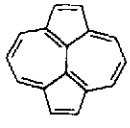

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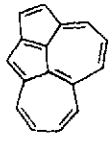

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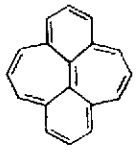

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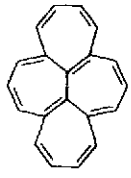

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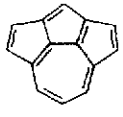

(77)

I am grateful to Prof. G. Kresze for his interest and to Dr. J. Koutecký for a discussion on the theory of non-alternant compounds. I should also like to thank my colleagues, and in particular Dr. J. Michl, who has enthusiastically contributed to our work. I am also grateful to Dr. C. Párkányi and Mr. J. Pancíř for their assistance.

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Translated by Express Translation Service, London

[89] *V. Boekelheide* and *G. K. Vick*, J. Amer. chem. Soc. *78*, 653 (1956).

[90] *P. D. Gardner*, *C. E. Wulfman*, and *C. L. Osborn*, J. Amer. chem. Soc. *80*, 143 (1958).

[91] *D. H. Reid*, *W. H. Stafford*, and *J. P. Ward*, J. chem. Soc. (London) *1955*, 1193.

[92] *A. Rosowsky*, *H. Fleischer*, *S. T. Young*, *P. Partch*, *W. H. Saunders Jr.*, and *V. Boekelheide*, Tetrahedron *11*, 121 (1960).

[93] *K. Hafner*, *R. Fleischer*, and *K. Fritz*, Angew. Chem. *77*, 42 (1965); Angew. Chem. internat. Edit. *4*, 69 (1965).

[94] *R. Zahradník* and *P. Hochmann*, unpublished work.

Sequence Distribution in Copolymers

Physical Property Studies

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The physical properties of copolymers are determined by their compositions and by the distribution of monomeric sequences in their chains. In some cases, sequence distributions can be determined from or correlated with physical properties observed for copolymers. Such determinations or correlations are relatively simple when calculations are based on run numbers.

A. Introduction

Knowledge of the detailed structure of copolymers can be valuable in studies on copolymerization mechanism and on the physical and chemical properties of copolymers. Chemical methods for characterizing sequence distribution in copolymers were surveyed in an earlier review [1] and the use of run numbers [2] in such studies was illustrated.

Physical methods for characterizing sequence distribution in copolymers will be reviewed in this article. The techniques covered are also used to characterize stereoregular polymers [4, 5].

B. General Methods for Correlating Physical Properties with Copolymer Structure

If the magnitude of a physical property (extinction coefficient, molar polarization, specific volume, *etc.*) associated with an A unit in a copolymer containing A and B units is dependent upon the nature of its neighbors, then measurements of the property can provide information about sequence distribution in the copolymer. Assuming that only nearest neighbors influence A units, the average value of the property, $P_{A,av.}$, observed for the copolymer is given by Equation (a), where f_{AAA},

$$P_{A,av.} = f_{AAA} \cdot P_{AAA} + f_{BAA} \cdot P_{BAA} + f_{BAB} \cdot P_{BAB} \qquad (a)$$

f_{BAA}, and f_{BAB} refer to the fractions of A units centered in $\overset{*}{A}AA$, $A\overset{*}{A}B$ (and $B\overset{*}{A}A$), or $B\overset{*}{A}B$ triads, respectively, and where P_{AAA}, P_{BAA}, and P_{BAB} represent the values of the property associated with A groups centered in these triads. (More terms are needed when copolymer stereochemistry must be considered or where the properties of A units depend on pentadic, *etc.*, environment).

Since f_{AAA}, f_{BAA}, and f_{BAB} are related, through Equations (b), (c), and (d), to copolymer composition and run number [1, 3], experimentally determined $P_{A,av.}$ values can be used for the evaluation of run numbers, provided P_{AAA}, P_{BAA}, and P_{BAB} are known. Unfortunately, suitable reference models for evaluating P_{BAA} and P_{BAB} are difficult to obtain and

$$f_{AAA} = \frac{(\%\,A - R/2)^2}{\%\,A^2} \qquad (b)$$

$$f_{BAA} = \frac{R\,(\%\,A - R/2)}{\%\,A^2} \qquad (c)$$

$$f_{BAB} = \frac{R^2}{4\,(\%\,A)^2} \qquad (d)$$

it is at present not possible to calculate these quantities theoretically. They can, however, be estimated in some cases from investigations on appropriate copolymers. The quantity P_{AAA} can be obtained from studies on the homopolymer of A, and P_{BAB} from studies on copolymers containing only small amounts of A. In such copolymers ($R \simeq 2\ \%A$), the A units are essentially isolated ($f_{BAB} \simeq 1.0$). The quantity P_{BAA} can be estimated from the properties of copolymers having low B contents ($R \simeq 2\ \%B$). In such copolymers, A units are present in both $A\overset{*}{A}A$ and $B\overset{*}{A}A$ triads and the measurements must be corrected for the contribution of A units in $\overset{*}{A}AA$ triads before the properties of A units in $B\overset{*}{A}A$ triads can be assessed. The correction is easily made, however, for the proportions of A units centered in $\overset{*}{A}AA$ and $B\overset{*}{A}A$ triads are $(1 - \%B/\%A)^2$ and $2\,(\%B/\%A)\,(1 - \%B/\%A)$, respectively, when $R \simeq 2\ \%B$.

In some copolymerizations, one of the monomers (B) is reluctant to combine with itself (*e.g.*, styrene-maleic anhydride); run numbers of copolymers obtained from such systems are directly proportional to composition ($R = 2\ \%B$) at even high B contents and the above approximations are

[1] *H. J. Harwood*, Angew. Chem. *77*, 405 (1965); Angew. Chem. internat. Edit. *4*, 394 (1965).

[2] The run number, R, is defined as the average number of monomer sequences (or blocks) which are present per one hundred monomer units in a copolymer chain. This quantity is related by simple equations to copolymer composition and measurable aspects of copolymer structure [1, 3]. The run number is a convenient parameter for characterizing sequence distribution in copolymers.

[3] *H. J. Harwood* and *W. M. Ritchey*, Polymer Letters *2*, 601 (1964).

[4] *C. E. H. Bawn* and *A. Ledwith*, Quart. Rev. (Chem. Soc., London) *16*, 361 (1962).

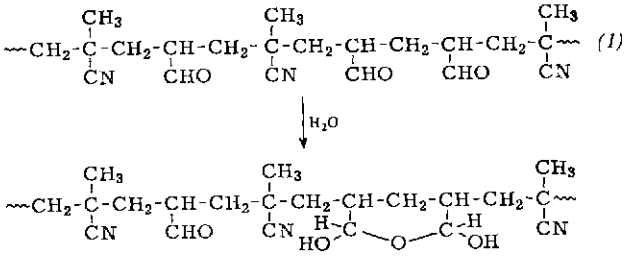
[5] *W. R. Krigbaum* in *B. Ke* (ed.): Newer Methods of Polymer Characterization. Interscience ,New York 1964, Chapter 1.

quite reliable. In other systems, the best that can be accomplished, at present, is an empirical assignment of values to P_{BAA} and P_{BAB} which allow $P_{A,av.}$ to be correlated with calculated sequence distributions.

C. Infrared Absorption Studies

The ideal situation for measuring sequence distribution in copolymers by physical methods is obtained when the property measured is due only to monomer units in a specific environment (*e.g.*, $P_{AAA} = 0$, $P_{BAA} = 0$, $P_{BAB} \neq 0$).

Schulz, *Kaiser*, and *Kern* [6] noted that the carbonyl absorption of acrolein-methacrylonitrile or methacrolein-methacrylonitrile copolymers is directly proportional to the concentration of isolated acrolein or methacrolein units (only methacrylonitrile neighbors) in copolymers containing less than 66 mole-% acrolein or methacrolein. The results were attributed to the tendency of acrolein and methacrolein units to form cyclic acetal or hemiacetal units when present in sequences of two or more units. Such cyclic units do not absorb in the carbonyl



(1)

region. Furthermore, the carbonyl absorption of copolymers containing up to 95 % methacrolein could be correlated with calculated sequence distributions if 20 % of the methacrolein units in sequences containing four or more such units were assumed to be in the free state.

Ang and *Harwood* [7] noted that phenyl absorption at 700 cm^{-1} in styrene (S)-maleic anhydride (M) copolymers is independent of sequence distribution ($P_{SSS} = P_{MSS} = P_{MSM}$) and hence useful for determining copolymer compositions. Phenyl absorption occurring at 760 cm^{-1} is not independent of sequence distribution, however; the relative intensities of the 700 and 760 cm^{-1} bands ($\varepsilon_{760}/\varepsilon_{700}$) decrease as the styrene content of the copolymers decreases (Fig. 1). In relating the relative absorbances observed for these bands to copolymer structure, Equation (e) was used (a, b, and c represent the extinction coefficients of the 760 cm^{-1} band for styrene units centered respectively in SSS, MSS, and MSM triads divided by the extinction coefficient of the 700 cm^{-1} band).

$$\frac{\varepsilon_{760}}{\varepsilon_{700}} = a \cdot f_{SSS} + b \cdot f_{MSS} + c \cdot f_{MSM} \qquad (e)$$

[6] *R. C. Schulz*, *E. Kaiser*, and *W. Kern*, Makromolekulare Chem. *76*, 99 (1964).

[7] *T. L. Ang* and *H. J. Harwood*, Amer. Chem. Soc. Polymer Preprints *5* (*1*), 306 (1964).

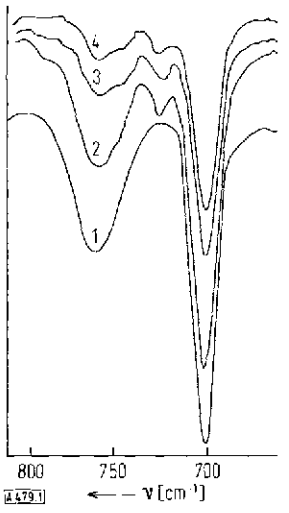


Fig. 1. Infrared spectra of styrene-maleic anhydride copolymers. Styrene contents: Curve 1: 100; 2: 64.6; 3: 59.4; 4: 50 mole-% [7].

Coefficient a was evaluated from the spectrum of polystyrene. Investigation of copolymers having low M contents ($f_{MSM} \simeq 0$) showed that $b \simeq a$. From the spectra of copolymers in which the styrene units were essentially isolated ($f_{MSM} \simeq 1.0$), it was found that $c \simeq a/2$. These results and the requirement that f_{SSS}, f_{MSS}, and f_{MSM} total unity lead to Equation (f).

$$f_{MSM} = \frac{a - \varepsilon_{760}/\varepsilon_{700}}{a - c} = \frac{0.295 - \varepsilon_{760}/\varepsilon_{700}}{0.144} \qquad (f)$$

Assuming maleic anhydride units to be essentially isolated in all the copolymers ($r_M \simeq 0$), run numbers ($R = 2\,\%M$) and f_{MSM} values [Eq. (g)] can be calculated from their compositions (Table 1).

$$f_{MSM} = \frac{R^2}{4\,(\%S)^2} = \left(\frac{\%M}{\%S}\right)^2 \qquad (g)$$

Table 1. Sequence distribution in styrene-maleic anhydride copolymers [7].

Mole-% of styrene		$\varepsilon_{760}/\varepsilon_{700}$	$f_{MSM(obs.)}$	f_{MSM} (calc.)	
Feed mixture	Copolymer			[a]	[b]
100.0	—	0.295	—	—	—
99.7	86.3	0.292	0.02	0.03	0.02
99.0	76.0	0.276	0.13	0.10	0.12
98.0	64.6	0.246	0.34	0.30	0.26
95.2	59.4	0.215	0.56	0.47	0.52
90.9	55.3	0.190	0.73	0.65	0.71
50.1	(50)	0.151	—	—	—
21.3	(50)	0.153	—	—	—
12.3	(50)	0.150	—	—	—

[a] Calculated from copolymer composition [Eq. (g)].

[b] Calculated for low conversion copolymers from feed compositions ($\%S_f$ and $\%M_f$) according to Equations (d) and (g'). The reactivity ratios of the monomers S and M are $r_S = 0.019$ and $r_M = 0.0$ respectively. If ——M· and ——S· denote growing copolymer chains, we have the following reactions and corresponding rates.

——M· + M → ——M·	k_{MM}[——M·][M]
——M· + S → ——S·	k_{MS} [——M·][S]
——S· + M → ——M·	k_{SM} [——S·][M]
——S· + S → ——S·	k_{SS} [——S·][S]

The reactivity ratios are defined as

$$r_S = \frac{k_{SS}}{k_{SM}} \qquad r_M = \frac{k_{MM}}{k_{MS}}$$

$$R = 200/(2 + r_S \cdot \%S_f/\%M_f + r_M \cdot \%M_f/\%S_f) \qquad (g')$$

$$\frac{\%S}{\%M} = \frac{\%S_f}{\%M_f} \cdot \frac{r_S\,(\%S_f/\%M_f) + 1}{r_M\,(\%M_f/\%S_f) + 1}$$

Enomoto[8] noted that the tertiary C–H deformation mode of vinyl chloride units in vinyl chloride (VC)-vinylidine dichloride (VDC) copolymers shifts to lower frequencies as the proportion of vinylidine chloride in the copolymers increases. He concluded that the C–H deformation of vinyl chloride units occurs at 1247, 1235, and 1197 cm^{-1} when these units are centered, respectively, in VC–$\overset{*}{V}$C–VC, VDC–$\overset{*}{V}$C–VC, and VDC–$\overset{*}{V}$C–VDC triads. The three absorptions overlap considerably and it is necessary to evaluate absorption coefficients for VC units in the various environments at each wavelength (cf. Section B).

By measuring the absorption of copolymers at the three wavelengths, and by using three simultaneous equations of form (a), *Enomoto* calculated the quantities of VC units present in the various triadic environments in the copolymers. His results, expressed according to our terminology, are shown in Table 2. The results are in reasonably good agreement with calculated sequence distributions, even though his treatment ignores the head-head linkages subsequently suggested (see Section E) to be present in such copolymers. The C–H deformation mode of vinyl bromide units in vinyl bromide-vinylidine chloride copolymers is also sensitive to environment[8].

Germar recently studied methylene absorption (1390 to 1440 cm^{-1}) in vinyl chloride (VC) – vinylidine dichloride (VDC) copolymers[8a]. Absorption at 1405, 1420, and 1434 cm^{-1} provides a measure of methylene units in $-CCl_2-CH_2-CCl_2-$, $-CHCl-CH_2-CCl_2-$, and $-CHCl-CH_2-CHCl-$ environments, respectively. The relative intensities of these bands thus provide a measure of the relative amounts of VDC–VDC, VDC–VC, and VC–VC linkages in the polymers. These were in excellent agreement with calculated values (see Equations (a), (b), and (c) in Ref.[1]), based on monomer feed composition data and on r_{VC} and r_{VDC} values of 0.20 and 3.2, respectively. *Germar* found no evidence for the presence of head-head structure in these copolymers.

In a related study, *Oswald* and *Kubu*[9] used infrared analysis to characterize chlorinated polyethylene samples. Bands in the 1400–1475 cm^{-1} region (CH_2 bending) were used to determine the proportions of methylene groups centered in $-CH_2CH_2CH_2-$, $-CH_2CH_2CHCl-$, and $-CHClCH_2CHCl-$ triads.

By considering the chlorinated polymers to be terpolymers of ethylene, vinyl chloride, and 1,2-dichloroethylene, glass transition temperatures of the copolymers can be predicted from the infrared results with considerable accuracy. No evidence for the presence of $-CCl_2-$ units in the copolymers was obtained, in agreement with the results of *Nambu*[10] and of *Fuchs* and *Louis*[11] who studied chlorinated poly(vinyl chloride) samples. *Germar* has also published an infrared study of the microstructure of chlorinated poly(vinyl chloride)[11a].

The infrared absorption of ethylene copolymers in the 700–850 cm^{-1} region can provide information about their sequence distributions. Studies on model hydrocarbons[12–14] have shown that the absorption of methylene groups in this region is dependent on the size of methylene sequences in the compounds. Methylene absorptions observed in this region and their relation to structures occurring in ethylene copolymers are shown in Table 3.

Table 2. Sequence distribution in vinyl chloride-vinylidine chloride copolymers [8].

% Vinyl chloride Feed	% Vinyl chloride Copolymer	Conversion [%]	$f_{VDC-VC-VDC}$	$f_{VC-VC-VC}$	$R_{av.}$ [a]	$R_{calc.}$ [b]
28.0	10.6	1.1	1.00	–	21	19
40.0	16.5	1.6	1.00	–	33	29
51.0	22.0	1.1	0.75	–	38	37
61.0	31.5	0.9	0.58	–	46	43
70.0	39.2	1.1	0.48	0.07	55	51
78.5	49.0	1.4	0.31	0.33	[c]	55
86.3	61.0	1.6	0.19	0.38	46	73
93.3	76.2	2.8	–	0.83	14	28

[a] Average of values derived from measured triad distributions and copolymer compositions.
[b] Calculated for initial copolymers from feed compositions assuming $r_{VC} = 0.2$ and $r_{DCV} = 3.2$. [c] Values obtained: 55, 75, 41.

In copolymers of ethylene (E) with monomers such as 2-butene (B) [containing structures *(3b)* and *(5b)*] absorption at 751 cm^{-1} can provide a measure of the number of ethylene units centered in BEB triads. Indeed,

Table 3. Methylene absorption and copolymer structure responsible for absorption in ethylene copolymers.

$-(CH_2)_n-$	ν [cm^{-1}]	Sequence
$(CH_2)_1$	815	~~$CH_2CHRCH_2CHRCH_2CHR$~~ *(2)*
$(CH_2)_2$	751	~~$CH_2CHRCH_2CH_2CHRCH_2$~~ *(3a)*
		or
		~~$CHRCHRCH_2CH_2CHRCHR$~~ *(3b)*
$(CH_2)_3$	733	~~$CH_2CHRCH_2CH_2CH_2CHR$~~ *(4)*
$(CH_2)_4$	726	~~$CH_2CHR(CH_2CH_2)_2CHRCH_2$~~ *(5a)*
		or
		~~$CHRCHR(CH_2CH_2)_2CHRCHR$~~ *(5b)*
$(CH_2)_{>4}$	722	~~$CH_2CHR(CH_2CH_2)_nCH_2CHR$~~ *(6)*

[8] *S. Enomoto*, J. Polymer Sci. *55*, 95 (1961).
[8a] *M. Germar*, Makromolekulare Chem. *84*, 36 (1965).
[9] *H. J. Oswald* and *E. T. Kubu*, Soc. Plastics Eng. Trans. *3*, 168 (1963).
[10] *K. Nambu*, J. appl. Polymer Sci. *4*, 69 (1960).
[11] *W. Fuchs* and *D. Louis*, Makromolekulare Chem. *22*, 1 (1957).
[11a] *M. Germar*, Makromolekulare Chem. *86*, 89 (1965).
[12] *H. L. McMurry* and *V. Thornton*, Analytic. Chem. *24*, 318 (1952).
[13] *J. van Schooten*, *E. W. Duck*, and *R. Berkenbosch*, Polymer *2*, 357 (1961).
[14] *G. Bucci* and *T. Simonazzi*, J. Polymer Sci. *C 7*, 203 (1964).

Natta and coworkers [15] cited the intense absorption shown by such copolymers at 751 cm^{-1} (13.29 μ) as evidence for their highly alternating structures.

The absorption at 724 and 731 cm^{-1} of several ethylene (E)–propylene (P) copolymers have been assigned [16] to structures *(6)* and *(4)*, respectively. The relative intensities observed were qualitatively consistent with sequence distributions calculated for the copolymers, assuming reactivity ratios of 7.08 and 0.088 for ethylene and propylene, respectively. *Veerkamp* and *Veermans* [17] subsequently developed a technique to measure the intensities of these absorptions accurately. By assuming similar extinction coefficients for the two bands, the ratio of methylene units in $(CH_2)_3$ and larger methylene sequences in a number of copolymers was determined. The results agreed reasonably well with theoretical values based on *Natta*'s calculations.

More recently, the presence of $(CH_2)_2$ sequences in ethylene-propylene copolymers has been considered in studies of their structure [18]. Such sequences could result from the tail-head incorporation of propylene units into the copolymers [structure 3a]. By measuring absorption at 815, 752, 733, and 727 cm^{-1}, *Bucci* and *Simonazzi* [19] were able to quantitatively account for methylene groups present in the copolymers. Their results are shown in Fig. 2.

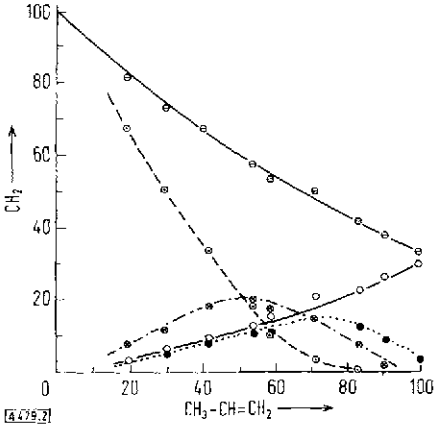


Fig. 2. Distributions of $(CH_2)_n$ sequences in ethylene-propylene copolymers [14].
○ $(CH_2)_1$; ● $(CH_2)_2$; ⊗ $(CH_2)_3$; ○ $(CH_2)_5$; ⊖ total (CH_2), curve was calculated from the propylene content of the copolymers.
Ordinate: Weight-% of CH_2 in the copolymer.
Abscissa: Mole-% of propylene in the copolymer.

Copolymers of tetrafluoroethylene with ethylene [19], propylene [20], or isobutylene [21], prepared at low temperatures in the presence of ionizing radiation, show infrared absorption which is significantly different from that observed for the corresponding homopolymers, indicating that they do not have block or polyblend structures. The tetrafluoroethylene-isobutylene copolymer was believed to have an alternating structure.

Yanagisawa [22] investigated the absorption of a series of styrene copolymers in the 1000–1300 cm^{-1} and 500–650 cm^{-1} regions and concluded that strong phenyl absorption (coupled with skeletal vibrations) occurs at 543 cm^{-1} only when the average styrene sequence length is greater than three. Copolymers having shorter average styrene sequences absorb at higher frequencies. These results suggest that the 543 cm^{-1} band might provide a measure of $\overset{\blacktriangle}{S}SS$ structure and that bands at higher frequencies might be found for other styrene-centered triads. Similarly, the absorption observed at 1068 cm^{-1} in polystyrene shifts to about 1075 cm^{-1} in copolymers having low styrene contents. Shifts of bands observed at 1191 and 1148 in poly(methyl methacrylate) to higher and lower frequencies, respectively, in styrene-methyl methacrylate copolymers were also noted. The magnitude of the shifts depends on the average sequence length of the methyl methacrylate units in the copolymers. Similar results were obtained with styrene-ethyl methacrylate copolymers.

Shirakawa, *Yamazaki*, and *Kambara* [23] used ionic polymerization techniques to prepare α-methylstyrene-methylene block copolymers *(7)* having controlled sequence lengths. Many bands in the infrared spectra

$$[\text{-}(\alpha\text{-methylstyrene})_m\text{-}(CH_2)_x\text{-}]_n \qquad (7)$$

(600–1300 cm^{-1}) of these copolymers were noted to increase or decrease in intensity with increasing length of the α-methylstyrene sequences. The spectra of α-methylstyrene blocks in the copolymers are essentially identical to those of poly(α-methylstyrene) samples of comparable size. These workers concluded that planar C–H deformations of monosubstituted benzene rings increase in intensity as the number of α-methylstyrene units in a sequence increase. The opposite seems to hold for out of plane deformations.

D. Ultraviolet Absorption Studies

When poly(methyl vinyl ketone) is heated *in vacuo* at 250 °C, it slowly develops color due to the formation of condensed structures *(9)–(11)* in the polymer chain. From the kinetics of this process, *Hay* concluded [24] that the cyclization occurs randomly, and predicted the relative amounts of cyclized sequences which should be present in the polymers after various extents of cyclization. These predictions are compared with values obtained by absorption measurements at 235, 285, and 335 mμ according to Equation (g″) in Table 4. A_{235}, A_{285}, and A_{335} are the absorbance values (log I_0/I) observed at the indicated wavelengths for a cyclized sample.

[15] *G. Natta, G. Dall'Asta, G. Mazzanti*, and *F. Ciampelli*, Kolloid-Z. *182*, 50 (1962).

[16] *G. Natta, G. Mazzanti, A. Valvassori, G. Sartori*, and *D. Morero*, Chim. e Ind. (Milano) *42*, 125, 132 (1960).

[17] *Th. A. Veerkamp* and *A. Veermans*, Makromolekulare Chem. *50*, 147 (1961).

[18] *J. van Schooten* and *S. Mostert*, Polymer *4*, 135 (1963).

[19] *Y. Tabata, H. Shibano*, and *H. Sobue*, J. Polymer Sci. A *2*, 1977 (1964).

[20] *Y. Tabata, K. Ishigure*, and *H. Sobue*, J. Polymer Sci. A *2*, 2235 (1964).

[21] *Y. Tabata, K. Ishigure, K. Oshima*, and *H. Sobue*, J. Polymer Sci. A *2*, 2445 (1964).

[22] *K. Yanagisawa*, Chem. High Polymers (Tokyo) *21*, 312 (1964); Makromolekulare Chem. *79*, 232 (1964). The author is grateful to Dr. *Yanagisawa* for providing an English translation of this article.

[23] *H. Shirakawa, N. Yamazaki*, and *S. Kambara*; personal communication from Dr. *N. Yamazaki*, Tokyo Institute of Technology.

[24] *J. N. Hay*, Makromolekulare Chem. *67*, 31 (1963).

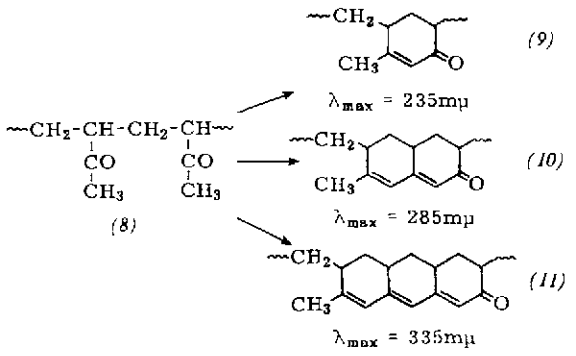


Table 4. Cyclized units in heated poly(methyl vinyl ketone) samples [24]

% Cyclization	% (9)		% (10)		% (11)	
	calc.	found	calc.	found	calc.	found
20	90	84	9	14	1	3
45	80	78	16	20	4	2
60	70	70	21	25	6	5
75	66	63	25	28	9	8

(The molar extinction coefficient was assumed to be inversely proportional to the number of conjugated double bonds present in the absorbing structure.)

$$\%\ (9) = 100 \cdot A_{235}/(A_{235} + \tfrac{1}{2} A_{285} + \tfrac{1}{3} A_{335})$$

$$\%\ (10) = 100 \cdot (\tfrac{1}{2} A_{285})/(A_{235} + \tfrac{1}{2} A_{285} + \tfrac{1}{3} A_{335}) \qquad (g'')$$

$$\%\ (11) = 100 \cdot (\tfrac{1}{3} A_{335})/(A_{235} + \tfrac{1}{2} A_{285} + \tfrac{1}{3} A_{335})$$

E. Nuclear Magnetic Resonance Studies

Nuclear magnetic resonance has become a powerful tool for characterizing the structures of polymers [25–27]. The use of NMR for quantitative analysis is relatively easy, since the area under a given resonance peak is directly proportional to the number of nuclei responsible for the resonance.

Ferguson [28] was the first to use NMR to study sequence distribution in copolymers. By studying F^{19} resonance in vinylidine fluoride (VF)-hexafluoropropylene (HFP) copolymers, he established that no HFP–HFP linkages are present in the copolymers and that a small proportion (5–7%) of both VF and HFP units are present in head-head arrangements. By comparing appropriate resonance areas, the fraction, n, of vinylidene fluoride CF_2 groups in $-CH_2\dot{C}F_2CH_2CF_2-$ and $-CH_2\dot{C}F_2CF_2CH_2-$ environments was determined. This fraction is approximately equal to the number of VF–VF linkages in the copolymer divided by the number of VF units present:

$$n = \frac{\%\,VF - VF\ linkages}{\%\,VF} = \frac{\%\,VF - R/2}{\%\,VF} \qquad (h)$$

Since HFP units are isolated in the copolymers, R = 2·%HFP and n can be expressed in terms of copolymer composition, as follows:

$$n = 1 - \%\,HFP/\%\,VF \qquad (h')$$

Table 5 compares values of n determined by *Ferguson* (taken from his graph) with those calculated from Eq. (h').

Table 5. Fraction (n) of vinylidine fluoride CF_2 groups in $-CH_2CF_2CH_2CF_2-$ and $-CH_2CF_2CF_2CH_2-$ environments in vinylidine fluoride-hexafluoropropylene copolymers [28].

% VF	n	
	found	calc. [Eq. (h')]
85	0.81	0.82
78	0.68	0.72
70	0.56	0.57
61	0.38	0.36

Chujo and coworkers [29] reported the NMR spectrum of a vinyl chloride–vinylidine chloride copolymer. Separate resonance areas were observed for methylene protons centered in $-CHClCH_2CHCl-$ and $-CCl_2CH_2CCl_2-$ environments. From the relative resonance areas observed, they calculated the percentages of vinyl-vinyl, *etc.*, linkages present in the copolymers. This spectrum has been reinterpreted [30] in terms of head-head linkages in vinylidine chloride sequences, these linkages occurring only at sequence junctions. This new interpretation is based on a comparison of the copolymer spectrum with that of partially chlorinated poly(2,3-dichlorobutadiene). Other model systems should be studied before this interpretation is accepted. *Okuda* [31] observed reasonably intense $-CHClCH_2CHCl-$ type resonance in copolymers having high vinylidine chloride contents and concluded that the copolymers have block structures. This result is inconsistent with the relatively low reactivity ratio observed for vinyl chloride (0.3) in this system.

Nishioka and coworkers [32, 33] and also *Bovey* [34] measured the NMR spectra of styrene–methyl methacrylate and *p*-xylylene–methyl methacrylate copolymers in chloroform and carbon tetrachloride solution. They observed three types of methoxy resonance and concluded that this resonance might be used to characterize sequence distribution and possibly also tacticity in the copolymers. Similar results [35] have been obtained for styrene–methyl methacrylate copolymers in thionyl chloride solution. *Bovey* [34] correlated the methoxy resonance patterns of styrene (S)-methyl methacrylate (M) copolymers ($CHCl_3$ solution) with calculated distributions of M centered triads by considering the

[25] *I. Y. Slonim*, Russian Chemical Reviews *31*, 308 (1962).
[26] *F. A. Bovey* and *G. V. D. Tiers*, Fortschr. der Hochpolymeren-Forsch. *3*, 139 (1963).
[27] *D. W. McCall* and *W. P. Slichter*, *op. cit.* [5], Chapter 8.
[28] *R. C. Ferguson*, J. Amer. chem. Soc. *82*, 2416 (1960); Kautschuk und Gummi, in press.
[29] *R. Chujo*, *S. Satoh*, *T. Ozeki*, and *E. Nagai*, J. Polymer Sci. *61*, S12 (1962).
[30] *R. Chujo*, *S. Satoh*, and *E. Nagai*, J. Polymer Sci. A *2*, 895 (1964).
[31] *K. Okuda*, J. Polymer Sci. A *2*, 1749 (1964).
[32] *A. Nishioka*, *Y. Kato*, and *N. Ashikari*, J. Polymer Sci. *62*, S10 (1962); Bull. chem. Soc. Japan *37*, 1630 (1964).
[33] *A. Nishioka*, *Y. Kato*, and *H. Mitsuoka*, J. Polymer Sci. *62*, S9 (1962).
[34] *F. A. Bovey*, J. Polymer Sci. *62*, 197 (1962).
[35] *H. J. Harwood* and *J. V. Pustinger*, unpublished results.

resonance of methoxy protons in SMM and SMS triads to be distributed among several methoxy resonance areas, rather than being associated with a given area. This was attributed to triad configurational effects. According to a recent interpretation [35a], the highest-field, methoxy resonance is due to SMS triads in which *both* styrene units have the same configuration (co-isotactic) as the central methyl methacrylate unit. The central methoxy resonance area is due to methoxy protons of methyl methacrylate units centered in SMM and SMS triads, where *one* of the styrene units has the same configuration as the central methyl methacrylate unit. The upfield shift of the resonance of such methoxy protons is probably due to shielding by diamagnetic regions of neighboring phenyl units. The resonance of the remaining methoxy protons (MMM and SMM or SMS where *none* of the styrene units has the same configuration as the central methyl methacrylate unit) occurs in the lowest-field resonance area.

On the basis of this interpretation, which permits the methoxy resonance patterns to be accounted for quantitatively, the probability that adjacent styrene-methyl methacrylate units have the same configuration (co-isotactic) in their copolymers is 0.48. The probability that adjacent styrene-methyl acrylate units have the same configuration in their copolymers was estimated to be much higher (0.80).

Ito and *Yamashita* [35a] and also *Overberger* and *Yamamoto* [35b] have studied the NMR spectra of styrene-methyl methacrylate copolymers prepared by anionic polymerization. They conclude that there are very few styrene-methyl methacrylate linkages in the copolymers (or polyblends).

Harwood and *Ritchey* [36] obtained spectra of the type shown in Fig. 3 for styrene-methyl methacrylate copolymers in deuteriobenzene solution. As in the other studies, methoxy resonance was observed in three general areas. For copolymers containing less than 50 mole percent styrene, the methoxy patterns observed were correlated with calculated distributions of M centered *pentads*; the fraction of methoxy resonance observed in the lowest-field peak is equal to the fraction of M units centered in $\overset{*}{M}MM\overset{*}{M}M$, $\overset{*}{M}MM\overset{*}{M}S$, $\overset{*}{S}M\overset{*}{M}MS$, and $\overset{*}{S}M\overset{*}{M}SM$ pentads, for example, and the fraction of methoxy resonance observed in the highest-field peak to the fraction of M units centered in $\overset{*}{M}S\overset{*}{M}SM$ pentads. Copolymers containing higher amounts of styrene have appreciable quantities of M units centered in SSMSS and SSMSM pentads and these units seem to be responsible for resonance in more than one general area. This phenomenon was attributed to pentad configurational effects.

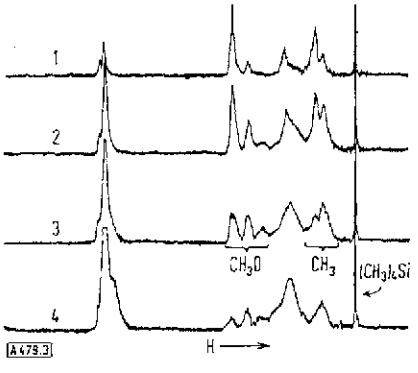


Fig. 3. NMR spectra of styrene-methyl methacrylate copolymers. Styrene contents, Spectrum 1, 16.8; 2, 33.3; 3, 50.2; 4, 72.6 mole-% [36].

α-Methyl resonance was observed for these copolymers in two general areas, the higher-field area being about the intensity expected for α-methyl protons centered in SMM and SMS triads. By combining Equation (b) with an expression (i) for the percentage, P′, of all copolymer resonance occurring in the high field α-methyl peak, Equation (j) relating run numbers to P′ values can be derived. Table 6 compares experimentally determined P′ and R values with those calculated from monomer feed compositions and monomer reactivity ratios.

$$P' = (3/8)\,(\%\,M)\,(1-f_{MMM}) \qquad (i)$$

$$R = 2\,(\%\,M)\,(1-\sqrt{1-8\,P'/(\%\,M)}/3) \qquad (j)$$

Table 6. Results of studies on high-field α-CH_3 resonance in styrene-methyl methacrylate copolymers [36].

Percent styrene		P′		R	
feed	copolymer	obs.	calc.	obs.	calc.
89.4	81.1	7	6.1	34	31
80.0	72.6	9.5	9.8	41	48
65.0	60.9	13	14.0	52	62
50.0	50.2	17	16.5	69	67
35.0	40.6	16.5	17.7	60	64
25.0	33.3	14.5	16.7	47	56
20.0	27.2	15	15.6	48	50
10.0	16.8	10.5	10.9	30	32

Nuclear magnetic resonance has not been used to characterize sequential structure in organic polycondensates, but *Van Wazer* and coworkers [37–39] have made good use of this technique in characterizing low molecular weight inorganic polymers, *e.g.* linear and branched polyphosphates, polyarsenites, and polysiloxanes having Cl, $N(CH_3)_2$, OCH_3, or F end groups, obtained through equilibration experiments. Equilibrium constants for the various exchange reactions were also established.

F. Electrical Polarization Studies

The application of dielectric measurements to the study of sequence distribution in copolymers is rather straightforward, especially if one of the monomers is nonpolar. In most cases, only nearest-neighbor interactions need be considered. The average molar polarization, $P_{av.}$, of a polar monomer unit A can be related to triad

[35a] *K. Ito* and *Y. Yamashita*, J. Polymer Sci. B *3*, 625, 631, 633 (1965).

[35b] *C. G. Overberger* and *N. Yamamoto*, J. Polymer Sci. B *3*, 569 (1965).

[36] *H. J. Harwood* and *W. M. Ritchey*, J. Polymer Sci. B *3*, 419 (1965).

[37] *K. Moedritzer* and *J. R. Van Wazer*, J. Amer. chem. Soc. *86*, 802 (1964).

[38] *J. R. Van Wazer*, *K. Moedritzer*, and *D. W. Matula*, *ibid.* *86*, 807 (1964).

[39] *M. D. Rausch*, *J. R. Van Wazer*, and *K. Moedritzer*, *ibid.* *86*, 814 (1964).

distributions and the molar polarizabilities, P, of monomer units centered in various triadic environments, by Equation (k).

$$P_{av.} = f_{AAA} \cdot P_{AAA} + f_{BAA} \cdot P_{BAA} + f_{BAB} \cdot P_{BAB} \qquad (k)$$

A six-term expression, in which each term is weighted according to copolymer composition, would be required to describe the average molar polarization of units in a copolymer containing two polar monomers. Even more terms, appropriately weighted, would be needed to treat differences in triad configurations. Fortunately, the three-term expression proved adequate for most studies. Styrene has been used as a relatively nonpolar comonomer in these studies and its molar polarization has been considered constant.

Work and *Trehu* [40] developed a general expression for the average dipole moments of polar-polar and polar-nonpolar copolymers in terms of sequence distribution, the dipole moments of equivalent isolated units present, and the average cosines of the angles between neighboring dipoles in the copolymers. The dielectric polarization of *p*-chlorostyrene-styrene copolymers was then correlated *via* this expression with calculated sequence distributions, and the average cosines of the angles between various dipoles in the copolymers were estimated. Excellent agreement is obtained between theory and experiment when only nearest-neighbor dipolar interactions are treated.

Shima [41a] subsequently determined the molar polarizations and average dipole moments of a series of styrene-methyl methacrylate copolymers. The effective dipole moment of methyl methacrylate units in the copolymers increases as the percentage of styrene increases; the limiting value is close to that observed for simple esters. The results were correlated by a least squares procedure with calculated sequence distributions, through use of Equation (k). The fit obtained is shown in Table 7. Similar results have also been obtained for copolymers of styrene with *p*-chlorostyrene [41b], *p*-methoxystyrene [41b], methyl acrylate [42, 43] and methyl vinyl ketone [43].

Table 7. Results of dielectric studies on styrene-methyl methacrylate copolymers [41].

Mole-% styrene in copolymer	Temp. [°C]	$P_{av.}$ [cm³]	μ [Debye] obs.	μ [Debye] calc. [a]
0	10	64.3	1.36	—
	40	63.3	1.41	—
8.9	10	67.8	1.41	1.41
	40	66.4	1.46	1.46
21.3	10	72.4	1.49	1.48
	40	70.9	1.54	1.54
45.7	10	79.4	1.59	1.60
	40	76.2	1.63	1.64
54.4	10	82.5	1.64	1.63
	40	79.9	1.68	1.67

[a] The copolymers were prepared in total conversion from given monomer feeds. These calculated values are averages.

Although good correlations are obtained in these studies, this approach to sequence distribution measurement has limited sensitivity. The molar polarizability of methyl methacrylate units centered in SMS triads in styrene-methyl methacrylate copolymers is only about 20 % higher than that of units centered in MMM triads. The difference is even less for methyl acrylate units in styrene-methyl acrylate copolymers.

G. Thermochemical Measurements

1. Heats of Copolymerization

Alfrey and *Lewis* [44] suggested that four separate heats of reaction (ΔH_{AA}, ΔH_{AB}, *etc.*), one for each propagation step shown below, contribute to heats of copolymerization. Since equal numbers of A–B and B–A linkages

$$\sim\!\!\sim A\bullet + A \xrightarrow{-\Delta H_{AA}} \sim\!\!\sim AA\bullet$$

$$\sim\!\!\sim A\bullet + B \xrightarrow{-\Delta H_{AB}} \sim\!\!\sim AB\bullet$$

$$\sim\!\!\sim B\bullet + A \xrightarrow{-\Delta H_{BA}} \sim\!\!\sim BA\bullet$$

$$\sim\!\!\sim B\bullet + B \xrightarrow{-\Delta H_{BB}} \sim\!\!\sim BB\bullet$$

are established in copolymers, the cross-propagation reactions occur to equal extents and the corresponding heats of reaction (ΔH_{AB} and ΔH_{BA}) can be treated collectively. Equation (l) can then be written for the molar heat of copolymerization, $\Delta H_{cop.}$ (expressed per mole of repeating units).

$$\Delta H_{cop.} = \frac{1}{100}[\%\,AA \cdot \Delta H_{AA} + \%\,(AB + BA) \cdot (\Delta H_{AB} + \Delta H_{BA})/2 + \%\,BB \cdot \Delta H_{BB}] \qquad (l)$$

Following *Alfrey* and *Lewis*' treatment and a more recent treatment by *Sawada* [45], this equation can be written in terms of copolymer composition and run number, as follows [46].

$$\Delta H_{cop.} = \frac{1}{100}[\%\,A \cdot \Delta H_{AA} + \%\,B \cdot \Delta H_{BB} + R/2(\Delta H_{AB} + \Delta H_{BA} - \Delta H_{AA} - \Delta H_{BB})] \qquad (m)$$

Of the quantities in Equation (m), only R and ($\Delta H_{AB} + \Delta H_{BA}$) are not assessible independently (although R can be calculated from kinetic parameters). In most studies, a value is assigned to ($\Delta H_{AB} + \Delta H_{BA}$) which permits measured heats of copolymerization to be related to calculated sequence distribution parameters, such as R. For example, in Fig. 4 heats of copolymerization determined [47] for styrene–methyl methacrylate and for vinyl acetate–methyl methacrylate copolymerizations are plotted against the methyl methacrylate con-

[40] *R. N. Work* and *Y. M. Trehu*, J. appl. Physics *27*, 1003 (1956).

[41a] *M. Shima*, J. Polymer Sci. *56*, 213 (1962).

[41b] *M. Shima*, Bull. chem. Soc. Japan, in press.

[42] *M. Shima* and *A. Kotera*, Makromolekulare Chem. *64*, 172 (1963).

[43] *G. P. Mikhailov* and *L. V. Krasner*, Vysokomol. Soyed. *5*, 1091 (1963); Polymer Science U.S.S.R. *5 (1)*, 151 (1964).

[44] *T. Alfrey, Jr.* and *C. Lewis*, J. Polymer Sci. *4*, 221 (1949).

[45] *H. Sawada*, J. Polymer Sci. *2* A, 3095 (1965).

[46] The expression m_2P_{21} used by *Alfrey* and *Lewis* and the expression X_BP_1 used by *Sawada* can be shown to equal R/200. $\Delta H_{cop.}$ in these treatments is, of course, corrected for heat changes due to initiator decomposition, monomer mixing, solution of polymer in monomer mixtures, *etc.*

[47] *M. Suzuki, H. Miyama*, and *S. Fujimoto*, J. Polymer Sci. *31*, 212 (1958).

tent of the copolymers. Plots of Equation (m), in which calculated[1,3] values of R and assigned (ΔH_{AB} + ΔH_{BA}) values are employed, fit the experimental results reasonably well. Similar results[48] were obtained for copolymerizations of acrylonitrile with styrene, methyl methacrylate, and vinyl acetate.

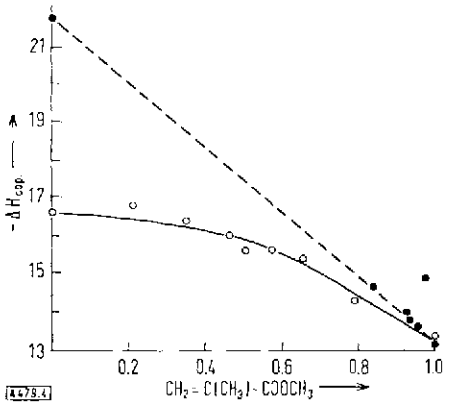


Fig. 4. Heats of copolymerization, $\Delta H_{cop.}$, for methyl methacrylate-styrene (○) and methyl methacrylate-vinyl acetate (●) copolymerizations [47].
– — Calculated for (ΔH_{SM} + ΔH_{MS}) = −32.7 kcal/mole;
---- calculated for (ΔH_{VM} + ΔH_{MV} − ΔH_{VV} − ΔH_{MM}) = 0.
Abscissa: Mole fraction of methyl methacrylate in the copolymer.

The sensitivity of $\Delta H_{cop.}$ to R depends on the magnitude of the expression (ΔH_{AB} + ΔH_{BA} − ΔH_{AA} − ΔH_{BB}); when this expression is zero, $\Delta H_{cop.}$ becomes independent of sequence distribution and linearly dependent on copolymer composition. This is almost the case with styrene-vinyl acetate copolymerization (Fig. 4). Values of (ΔH_{AB} + ΔH_{BA} − ΔH_{AA} − ΔH_{BB}) obtained for a number of copolymerization systems[47–50] range from 0 to 9 kcal/mole.

In copolymerizations where one of the monomers (B) fails to homopolymerize (r_B = 0; R = 2 %B), $\Delta H_{cop.}$ is related to copolymer composition by Equation (n). In such situations, $\Delta H_{cop.}$ varies linearly with copolymer composition and

$$\Delta H_{cop.} = \Delta H_{AA} + \frac{\%B}{100}(\Delta H_{AB} + \Delta H_{BA} - 2\Delta H_{AA}) \qquad (n)$$

(ΔH_{AB} + ΔH_{BA}) can be obtained from the value of $\Delta H_{cop.}$ when %B = 50. Results of this type were obtained by *Tong* and *Kenyon*[51] in studies on copolymerizations of vinyl acetate with diethyl maleate and diethyl fumarate.

2. Entropies of Copolymerization

Entropy changes associated with copolymerization reactions can be related to run numbers by an equation similar to (m), except that an additional term, C, must be included to account for the entropy of arranging monomer sequences in the copolymer chains. Calcula-

$$\Delta S_{cop.} = \frac{1}{100}[\%A \cdot \Delta S_{AA} + \%B \cdot \Delta S_{BB} + R/2(\Delta S_{AB} + \Delta S_{BA} - S_{AA} - S_{BB})] + C \qquad (o)$$

tions by *Orr*[52] and by *North* and *Richardson*[53] indicate C to be 0.5 to 1.5 cal deg^{-1} mole^{-1} of repeating units, so this term will seldom be responsible for more than 5 % of $\Delta S_{cop.}$. In what appears to be the only experimental study on copolymerization entropy, *Orr* noted that (ΔS_{SB} + ΔS_{BS}) is about 5 cal deg^{-1} mole^{-1} smaller than (ΔS_{SS} + ΔS_{BB}) in the copolymerization of styrene (S) with butadiene (B) at 30 °C.

H. Crystalline Contents and Melting Points of Copolymers

The melting points and crystalline contents of copolymers containing crystallizable (A) and non-crystallizable units (B) can provide information about sequence distribution. The simplest approach to take in correlating the crystalline content of such copolymers with their sequence distributions is to assume that all A units in sequences larger than a critical length m* are crystalline, whereas A nnits in shorter sequences and all B units are noncrystalline. The weight fraction of crystalline material, W_c, in a copolymer can then be calculated from Equation (p), where $\%A_w$ is the weight percentage of A units in the copolymer and f_{BA_mB}

$$W_c = \frac{\%A_w}{100} \cdot \sum_{m^*}^{\infty} m \cdot f_{BA_mB} = \frac{\%A_w}{100} \cdot \sum_{m^*}^{\infty} m \cdot (p_{AB})^2 \cdot (p_{AA})^{m-1} \qquad (p)$$

represents the fraction of A units in *each* position of sequences containing m A units[54]. Summations of Equation (p) have been evaluated algebraically[55,56] and a relationship similar to (p) has been used to predict W_c for various ethylene-propylene copolymers, assuming m* = 7[57].

In correlating W_c with calculated or measured sequence distributions, the critical sequence length, m*, is selected empirically. Ideally, m* corresponds to the sequence length which melts just above the temperature employed in determining W_c, but the value selected probably also corrects for incomplete crystallization due to kinetic or steric factors. Values of m* selected[55–60] in various studies on ethylene copolymers and stereoregular polymers range from 8 to 13. *Ring*[55] obtained a good correlation between calculated and observed W_c values for

[48] *H. Miyama* and *S. Fujimoto*, J. Polymer Sci. *54*, S33 (1961); *M. Suzuki*, *H. Miyama*, and *S. Fujimoto*, Bull. chem. Soc. Japan *35*, 57, 60 (1962).

[49] *R. M. Joshi*, Makromolekulare Chem. *66*, 114 (1963).

[50] *R. A. Nelson*, *R. S. Jessup*, and *D. E. Roberts*, J. Res. nat. Bur. Standards *48*, 275 (1952).

[51] *L. K. J. Tong* and *W. O. Kenyon*, J. Amer. chem. Soc. *71*, 1925 (1949).

[52] *R. J. Orr*, Polymer *2*, 74 (1961).

[53] *A. M. North* and *D. Richardson*, Polymer *5*, 227 (1964).

[54] Consider ~~BAAAAB~~ (1 2 3 4) sequences. The fraction of A units in positions 1 *or* 4 is $p_{AB} \cdot p_{AA} \cdot p_{AA} \cdot p_{AA} \cdot p_{AB}$ (*i.e.*, ~~BAAAAB~~ or BAAAAB). The fraction of A units in positions 3 *or* 4 is also $(p_{AB})^2(p_{AA})^3$. The fraction of A units in positions 1, 2, 3, *and* 4 is therefore $4(p_{AB})^2(p_{AA})^3$ and this corresponds to the fraction of A units in tetrameric sequences. The expression for the general case, $m(p_{AB})^2(p_{AA})^{m-1}$, can be obtained similarly; p_{AB}, for example, denotes the probability that an A unit in the copolymer is followed by a B unit.

[55] *W. Ring*, Polymer Letters *1*, 323 (1963).

[56] *R. L. Miller*, J. Polymer Sci. *57*, 975 (1962).

[57] *M. Berger*, J. Polymer Sci. A *1*, 1601 (1963).

[58] *K. H. Hellwege*, *U. Johnsen*, and *D. Kockott*, Kolloid-Z. *194*, 5 (1964).

[59] *H. G. Kilian*, Kolloid-Z. *189*, 23 (1963).

[60] *J. F. Jackson*, J. Polymer Sci. A *1*, 2119 (1963).

random ethylene–propylene copolymers by assuming m* to be 11, whereas *Jackson*[60] assumed m* to be about 8 in studies on a series of ethylene–propylene copolymers having block, random, or alternating type structure ($r_E r_P$ ranged from 0.09 to 1.73).

Should a reliable relationship of m* to temperature be available, the melting curve of a copolymer (W_c *vs.* T) can be used to construct a curve representing the integral weight distribution of A sequence lengths. *Gubler* and *Kovacs*[61] based assignments of m* at various temperatures on melting points reported for linear hydrocarbons. From melting curves observed for various polyethylene samples, they calculated the distributions of crystalline sequences present. By assuming one methyl (branch) unit to be associated with each amorphous sequence present, they calculated methyl contents for the polymers which where in fairly good agreement with those determined by infrared spectroscopy. *Flory*[62] has derived a theoretical relationship for m*. *Miller*[56] used *Flory*'s relationship and expressions analogous to (p) to construct melting curves for polypropylene fractions. The curves are in excellent agreement with experimental results.

Flory's treatment of copolymer crystallization[62], which was subsequently extended to treat stereoregular polymer crystallization[63], is more elaborate than the treatments outlined above. In addition to providing an expression for m* at various temperatures, his theory corrects W_c for the "solubility" of crystallizable sequences in the amorphous melt. Melting curves predicted by his theory are in reasonably good agreement with experimental results at temperatures somewhat removed from maximum copolymer melting points, T_m[*], but predicted W_c values are too high at very low temperatures and also in the vicinity of T_m[64].

According to *Flory*, the maximum melting point, T_m, of a copolymer is given by Equation (q), where T_m^o and ΔH_f are the melting point and enthalpy of fusion (per mole of repeating units) of the homopolymer of A, where $\Re$ is the molar gas constant and where P_{AA} is the probability ($1 - R/2\ \%A$) that an A unit is followed by another A unit in the copolymer chain. P_{AA} equals the mole fraction of A units present in random copolymers

$$\frac{1}{T_m} - \frac{1}{T_m^o} = \frac{-\Re}{\Delta H_f} \ln P_{AA} \qquad (q)$$

and it approaches unity in block copolymers. In the former case, the expression becomes identical with that which describes the melting points of low molecular weight mixtures.

Flory's melting point equation has been used extensively in studies on the melting behavior of copolymers[65] and for estimating the concentration of non-crystallizable units present in stereoregular polymers and in branched polyethylene samples. Unfortunately, the broad melting characteristics of copolymers preclude the accurate determination of T_m; the last 0.1 % of crystalline material in a copolymer can melt over a 5 or 10 degree range, for example. Experimentally determined T_m values are necessarily low and melting point depressions observed are consequently too large. Copolymer melting points can provide qualitative information about sequence distribution in many copolymers, however. Recently proposed extrapolation procedures[66] may be useful for obtaining reliable T_m values and hence reliable sequence distribution determinations may result from such procedures. When T_m observed for a copolymer is very close to T_m^o, the presence of a block copolymer or a polyblend is almost certain[31, 67, 68].

Wunderlich[69] has derived expressions for the melting points and crystalline contents of random copolymers crystallized by a "cold crystallization" process. Cold crystallization is an extreme case of nonequilibrium crystallization in which A units are assumed to crystallize only with adjacent A units; chain movement and the selective crystallization of large A sequences do not occur during this process. As most copolymer crystallizations occur under conditions which lie between the extremes of equilibrium and cold crystallization, the melting points and crystalline contents observed for copolymers are dependent on their thermal history. Differential thermal analysis[70–72] is a powerful tool for studying the influence of crystallization conditions on T_m and W_c.

Wunderlich and *Poland*[72] suggested that T_m^o in *Flory*'s melting point equation (q) be replaced by T_m^f, the melting point of homopolymer crystallized under the same conditions as the copolymer. By comparing the melting points of linear polyethylene and ethylene-propylene copolymer samples, these workers estimated the mole fraction of crystallizable units, X_a (P_{AA}), present in the copolymers. The fraction of noncrystallizable units ($1 - X_a$) proved to be twice the fraction of methyl carbon atoms in the copolymers. The authors concluded that both CH_3 and CH groups are noncrystallizable units[73].

Many physical properties of copolymers (tensile strength, elasticity, permeability, equilibrium swelling, *etc.*) are dependent upon their crystalline contents. Determinations of W_c, in fact, are often based on

[61] *M. G. Gubler* and *A. J. Kovacs*, J. Polymer Sci. *34*, 551 (1959).

[62] *P. J. Flory*, Trans. Faraday Soc. *51*, 848 (1955).

[63] *B. D. Coleman*, J. Polymer Sci. *31*, 155 (1958).

[*] In *Flory*'s equilibrium theory of copolymer crystallization T_m is the melting point of crystalline regions of infinite sequence length.

[64] *M. J. Richardson, P.J. Flory*, and *J. B. Jackson*, Polymer *4*, 221 (1963).

[65] *L. Mandelkern*: Crystallization of Polymers. McGraw-Hill, New York 1964, Chapter 4.

[66] *J. D. Hoffman* and *J. J. Weeks*, J. Res. nat. Bur. Standards A *66*, 13 (1962).

[67] *R. L. Merker, M. J. Scott*, and *G. G. Haberland*, J. Polymer Sci. A *2*, 31 (1964).

[68] *H. S. Makowski, B. K. C. Shim*, and *Z. W. Wilchinsky*, J. Polymer Sci. A *2*, 4973 (1964).

[69] *B. Wunderlich*, J. chem. Physics *29*, 1395 (1958).

[70] *A. P. Gray* and *K. Casey*, Polymer Letters *2*, 381 (1964).

[71] *Op. cit.* [5], Chapter 9.

[72] *B. Wunderlich* and *D. Poland*, J. Polymer Sci. A *1*, 357 (1963).

[73] In most of their samples, experimental X_a values agree well with the mole fraction of ethylene units present.

measurements of copolymer density or specific heat [74, 75].

When W_c can be correlated with copolymer composition and sequence distribution, then density, specific heat, or other properties can also be related to sequence distribution. The fraction of insoluble material in stereoregular polymers has been used as a qualitative index of stereoregularity [76, 77]. The solubility of block ethylene-propylene copolymers prepared by *Bier* and coworkers [78] increased as the average lengths of the blocks and the crystallinity decreased.

By using the kinetic theory of elasticity to describe the behavior of amorphous chains connecting crystalline regions in copolymer samples, *Flory* [62] derived an expression relating the elastic modulus of a copolymer to thermodynamic and sequence distribution parameters. Elastic moduli determined for copolymers recently [79] are an order of magnitude larger than values predicted by the theory. By correcting for the reinforcing action of crystallites, *Nielsen* and *Stockton* [80] obtained improved agreement between experimental and theoretical results, although calculated moduli were still too low.

I. Other Physical Properties

Glass transition temperatures of copolymers and solution properties of copolymers are dependent on intermolecular forces involving A and B units and on the flexibility of A–A, A–B, and B–B linkages. Glass transition temperatures, T_g, of copolymers have been related to copolymer compositions in most theoretical treatments [81]. *Kanig*'s recent treatment [82], which assumes that T_g is determined by intermolecular interactions between similar and dissimilar monomer units, can explain positive and negative deviations from linearity noted in many [83] T_g *vs.* copolymer composition plots. Recent work [83–85] indicates that the relative stiffness of A–A, A–B, and B–B bonds may also have an important effect on T_g in certain copolymers. In such cases, T_g will be sensitive to sequence distribution as well as copolymer composition.

Solution properties of random copolymers differ significantly from those of block copolymers. Attempts to treat the solution properties of copolymers theoretically have been made [86, 87], but only one attempt to correlate measured properties of copolymers in solution with their sequence distributions has been reported [88]. In this work, the apparent specific volume of vinyl acetate-vinyl chloride copolymers in dioxane was related to their compositions and sequence distributions through an equation analogous to (a). Unfortunately the author used an incorrect expression for P_{AA} and his calculations seem to account only for the properties of A units in various environments. Due to the difficulty of separating effects due to intermolecular forces and bond flexibilities, the correlation of T_g or solution properties of copolymers with the distribution of their sequences will be very difficult.

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[74] *B. Wunderlich* and *M. Dole*, J. Polymer Sci. *24*, 201 (1957).

[75] *M. Dole*, Fortschr. Hochpolymeren-Forsch. *2*, 221 (1960).

[76] *G. Natta*, *I. Pasquon*, *A. Zambelli*, and *G. Gatti*, Makromolekulare Chem. *70*, 191 (1964).

[77] *C. A. Russell*, J. appl. Polymer Sci. *4*, 219 (1960).

[78] *G. Bier*, *G. Lehmann*, and *H. J. Leugering*, Makromolekulare Chem. *44–46*, 347 (1961).

[79] *J. B. Jackson*, *P. J. Flory*, *R. Chaing*, and *M. J. Richardson*, Polymer *4*, 237 (1963).

[80] *L. E. Nielsen* and *F. D. Stockton*, J. Polymer Sci. A *1*, 1995 (1963).

[81] *R. F. Boyer*, Rubber Chem. Technol. *36*, 1374–1381 (1963).

[82] *G. Kanig*, Kolloid-Z. *190*, 1 (1963).

[83] *K. H. Illers*, Kolloid-Z. *190*, 16 (1963).

[84] *R. B. Beevers* and *E. F. T. White*, Polymer Letters *1*, 171 (1963); *2*, 793 (1964).

[85] *R. B. Beevers* and *E. F. T. White*, Trans. Faraday Soc. *56*, 1529 (1960).

[86] *M. L. Huggins*, J. Polymer Sci. C *(4)*, 445 (1963).

[87] *M. Lautout-Magat*, J. Polymer Sci. C *(4)*, 453 (1963).

[88] *H. Inagaki*, Makromolekulare Chem. *75*, 217 (1964).

The Structural Chemistry of Condensed Inorganic Phosphates [*]

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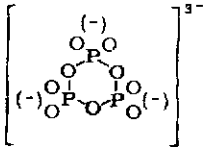
After it had become known that three types of condensed inorganic phosphates, i.e. metaphosphates, polyphosphates, and ultraphosphates, exist, attempts were made to elucidate their formation, properties, and mutual relationships. Metaphosphates and polyphosphates containing up to eight or ten monomer units can be separated chromatographically. In the melts, equilibria exist between the various types of phosphate anions. Annealing of the glasses leads to crystalline products, sometimes containing only one type of anion. The glass-crystal transition proceeds via monomeric XO_3^- anions. This has been shown in the case of polyarsenatophosphates, in which the As atoms are randomly distributed over the chains in the vitreous state, but are located at preferred positions in the crystalline state. The maximum degree of dissociation of polyphosphates and polyphosphoric acids in water is 30 %, which accounts for the ion exchange and the chelating effects. The cation-catalysed decomposition of polyphosphates can take place either by hydrolytic degradation from the chain ends, or by rearrangement within the chains to form metaphosphates.

Introduction

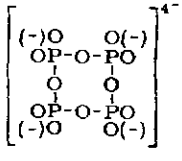
It has been known since 1955 [1a,1b] that condensed phosphates fall into the following three groups:

1. Metaphosphates, $M_n^I(PO_3)_n$ with cyclic anions, *e.g.* *(1)* and *(2)*.



(1)

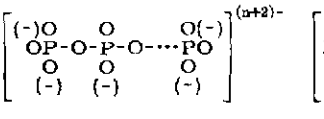
$[P_3O_9]^{3-}$
Trimetaphosphate anion



(2)

$[P_4O_{12}]^{4-}$
Tetrametaphosphate anion

2. Polyphosphates, $M_{n+2}^I(P_nO_{3n+1})$ or $M_n^IH_2(P_nO_{3n+1})$, with open-chain anions, *e.g.* *(3)* and *(4)* in which each of the n PO_4 tetrahedra (except those at the chain ends) is linked to each of its neighbors by an oxygen atom.



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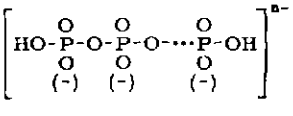

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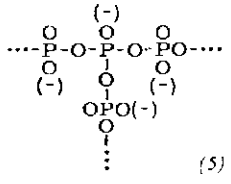
3. Cross-linked phosphates or ultraphosphates *(5)* containing "tertiary" P atoms which are linked to three other P atoms by three O atoms.



(5)

Since 1955, the first two types of phosphates in particular have been investigated by preparative and analytical methods, in order to elucidate their mutual relationships and their chemical properties [2a,2b], and by physicochemical methods, in order to explain the properties of their solutions and their complexing power [2b,3]. The present paper is concerned mainly with investigations of the former type, without giving a comprehensive survey of the literature. Whenever the cations of the salts are not explicitly named, sodium salts are to be understood.

A. Metaphosphates

Metaphosphates are always present in Graham's salt $Na_nH_2P_nO_{3n+1}$ [4a,4b], which is obtained by heating NaH_2PO_4 above 620 °C and rapidly cooling the resulting melt. The melt solidifies to form a glass, about 90 % of which consists of a mixture of high-molecular weight polyphosphates, the remainder being metaphosphates

[*] Based on lectures delivered in 1964.

[1a] *E. Thilo*, Angew. Chem. *67*, 141, 408 (1955).

[1b] *J. R. Van Wazer*: Phosphorus and its Compounds. Interscience, New York 1958, Vol. 1, p. 757.

[2a] *E. Thilo*, Naturwissenschaften *46*, 367 (1959).

[2b] *E. Thilo*, Advances inorg. Chem. Radiochem. *4*, 1–75 (1962).

[3] *U. P. Strauss et al.*, J. Amer. chem. Soc. *77*, 1473 (1955); *78*, 3553 (1956); *80*, 2366, 6494, 6498 (1958); *81*, 5292, 5295, 5299 (1959); *82*, 1311 (1960). J. physic. Chem. *66*, 2235 (1962); *67*, 2683 (1963); *G. Feitelson*, J. physic. Chem. *66*, 1295 (1962); *E. J. Griffith*, Analytic Chem. *28*, 525 (1956); *T. R. Meadowcroft* and *F. D. Richardson*, Trans. Faraday Soc. *59*, 1564 (1963).

[4a] *H. Grunze* and *E. Thilo*, S.-B. dtsch. Akad. Wiss. Berlin, Kl. Math. allg. Naturwiss., *1953*, No. 5.

[4b] *H. Grunze*, *E. Thilo*, and *W. Wieker*, 2nd ed. of [4a], Akademie-Verlag, Berlin 1955.

with cyclic anions of various degrees of polymerization. When this glass is annealed at 400 to 550 °C, it is converted into pure trimetaphosphate.

Trimetaphosphates of K, Rb, and Cs are obtained by the dehydration of potassium, rubidium, and cesium dihydrogen phosphates in the melts of the corresponding nitrates[5]. Pure tetrametaphosphates are formed when the dihydrogen phosphates of Al^{3+}, Cu^{2+}, Mg^{2+}, Ni^{2+}, Co^{2+}, Mn^{2+}, Fe^{2+}, Zn^{2+}, and Cd^{2+} are dehydrated at 400 to 500 °C, or when the glasses resulting on cooling of the melts are annealed at 400 to 500 °C[6a,6b]. The tetrametaphosphate $Na_4(P_4O_{12})$ can be prepared by the reaction of the copper salt with Na_2S, or by the reaction of the zinc and cadmium salts with Na_2CO_3. The same product is obtained in good yields by the alkaline hydrolysis of the volatile form of phosphorus(V) oxide[7].

The existence of higher metaphosphates, $Na_n(P_nO_{3n})$ with $n \geqslant 5$, was first observed by *van Wazer* and *Karl-Kroupa*[8a] in the chromatograms of hydrolysates of Graham's salt, and was confirmed by *Rudy* and *Ruf*[8b]. The stepwise addition of acetone to a solution of Graham's salt at first results in the precipitation of high-molecular weight polyphosphates. Subsequent treatment of the mother liquor with a large quantity of acetone leads to the separation of an oily substance in which metaphosphates are present in such a high concentration that they can be easily identified and quantitatively determined up to the octamers by two-dimensional paper chromatography (see Fig. 1)[9a,9b].

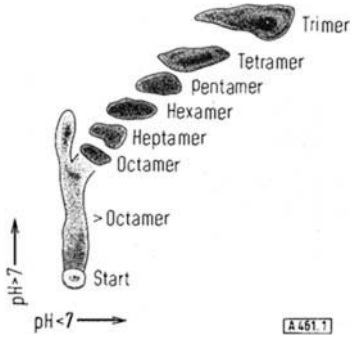


Fig. 1. Two-dimensional paper chromatogram of a metaphosphate fraction obtained from a solution of Graham's salt in water at 16 °C. Paper: Schleicher and Schüll 2043b mgl; Eluent: alkaline, after *Biberacher* [46f], and acidic, after *Pfrengle* [46g].

The concentrations of the individual metaphosphates in Graham's salt decrease exponentially as the number of atoms in the ring increases (cf. Fig. 2), indicating an equilibrium distribution. Only the pentamer content is lower than predicted by the exponential curve (see Fig. 2). The monomeric and dimeric metaphosphates are absent, being apparently incapable of existence at least at room temperature. The fact that monomeric metaphosphate $[PO_3]^{1-}$ with an electron deficiency on the P atom is isoelectronic with sulfur trioxide SO_3

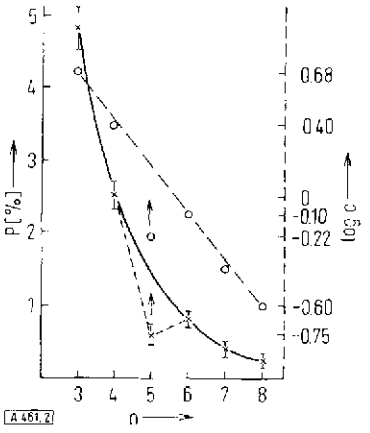
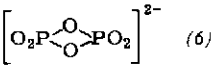


Fig. 2. The quantitative distribution of the individual metaphosphates in Graham's salt (see also Fig. 1).

Abscissa: n = number of phosphorus atoms per ring.
Ordinate, left: P[%] = percentage of phosphorus in a metaphosphate with n units, calculated on the total phosphorus present (full curve).
right: log c = logarithm of the metaphosphate concentration [g/100 g of Graham's salt] (broken curve).

and like this species is formed as an intermediate at higher temperatures will be discussed below (cf. Section B.2). No evidence has yet been found for the existence of a dimeric anion *(6)*. In fact, such an anion having two XO_4 tetrahedra

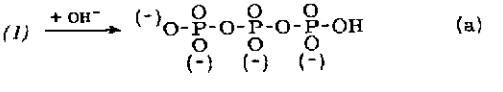


(6)

joined through a common edge should be incapable of existence, according to *Pauling*'s rules for the stability of tetrahedra chains in crystals[84]. The only exception to this rule is an unstable modification of SiO_2, in which SiO_4 tetrahedra are linked in this way to form high-molecular weight chains[10].

Pentametaphosphates and hexametaphosphates of Na, Ag, and Ba containing water of crystallization have been prepared on the gram scale by the fractionation of the metaphosphate components of Graham's salt *via* the silver and hexamminecobalt(III) salts[9b].

The proof of the structure of the metaphosphates is based on their ability to undergo ring cleavage to form the corresponding polyphosphates when attacked by nucleophilic reagents, such as OH^- ions. Thus trimetaphosphate *(1)*, for example, yields pure triphosphate[11]:



(a)

Tetrametaphosphate can be converted in a similar manner into tetraphosphate[12]. On the other hand, pentaphosphate and hexaphosphate cannot be pre-

[5] *M. Porthault* and *I. C. Merlin*, C. R. hebd. Séances Acad. Sci. *250*, 3332 (1960).

[6a] *E. Thilo* and *I. Grunze*, Z. anorg. allg. Chem. *290*, 209, 223 (1957).

[6b] *F. d'Yvoire*, Bull. Soc. chim. France *1962*, 1224, 1237, 1243.

[7] *R. N. Bell*, *L. F. Audrieth*, and *O. F. Hill*, Ind. Engng. Chem. *44*, 568 (1952); *E. Thilo* and *W. Wieker*, Z. anorg. allg. Chem. *227*, 27 (1954).

[8a] *J. R. Van Wazer* and *E. Karl-Kroupa*, J. Amer. chem. Soc. *78*, 1772 (1956).

[8b] *H. Rudy* and *F. Ruf*, personal communication.

[9a] *E. Thilo* and *U. Schülke*, Angew. Chem. *75*, 1175 (1963); Angew. Chem. internat. Edit. *2*, 742 (1963).

[9b] *U. Schülke*, Dissertation, Humboldt-Universität Berlin, 1965; *E. Thilo* and *U. Schülke*, Z. anorg. allg. Chem. *341*, 293 (1965).

[10] *Alarich* and *Armin Weiss*, Z. anorg. allg. Chem. *276*, 95 (1955).

[11] *E. Thilo* and *R. Rätz*, Z. anorg. Chem. *258*, 33 (1949).

[12] *E. Thilo* and *R. Rätz*, Z. anorg. Chem. *260*, 255 (1949).

pared in this way, since the polyphosphates formed on cleavage of the anion rings are largely degraded to lower phosphates, even before all the metaphosphate has reacted. The kinetics of the metaphosphate ring cleavage are first order with respect to the metaphosphate, and the rate constants depend on the size of the anion ring. It can be seen from Table 1 that the stability of the metaphosphates increases rapidly as the number n of the ring

Table 1. Half-lives of metaphosphates $Na_n(PO_3)_n$ and of methylcyclosiloxanes $(CH_3)_{2n}(SiO)_n$ on ring cleavage with NaOH and HI, respectively.

n	$Na_n(PO_3)_n$ using 0.1 N NaOH [9b] τ ½ [hours]	$(CH_3)_{2n}(SiO)_n$ using 0.01 N HI in CH_3OH [13] τ ½ [hours]
3	4.5	0.44
4	150	175
5	≈ 200	310
6	≈ 1000	1000

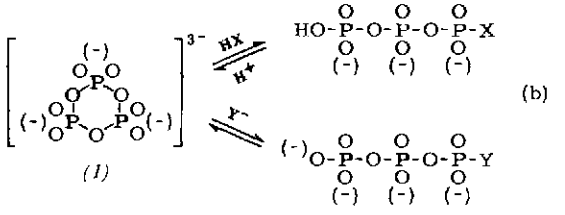
members increases. This observation is in contrast to the fact that the concentrations of these metaphosphates in the equilibrium melt of Graham's salt decrease with increasing ring size, but finds an analogy in the stability of the methylcyclosiloxanes towards cleavage with HI in methanol [13].

The ring structures of the following metaphosphate anions have been established by X-ray analysis: $Na_3P_3O_9$, $Na_3P_3O_9 \cdot H_2O$ [14], $LiK_2P_3O_9 \cdot H_2O$ [15], $(NH_4)_4P_4O_{12}$ [16], $Na_4P_4O_{12} \cdot 4H_2O$ [17], $Al_4(P_4O_{12})_3$ [18], $Na_2H_2P_4O_{12}$ [19], and $Na_6P_6O_{18} \cdot 6H_2O$ [20]. The compound $Al_4(P_4O_{12})_3$ is isomorphous with $Ti_4(P_4O_{12})_3$ [21]. The P–O bond lengths in the P–O–P linkages of the cyclic anions vary between 1.589 and 1.631 Å, when the phosphorus atoms of the rings lie in the same plane. No connection has, however, been found between the bond length and the ease of cleavage. In the case of extra-annular oxygen atoms, the P–O distance is between 1.457 and 1.493 Å. The P–O–P angles vary between 124.0 and 137.6°, while the O–P–O bond angles are between 97.5 and 123.5° (see Table 2).

Table 2. Mean bond lengths and bond angles in condensed phosphates [22].

P–O (in P–O–P)	1.62 Å
P–O (not in P–O–P)	1.49 Å
∢ POP	129°
∢ OPO	109°

Whereas ring cleavage of the metaphosphate anions with NaOH proceeds relatively slowly and practically quantitatively, the reactions with NH_3, alkylamines, H_2O_2, and F^- ions, which have been studied in detail for trimetaphosphate (although tetrametaphosphate behaves analogously), proceed to equilibrium [$N(CH_3)_3$ does not react]:



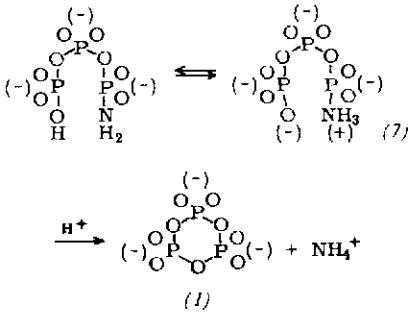
(b)

(1)

X = NH_2, $NHCH_3$, NHC_2H_5, $N(CH_3)_2$

$Y^- = O_2H^-$, F^-

The products are amidotriphosphate, *N*-alkylamidotriphosphate [23], peroxotriphosphate [24], and fluorotriphosphate [25] anions, of which, with the exception of the peroxo derivative, various stable salts (Na, K, NH_4, Ag, and Ba) have been isolated [23, 25]. Acidification of solutions of the amido derivatives results in the quantitative re-formation of the trimetaphosphate, the reaction proceeding *via* betaine-like intermediates *(7)*. The fluoro derivatives can also be recyclized, but in alkaline



(7)

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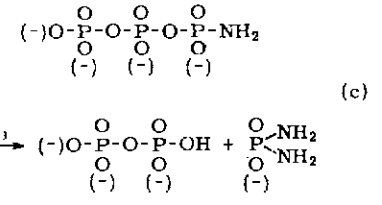
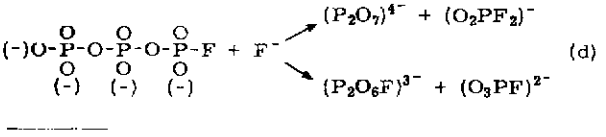
solutions. In excess ammonia or amine, the amido derivatives are degraded to the diphosphate with elimination of the corresponding diamidomonophosphates [Equation (c)], whereas in the presence of an excess of fluoride



(c)

ions, fluorotriphosphate is converted by a similar reaction [Equation (d)] into the diphosphate and difluoromonophosphate, minor quantities of fluorodiphosphate and fluoromonophosphate also being formed. Similarly,



(d)

[13] *K. Dimm, D. Gölitz*, and *W. Noll*, Angew. Chem. *76*, 273 (1964); Angew. Chem. internat. Edit. *3*, 310 (1964).

[14] *H. M. Ondik*, Acta crystallogr. *16*, A 31 (1963).

[15] *E. D. Eanes* and *H. M. Ondik*, Acta crystallogr. *15*, 1280 (1962).

[16] *C. Romers, J. A. A. Ketelaar*, and *C. H. MacGillavry*, Acta crystallogr. *4*, 114 (1951); *D. W. J. Cruickshank, ibid. 17*, 674 (1964).

[17] *H. M. Ondik, S. Block*, and *C. H. MacGillavry*, Acta crystallogr. *14*, 555 (1961); *H. M. Ondik, ibid. 17*, 1139 (1964).

[18] *L. Pauling* and *J. Sherman*, Z. Kristallogr., Mineralog. Petrogr., Abt. A *96*, 481 (1937).

[19] *O. H. Jarchow*, Acta crystallogr. *17*, 1253 (1964).

[20] *K. H. Jost*, Acta crystallogr. *19*, 555 (1965).

[21] *F. Liebau* and *H. P. Williams*, Angew. Chem. *76*, 303 (1964); Angew. Chem. internat. Edit. *3*, 315 (1964).

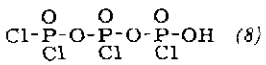
[22] *F. Liebau*, Angew. Chem. *75*, 735 (1963); Angew. Chem. internat. Edit. *2*, 562 (1963).

[23] *O. T. Quimby* and *T. J. Flautt*, Z. anorg. allg. Chem. *296*, 220 (1958); *W. Feldmann* and *E. Thilo, ibid. 328*, 113 (1964); *327*, 159 (1964); *W. Feldmann*, Z. Chem. *5*, 26 (1965).

[24] *P. W. Schenk* and *K. Dommain*, Z. anorg. allg. Chem. *326*, 139 (1963).

[25] *W. Feldmann*, Z. anorg. allg. Chem. *338*, 235 (1965).

the peroxo derivatives lose peroxomonophosphate to form diphosphate or triphosphate [24]. Acetyl triphosphate (which is obtained when triphosphate is treated with acetic acid/acetic anhydride) is cyclized to trimetaphosphate [26], and tetrachlorotriphosphoric acid *(8)* to trimetaphosphoric acid trichloride $(ClPO_2)_3$ [27a]. This tendency to cyclize, which is not observed with



(8)

pure triphosphate and which is found only if at least one terminal group is substituted, is explained by the shape of the anions in the two crystalline modifications of sodium triphosphate, $Na_5P_3O_{10}$, and in that of the amidotriphosphate $K_4P_3O_9NH_2$ (see Figures 3 and 4). The anions are linear in both forms of the triphosphate [27b], and angular in the amidotriphosphate [27c].

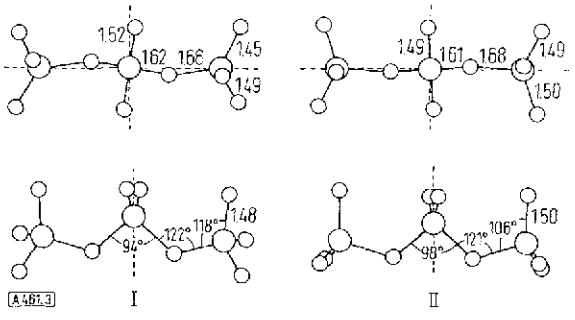


Fig. 3. Bond lengths and bond angles in the $[P_3O_{10}]^{5-}$ anions in the crystalline modifications I and II of sodium triphosphate $Na_5[P_3O_{10}]$ [27b].

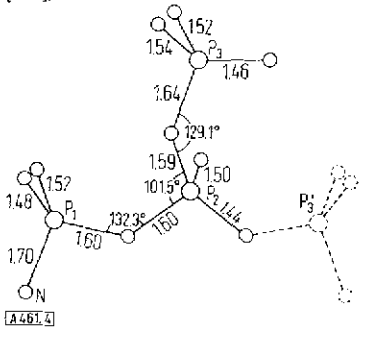


Fig. 4. The shape of the amidotriphosphate anion $[P_3O_9NH_2]^{4-}$ in potassium amidotriphosphate $K_4[P_3O_9NH_2]$ (see [27c]). The position of the third PO_4 tetrahedron P_3' in the triphosphate anion is shown for comparison by broken lines (cf. Fig. 3).

The cleavage of P–O–P bonds is catalysed by any cation (cf. Section B 4). This also applies to the ring cleavage of metaphosphates [28], which is generally accompanied by the degradation of the resulting polyphosphates. With uranyl ions, however the trimetaphosphate is quantitatively converted into the sparingly soluble uranyl triphosphate [29].

Most alkali metal metaphosphates crystallize with water of crystallization. On thermal dehydration, side reactions generally begin when only part of the water of crystallization has been eliminated. The elimination of the remaining water is usually accompanied by ring cleavage to form acid polyphosphates. In the case of the sodium derivatives, heating of the acidic intermediates above 350 °C invariaby leads to anhydrous sodium trimetaphosphate. On the oher hand, when the potassium and lithium metaphosphates containing water of crystallization are heated, the reaction proceeds *via* hydrolysis products to yield high-molecular weight polyphosphates [30a–30c]. Some anhydrous alkali metal metaphosphates react similarly. $Na_4(P_4O_{12})$ and $K_4(P_4O_{12})$, for example, are converted *via* free-radical intermediates into $Na_3(P_3O_9)$ and high-molecular weight potassium polyphosphate $(KPO_3)_x$ [31].

The acids corresponding to the metaphosphates can be easily prepared in solution by the use of ion exchangers. They behave as strong monobasic acids when titrated with alkalis [32]. Even in the case of hexametaphosphoric acid containing six OH groups per molecule, only one dissociation constant has been found [9a,9b]. Unlike the corresponding polyphosphates, the metaphosphates show only a very low tendency to bind ions. The electrical conductivity of metaphosphate solutions and the solubility data indicate the formation of charge-carrying "ion pairs" such as $[M^{II}(P_3O_9)]^{\ominus}$ in small amounts [33].

B. Polyphosphates

There are two types of polyphosphates: low-molecular weight oligophosphates with chain-lengths of up to n = 12, which can be separated by chromatography, and high-molecular weight polyphosphates with chain lengths up to and above $n = 10^3$. Glassy and crystalline forms are known in both groups. The glasses always contain mixtures of salts with anions of different chain lengths. The crystalline oligophosphates contain only one anionic species. It is doubtful whether this is also true of the high-molecular weight crystalline polyphosphates.

1. Oligophosphates

When mixtures of NaH_2PO_4 and Na_2HPO_4 are heated until they lose their water of constitution, rapid cooling of the resulting melts yields glasses; the average chain-length $\bar{n}$ of the anions in these glasses can be calculated from the Na:P ratio in the initial mixture with the aid of the formula $Na_{n+2}P_nO_{3n+1}$. As long as the Na:P

[26] *E. Thilo, I. Grunze*, and *H. Grunze*, Mber. dtsch. Akad. Wiss. Berlin *1*, 40 (1959); *I. Grunze, E. Thilo*, and *H. Grunze*, Chem. Ber. *93*, 2631 (1960).

[27a] *H. Grunze*, Z. anorg. allg. Chem. *298*, 152 (1959).

[27b] *D. R. Davies* and *D. E. C. Corbridge*, Acta crystallogr. *11*, 315 (1958); *D. E. C. Corbridge, ibid. 13*, 263 (1960).

[27c] *W. Hilmer*, Acta crystallogr. *19*, 362 (1965).

[28] *A. Indelli*, Ann. Chimica *46*, 717 (1956).

[29] *A. Indelli* and *G. Saglietto*, J. inorg. nuclear Chem. *25*, 1259 (1963).

[30a] *E. Thilo* and *U. Hauschild*, Z. anorg. Chem. *261*, 324 (1950).

[30b] *E. Thilo* and *M. Wallis*, Chem. Ber. *86*, 1213 (1953).

[30c] *W. Wieker, H.-P. Walter*, and *E. Thilo*, Chem. Ber. *97*, 2385 (1964).

[31] *H. Grunze* and *E. Thilo*, Z. anorg. allg. Chem. *281*, 284 (1955).

[32] *H. Rudy* and *H. Schlosser*, Ber. dtsch. chem. Ges. *73*, 484 (1940); *O. Samuelson*, Svensk kem. Tidskr. *56*, 343 (1944).

[33] *C. W. Davies* and *C. B. Monk*, J. chem. Soc. (London) *1949*, 413; *H. W. Jones, C. B. Monk*, and *C. W. Davies, ibid. 1949*, 2693.

ratio is between 1 and 2, the glasses contain no monophosphate, hut only anions with $n > 1$, the distribution

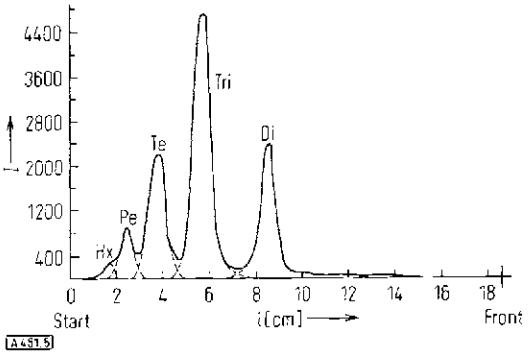


Fig. 5. Distribution of oligophosphate anions in a triphosphate (Na: P = 5:3) glass labelled with ^{32}P. The area under each peak in the curve gives the concentration of the corresponding oligophosphate in % phosphorus of the total phosphorus content. (Di = diphosphate, Tri = triphosphate, Te = tetraphosphate, Pe = pentaphosphate, Hx = hexaphosphate). Abscissa: Distance from start *l*. Ordinate: I = counts/min.

of which depends on the Na:P ratio, and can be determined by paper chromatography (Fig 5.) [4b, 34a–35]. Assuming that PO_3^- and $P_2O_7^{4-}$ or combinations of these are the only low-molecular weight anions present in the melts, the equilibrium distribution of the $(P_nO_{3n+1})^{(n+2)-}$ anions of various chain-lengths in the glasses can be calculated to a good approximation by a statistical method [36]. The result of the calculation for a glass in which $\bar{n} = 6$ is shown in two approximations (curves I and II) in Figure 6, together with experimental values

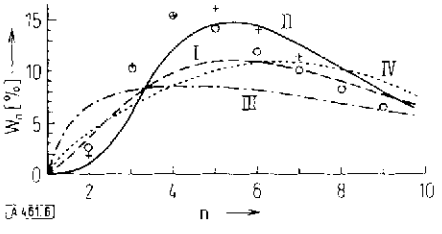


Fig. 6. The percentage W_n of phosphorus present in chains of length n in a "sodium hexaphosphate" glass ($\bar{n} = 6$). Experimental values after *Westman* [34a] (o) and after *Grunze* [34b] (+). Theoretical values by *Jost* [36] (curve I: first approximation; curve II: second approximation), and by *Van Wazer* [1b] (curve III: flexible chains; curve IV: rigid chains).

found by *Westman* and by *Grunze* [34]. Curves III and IV were obtained by calculation, assuming that more highly charged units such as PO_4^{2-} and PO_3^{2-} are present in the anion chains as well as PO_3^- [37]. These calculations refer to sodium phosphate glasses. Somewhat different distribution curves were obtained for glasses with other cations and mixtures of cations [38], indicating that the chain-length distribution in the oligophosphate glasses depends on the nature of the cation.

Oligophosphates of uniform chain length are only occasionally obtained directly from the melts. In the case of the sodium salts, this is possible only for the monophosphate and diphosphate (= pyrophosphate), and for the triphosphate by the tempering of melts with an Na:P ratio of 5:3 [Equation (e)]. This reaction involves various intermediates, depending on the water content [2b].

$$2\,Na_2HPO_4 + NaH_2PO_4 \rightarrow Na_5P_3O_{10} + 2\,H_2O \qquad (e)$$

The resulting triphosphate decomposes on remelting to give a mixture of high- and low-molecular weight polyphosphates containing a high proportion of diphosphate (= pyrophosphate). As the temperature of the melt is raised, the equilibrium distribution is established slowly at first, and then rapidly at temperatures above 900 °C. This equilibrium distribution is retained in the glass on quenching. When the glass is annealed, pure triphosphate is slowly re-formed at a rate that depends on the temperature, and also to a large extent on the rate of dissolution of the initially formed $Na_4P_2O_7$ crystallites, *i.e.* on the rate with which the Na:P ratio in the glass rises again to 5:3 [34b, 39].

Pure tetraphosphates are obtained directly by heating mixtures of Pb or Bi monophosphates with the correct M:P ratio to over 550 °C (elimination of water [40]). The ring opening of sodium tetrametaphosphate by NaOH leads to sodium tetraphosphate [12]:

$$Na_4[P_4O_{12}] + 2\,NaOH \rightarrow Na_6[P_4O_{13}] + H_2O \qquad (f)$$

The compound obtained is amorphous, and can be used to prepare the crystalline tetraacridinium dihydrogen salt and the neutral hexaguanidinium salt [41]. The treatment of $Pb_3P_4O_{13}$ with solutions of $(NH_4)_2S$ leads to the formation of crystalline $(NH_4)_6P_4O_{13}\cdot 6H_2O$ [42]. When glasses with the composition $4CaO:3P_2O_5$ are annealed they are converted into trömelite [43], which has recently been identified as calcium hexaphosphate $Ca_4P_6O_{19}$ [44]. Pure crystalline hexamminecobalt hexaphosphate has been prepared from calcium hexaphosphate which was solubilized by means of sodium ethylenediaminetetraacetate [44]. Besides sodium hexaphosphate, pure sodium pentaphosphate, heptaphosphate, and octaphosphate have also been prepared in milligram quantities from aqueous solutions of octaphosphate glass using anion exchange columns (Dowex 1 X 10) [45–46b].

[34a] *A. E. R. Westman* and *J. P. Crowther*, J. Amer. ceram. Soc. *37*, 420 (1954).

[34b] *H. Grunze*, Silikattechnik *7*, 134 (1956).

[34c] *A. E. R. Westman* and *P. A. Gartaganis*, J. Amer. ceram. Soc. *40*, 293 (1957).

[35] *J. Meissner*, Z. anorg. allg. Chem. *281*, 293 (1955).

[36] *K.-H. Jost* and *F. Wodtcke*, Makromolekulare Chem. *53*, 1 (1962).

[37] *J. R. Parks* and *J. R. Van Wazer*, J. Amer. chem. Soc. *79*, 4890 (1957).

[38] *M. K. Murthy, M. J. Smith*, and *A. E. R. Westman*, J. Amer. ceram. Soc. *44*, 97 (1961); *A. E. R. Westman* and *M. K. Murthy*, *ibid. 44*, 475 (1961); *45*, 401 (1962).

[39] *H. Grunze* and *E. Thilo*, Mber. dtsch. Akad. Wiss. Berlin *1*, 510 (1959).

[40] *R. K. Osterheld* and *R. P. Langguth*, J. physic. Chem. *59*, 76 (1955); *I. Schulz*, Z. anorg. allg. Chem. *287*, 106 (1956).

[41] *O. T. Quimby*, J. physic. Chem. *58*, 603 (1954).

[42] *E. J. Griffith*, J. inorg. nuclear Chem. *26*, 1381 (1964).

[43] *W. L. Hill, G. T. Faust*, and *D. S. Reynolds*, Amer. J. Sci. *242*, 457 (1944).

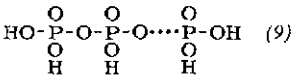
[44] *W. Wieker, A.-R. Grimmer*, and *E. Thilo*, Z. anorg. allg. Chem. *330*, 78 (1964).

[45] *J. Beukenkamp, W. Riemann III*, and *S. Lindenbaum*, Analytic. Chem. *26*, 505 (1954).

[46a] *W. Wieker*, Z. Chem. *1*, 211 (1961).

[46b] *W. Wieker*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *64*, 1047 (1960).

These substances are identified and their purity determined by means of paper chromatography. Their chain-lengths (or the average chain lengths in the case of glasses) are determined by alkalimetric techniques based on the fact that the terminal OH groups in the polyphosphoric acids *(9)* are weakly dissociated, whereas the non-terminal groups are strongly dissociated.



(9)

The dissociation constants of polyphosphoric acids, as reported by *Watters* [46c,46d] and by *Irani* and *Callis* [46e], are listed in Table 3.

Table 3. The dissociation constants pK_a of polyphosphoric acids $H_{n+2}P_nO_{3n+1}$ in solutions of ionic strength = 1 [$N(CH_3)_4Hal$], starting with the n-th proton (the values in brackets are uncertain).

Proton	pK_a n	n-1	n-2	n-3	n-4	Ref.
H_3PO_4	11.1	6.61	2.36			[46g]
$H_4P_2O_7$	8.74	5.98	1.75	(1.7)		[46g]
$H_5P_3O_{10}$	8.56	5.69	2.04	1.15	(0.5)	[46g]
	8.81	5.83	2.11	1.06		[8a]
$H_6P_4O_{13}$	8.34	6.63	2.23	1.36		[46f]
	8.13	5.98	2.19	(2.1)		[46g]
$H_{n+2}P_nO_{3n+1}$ ($\bar{n}$ = 40)	8.17	7.22	?	?		[46g]

The alkali metal salts of the oligophosphoric acids dissolve readily in water, whereas the corresponding salts of silver and of polyvalent cations are only sparingly soluble. From the triphosphate onwards, the oligophosphates exhibit a strong tendency to bind cations (see Section B.3).

As in the metaphosphates containing water of crystallization, only part of the water is generally eliminated without side reactions from oligophosphates containing water of crystallization. The anions are hydrolysed to fragments of shorter chain-lengths by the last parts of the water of crystallization. Thus the dehydration of *e.g.* sodium triphosphate hexahydrate initially yields the diphosphate and dihydrogen monophosphate:

$$Na_5P_3O_{10}\cdot 6\,H_2O \rightarrow Na_4P_2O_7 + NaH_2PO_4 + 5\,H_2O \qquad (g)$$

Monophosphate that has already been formed is then phosphorylated to the diphosphate in a side reaction with as yet unchanged triphosphate. Consequently, the dehydration product of the triphosphate hexahydrate contains more diphosphate than is expected from Equation (g), the actual quantity depending on the temperature and the water vapor pressure [47a–47d]. The dehydration of acidic oligophosphates is also complex [6b, 47e–47i].

2. High-Molecular Weight Polyphosphates

The most important of the glassy polyphosphates with $n \gtrsim 20$ is Graham's salt which is formed when NaH_2PO_4 is melted and then rapidly cooled; the melt solidifies as a glass. Similar glasses are formed with other cations. (Only in the case of the potassium salt a crystalline substance, *i.e.* Kurrol's potassium salt $(KPO_3)_x$, is formed, unless small amounts are quenched very rapidly.) These glasses also contain mixtures of salts with anions of different chain-lengths, always including metaphosphates and small quantities of cross-linked phosphates [6a,4b, 48,49a].

The average chain-length in Graham's salt depends on several factors: it increases with increasing temperature and with decreasing water vapor pressure of the parent melt (Fig. 7).

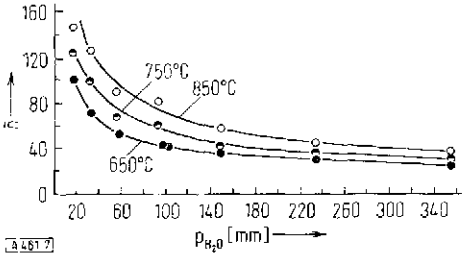


Fig. 7. The variation of the average chain length $\bar{n}$ in aqueous solutions of Graham's salt with the temperature and the water vapor pressure at which the NaH_2PO_4 melts were annealed for 20 h.

An equilibrium distribution of the various chain lengths is established in these melts in the course of about 20 hours, independently of whether the starting material is hydrated NaH_2PO_4 or anhydrous trimetaphosphate $Na_3P_3O_9$ (see Fig. 8). Whereas the former loses water, the latter takes up water vapor from the atmosphere to form the terminal free OH groups. The average chain

[46c] *J. I. Watters, E. Dan Loughran*, and *S. M. Lambert*, J. Amer. chem Soc. *78*, 4855 (1956).

[46d] *J. I. Watters, P. E. Sturrock*, and *R. E. Simonaitis*, Inorg. Chem. *2*, 765 (1963).

[46e] *R. R. Irani* and *C. F. Callis*, J. physic. Chem. *65*, 934 (1961).

[46f] *G. Biberacher*, Z. anorg. allg. Chem. *285*, 86 (1956).

[46g] *O. Pfrengle*, Z. analyt. Chem. *158*, 81 (1957).

[47a] *C. Y. Shen, J. S. Metcalf*, and *E. V. O'Grady*, Ind. Engng. Chem. *51*, 717 (1959).

[47b] *A. C. Zettlemoyer, C. H. Schneider, H. V. Anderson*, and *R. J. Fuchs*, J. physic. Chem. *61*, 991 (1957).

[47c] *W. O. Groves* and *J. W. Edwards*, J. physic. Chem. *65*, 645 (1961).

[47d] *D. Schultze*, Dissertation, Humboldt-Universität Berlin, 1964.

[47e] *A. Boullé* and *C. Morin*, C. R. hebd. Séances Acad. Sci. *245*, 1928 (1957).

[47f] *M. Porthault* and *J. C. Merlin*, C. R. hebd. Séances Acad. Sci. *250*, 1067 (1960).

[47g] *C. Morin*, Bull. Soc. chim. France *1961*, 1719, 1726.

[47h] *M. M. Crutchfield, C. F. Callis*, and *E. E. Kaeble*, Inorg. Chem. *1*, 389 (1962).

[47i] *J. M. Verdier, C. Dorémieux-Morin*, and *A. Boullé*, C. R. hebd. Séances Acad. Sci. *257*, 917 (1963).

[48] *E. Thilo, G. Schulz*, and *E.-M. Wichmann*, Z. anorg. allg. Chem. *272*, 182 (1953).

[49a] *A. Winkler* and *E. Thilo*, Z. anorg. allg. Chem. *298*, 302 (1959); *M. Nakagaki, H. Inoue, T. Fujie*, and *S. Ohashi*, Bull. chem. Soc. Japan *36*, 595 (1963).

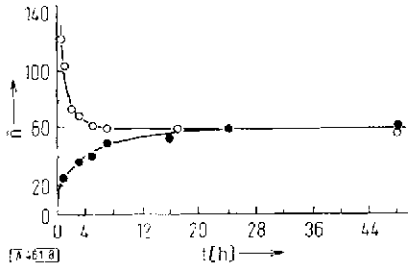


Fig. 8. The variation of the average chain length $\bar{n}$ of the polyphosphates with the duration of melting at 650 °C and p_{H_2O} = 55.3 mm Hg; Starting material: NaH_2PO_4 (●) and $Na_3[P_3O_9]$ (○).

length $\bar{n}$ of the glass at equilibrium is given by Equation (h), where p_w is the water vapor pressure in mm Hg [49a].

$$\bar{n} = \exp[8.87 - (5100/RT) - 0.5 \ln p_w] \qquad (h)$$

Graham's salt is soluble in water, and the anions have strong binding properties, particularly for polyvalent cations (see Section B.3). When glassy Graham's salt is annealed, it is converted into one of the two forms of the high-molecular weight Kurrol's sodium salt $(NaPO_3)_x$, into Maddrell's salt, or into one of the three forms [49b, 49c] of sodium trimetaphosphate $Na_3[P_3O_9]$, depending on the temperature and the water vapor pressure. The stable form of sodium trimetaphosphate is obtained as a pure product at about 400 °C when the Na:P ratio is exactly 1:1 (see Fig. 9).

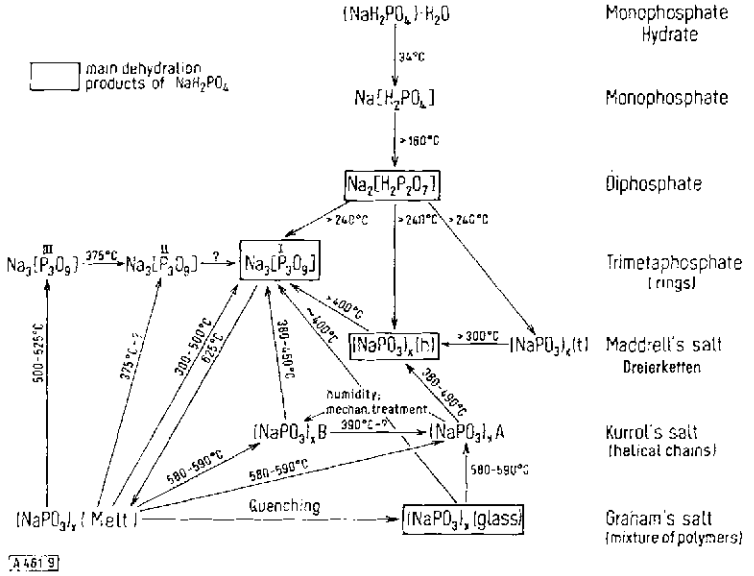
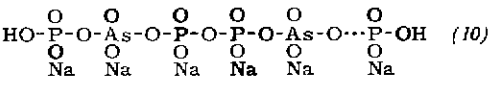


Fig. 9. Condensed phosphates obtained from NaH_2PO_4 by heating, and their mutual relationships.

The glasses obtained from dihydrogen monophosphates of the bivalent cations of Cu, Mg, Ni, Co, Fe, and Mn are ultimately converted to tetrametaphosphates on annealing, whereas the glasses of the salts of Li, K, Rb, Cs, Be, Hg^{2+}, Ca, Sr, Ba, Pb, Cr^{3+}, Fe^{3+}, and Bi^{3+} are converted into crystalline high-molecular weight polyphosphates, which generally occur in various polymorphic modifications. The glasses of Zn, Cd, and Al polyphosphates yield tetrametaphosphates or polyphosphates, depending on the conditions [6a, 6b].

The fact that the high-molecular weight polyphosphates form open-chain anions has been established by the investigation of the corresponding arsenatophosphates, which are obtained from the melts of NaH_2PO_4/NaH_2AsO_4 mixtures. The P–O–As and the As–O–As linkages in arsenatophosphates $Na_nH_2(P,As)_nO_{3n+1}$ *(10)* can be readily hydrolysed, the salts then being converted into monoarsenate/polyphosphate mixtures. The



(10)

distribution of the As atoms in the chains can be found from the chromatographic determination of the quantities of oligophosphates formed on hydrolysis. It is approximately random, though with a slight preference for As–O–P bonds [50]. The presence of larger quantities of oligophosphates with $n \geqslant 5$ in the hydrolysate shows that the high-molecular weight arsenatophosphate anions exist in the form of open chains. However, in the cases of potassium trimetaarsenatophosphate, which contains the anions *(1)* to *(1c)* in a statistical distribution [51], and magnesium tetrametaarsenatophosphate, which contains mixed tetrameric cyclic anions [52], the hydrolysates contain (apart from trimetaphosphate and tetrametaphosphate) only oligophosphates with a maximum of two and three phosphorus atoms, respectively, *i.e.* the number of P atoms in each case is one less than the number of P and As atoms in the ring.

The fact that the anions form long chains of PO_4 tetrahedra has also confirmed by the X-ray analysis of Maddrell's salt

[49b] *K.-H. Jost, H. Worzala,* and *E. Thilo,* Z. anorg. allg. Chem. *325,* 98 (1963).

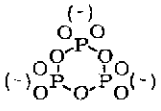
[49c] *R. W. Liddell,* J. Amer. chem. Soc. *71,* 207 (1949).

[50] *E. Thilo* and *L. Kolditz,* Z. anorg. allg. Chem. *278,* 122 (1955); *A. Winkler* and *E. Thilo, ibid. 337,* 149 (1965).

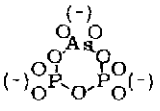
[51] *E. Thilo* and *K. Dostál,* Z. anorg allg. Chem. *298,* 100 (1959); *I. Grunze, K. Dostál,* and *E. Thilo, ibid. 302,* 221 (1959); *F. Wodtcke* and *E. Thilo,* Mber. dtsch. Akad. Wiss. Berlin *1,* 508 (1959).

[52] *I. Grunze* and *E. Thilo,* Z. anorg. allg. Chem. *331,* 102 (1964).

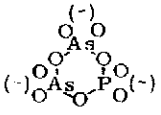
$(NaPO_3)_x$[53], acid sodium polyphosphate $[Na_2H(PO_3)_3]_x$[54], both modifications A and B of Kurrol's sodium salt $(NaPO_3)_x$[55], Kurrol's silver salt $(AgPO_3)_x$[56], potassium polyphosphate $(KPO_3)_x$[57], $[Pb(PO_3)_2]_x$[58], $(LiPO_3)_x$ which is isomorphous with $(LiAsO_3)_x$[59], and rubidium polyphosphate[60,61].



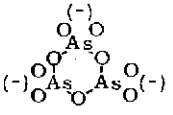
(1)



(1a)



(1b)



(1c)

Six types of chains have so far been distinguished (see Fig. 10). The Rb, Cs, and K polyphosphates and the low-temperature form of lithium polyphosphate

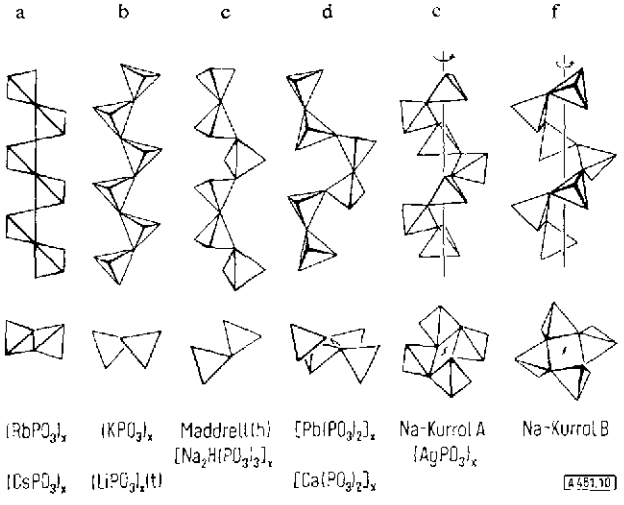


Fig. 10. The six known types of anion chains present in high-molecular weight crystalline polyphosphates. Above: vertical projections; below: projections along the chain axis.

$(LiPO_3)_x$(t), contain "Zweierketten"[62] with two PO_4 tetrahedra as the repeating unit, while the high-temperature form of Maddrell's salt $(NaPO_3)_x$(h), contains "Dreierketten" and the polyphosphates of Pb and Ca contain "Viererketten". The anion chains in Kurrol's sodium salts and in silver polyphosphate form different helices. The length of the P–O bridges in the chains is 1.57 to 1.64 Å, that of the non-bridging P=O bonds 1.44 to 1.52 Å. The P–O–P angles are between 124 and 134° and the O–P–O angles between 98 and 120°. The averages of these values are practically the same as those for the metaphosphates (cf. Table 2).

The transition from the melts to high-molecular weight crystalline polyphosphates does not take place by ordering of the chains present in the amorphous phase, as in the case of organic polymers, but by cleavage into monomeric $XO_3^{\ominus}$ anions, followed by the formation of new chains in the crystalline arrangement. This is shown by the fact that the As atoms in the arsenatophosphate glass of the Graham's salt type are approximately statistically distributed over the anion chains, whereas in crystalline sodium arsenatophosphate, which crystallizes with the structure of Maddrell's salt when the glass is annealed, the As atoms preferentially occupy the centers of the XO_4 tetrahedra forming the "noses" of the "Dreierketten" [cf. Fig. 10, third column from the left].

X-ray crystallographic investigations were carried out on a crystalline arsenatophosphate with an As:P ratio of 1:2.7. This ratio was selected since salts with higher arsenic contents are highly hygroscopic, whereas those with higher phosphorus contents are too difficult to dissolve. The results show that about 43% of the central positions in the projecting tetrahedra [see Fig. 10, third column] and only about 19% of the central positions in each of the two other tetrahedra are occupied by arsenic atoms[49b]. In a statistical distribution, on the other hand, 37% of the central positions of all the tetrahedra should be occupied by As. The non-statistical distribution in the crystals can also be seen if the chromatograms of the hydrolysates of the glasses are compared with those of the hydrolysates of the crystals (see Fig. 11).

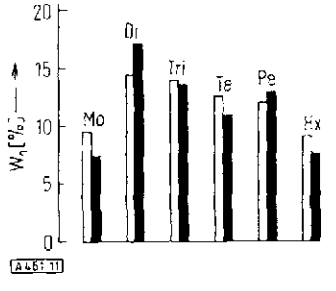


Fig. 11. The percentage distribution W_n of oligophosphates in the hydrolysates of high-molecular weight sodium arsenatophosphates. Hydrolysates of the glass (□) and of the crystalline phase of the same composition (■).

The latter contain more di- and pentaphosphates and less of the other oligophosphates than the hydrolysates of the glasses. This must be the case if the arsenatophosphate chains are preferentially cleaved at the bonds leading to the "nose tetrahedra" [cf. Fig. 10, third column], since this must favor the formation of oligophosphates with chain lengths $n = 2, 5, 8, \ldots (2 + 3x)$. This result also shows that monomeric PO_3^- anions or $NaPO_3$ groups occur as intermediates in the polyphosphate melts. The existence of these species at higher temperatures was postulated previously to explain the chain-length distribution in oligophosphate glasses.

[53] *K. Dornberger-Schiff, F. Liebau,* and *E. Thilo,* Naturwissenschaften *41,* 551 (1954); Acta crystallogr. *8,* 752 (1955); *K.-H. Jost, ibid. 16,* 428 (1963).

[54] *K.-H. Jost,* Acta crystallogr. *15,* 951 (1962).

[55] *K.-H. Jost,* Chem. Zvesti *13,* 738 (1959); Acta crystallogr. *14,* 844 (1961); *16,* 640 (1963).

[56] *K.-H. Jost,* Z. anorg. allg. Chem. *296,* 154 (1958); Acta crystallogr. *14,* 779 (1961).

[57] *K.-H. Jost,* Naturwissenschaften *49,* 229 (1962); Acta crystallogr. *16,* 623 (1963).

[58] *K.-H. Jost,* Naturwissenschaften *50,* 688 (1963); Acta crystallogr. *17,* 1539 (1964).

[59] *W. Hilmer* and *K. Dornberger-Schiff,* Acta crystallogr. *9,* 87 (1956).

[60] *D. E. C. Corbridge,* Acta crystallogr. *8,* 520 (1955); *9,* 308 (1956).

[61] *D. W. J. Cruickshank,* Acta crystallogr. *17,* 671 (1964).

[62] *F. Liebau,* Z. physik. Chem. *206,* 73 (1956).

3. The Ability of the Polyphosphates to Bind Cations

The technical importance [*] of the oligophosphates and high-molecular weight polyphosphates is mainly due to the ability of these substances to combine with polyvalent cations and to keep them in solution, so that they can no longer be detected by means of the common precipitants. In view of the large number of papers already published on this topic [63], only the essential features are discussed here.

Schindewolf and *Bonhoeffer* [64] have found that the maximum degree of dissociation of the polyphosphates in aqueous solutions is only 30%. This also applies to the free polyphosphoric acids, although all the OH groups present, with the exception of the two terminal groups [cf. Formula *(9)*], behave as strong acids on titration. If salts of any cation are added to solutions of the acids corresponding to Graham's salts, the H^+ concentration in the solutions will increase. An ion exchange takes place between the previously non-dissociated H^+ ions and the added cations, which is described by the Rothmund equation [65,66]:

$$K\cdot([H^+]^n/[M^{n+}])_P^\sigma = ([H^+]^n/[M^{n+}])_L \qquad (i)$$

In this equation, n is the number of charges on the cation, P and L respectively denote ions bound to the polyphosphate and those moving freely in the solution. The concentration of the latter can be calculated from the pH of the solution and from the known concentrations of the polyphosphate and of the cations. σ is an empirical exponent denoting the deviation of the solutions from ideal behavior; K is the constant for the exchange of the individual cations for the proton of the polyphosphoric acid.

The exchange constant K and the values of σ for ions of alkali metals (M^+) and alkaline earth metals (M^{2+} = Ba^{2+}, Sr^{2+}, Ca^{2+}, and Mg^{2+}), as well as for NH_4^+, are listed in Table 4. These data show that the bivalent ions

Table 4. Exchange constant K and values of σ for the exchange between protons and cations in an 0.1 base-molar [*] aqueous solution of the acid $H_{n+2}P_nO_{3n+1}$ corresponding to Graham's salt.

	M^{2+}	Li^+	Na^+	NH_4^+	K^+
K	2.5	5.13	5.75	7.6	13.8
σ	0.5	0.79	1.43	(0.77)	2.3

[*] The concentration is based on the $(PO_3)^-$ units.

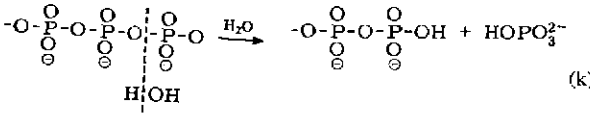
are much more tenaciously bound than the alkali metal ions, and that the bond strength of the latter decreases in the order $Li^+ > Na^+ > NH_4^+ > K^+$. This suggests at first that the low degree of dissociation of the polyphosphates, which is obvious even in the triphosphate $Na_5[P_3O_{10}]$, is due to the fact that the anionic charge increases with the number of dissociated cations to such an extent as to prevent the dissociation of the remaining cations on purely electrostatic grounds. However, this cannot be the only reason, since the soluble hexametaphosphates are almost fully dissociated, and show no tendency to bind counter-ions (see Section A). It is more probable that the ion-exchange tendency of polyphosphates is also caused by the ability of the PO_4 tetrahedra to rotate freely about the P–O–P bonds, the resulting mobility of the polyphosphate chains making possible the formation of relatively stable chelates [67a], in which the cations are linked to more than one PO_3^- group. This is supported by the observation that several phosphorus atoms bound in polyphosphates are always required for firm combination with Ca^{2+} ions [1a, 2a, 2b, 63, 67a].

High-molecular weight crystalline polyphosphates also act as ion-exchangers [67b]. This is shown, *inter alia*, by the fact that the crystalline alkali metal polyphosphates, which are practically insoluble in water, can be solubilized by solutions of salts containing other cations, and by the fact that 1:1 mixtures of Maddrell's salt $(NaPO_3)_x$ and Kurrol's potassium salt $(KPO_3)_x$, both of which are insoluble by themselves, dissolve when shaken with water [2b].

4. The Degradation of Polyphosphates

Polyphosphates are stable in aqueous solutions at pH *ca.* 7 and 25 °C. However, they are degraded at higher temperatures, higher hydrogen ion concentrations, and in the presence of cations. The reaction proceeds in two ways [68a–68d]:

The first type of degradation [Equation (k)] is of zero order with respect to the total polyphosphate. Mono-



(k)

phosphate units are removed, one at a time, from the chain ends, and a new OH group, which can be directly titrated, is formed at the chain end. The reaction appears to be of zero order kinetics, since no change in the number of terminal groups can be detected chromat-

[*] For example, in the softening of boiler water and cooling water, for washing liquids and dye baths, and in the food industry.

[63] *J. R. Van Wazer* and *C. F. Callis*, Chem. Reviews *58*, 1011 (1958).

[64] *H. Schindewolf* and *K.-F. Bonhoeffer*, Z. Elektrochem., Ber. Bunsenges. physik. Chem. *57*, 216 (1953).

[65] *V. Rothmund* and *G. Kornfeld*, Z. anorg. allg. Chem. *103*, 129 (1918).

[66] *W. Wieker*, *A. Grossmann*, and *E. Thilo*, Z. anorg. allg. Chem. *307*, 42 (1960).

[67a] *R. R. Irani* and *C. F. Callis*, J. physic. Chem. *64*, 1398 (1960); *R. R. Irani*, *ibid. 65*, 1463 (1961); *K. K. Andress* and *R. Nachtrab*, Z. anorg. allg. Chem. *311*, 1, 13, 22 (1961); *M. M. Crutchfield*, *C. F. Callis*, *R. R. Irani*, and *G. C. Roth*, Inorg. Chem. *1*, 813 (1962); *J. I. Watters* and *S. L. Lambert*, J. Amer. chem. Soc. *81*, 3201 (1959); *79*, 5606 (1957); *F. T. Wall* and *R. H. Doremus*, *ibid. 76*, 868 (1954); *H. Rudy*, Angew. Chem. *54*, 447 (1941).

[67b] *Bouchetal de la Roche* and *G. Perot*, Bull. Soc. chim. France *1953*, 307; *R. Viovy*, C. R. hebd. Séances Acad. Sci. *253*, 454 (1961); *S. Ohashi* and *K. Yamagishi*, Bull. chem. Soc. Japan *33*, 1431 (1960); *S. Ohashi* and *T. Nakamura*, *ibid. 35*, 498 (1962).

[68a] *J. P. Crowther* and *A. E. R. Westman*, Canad. J. Chem. *32*, 42 (1954); *34*, 969 (1956).

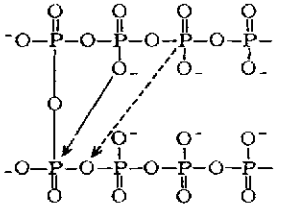
[68b] *E. Thilo* and *W. Wieker*, Z. anorg. allg. Chem. *291*, 164 (1957).

[68c] *W. Wieker*, unpublished work.

[68d] *W. Wieker* and *E. Thilo*, Z. anorg. allg. Chem. *306*, 48 (1960); *313*, 296 (1961).

ographically, at least until the long chains have been degraded to oligomers. The latter are also degraded by the stepwise removal of monophosphate units from the chain ends, but this reaction is of first order [46a,46b,68a].

A second route of degradation becomes increasingly important as the chain length increases beyond the pentaphosphate stage. It leads to metaphosphates, and in particular to trimetaphosphate [46a,46b,68b–68d], which can also be obtained from tetraphosphate at pH 1, *i.e.* when the substrate is present in the form of hydrogen tetraphosphate [68c]. The cyclic metaphosphate anions are formed from the internal units of the chains, the reaction being of the first order and proportional to the concentration of the P–O–P bonds still present. The metaphosphates are not formed as a result of hydrolysis; when the degradation is carried out in water labelled with ^{18}O, the latter is not detected in the metaphosphates. Anhydrous polyphosphates containing long-chain alkylammonium ions are converted in anhydrous benzene in 90% yield into trimetaphosphate in three days at 60 °C. The formation of the trimetaphosphate must therefore proceed as a rearrangement [Scheme (I)], *i.e.*



(I)

the folded polyphosphate chains give rise to the metaphosphate and to an anion chain, which is shorter by three (or four) PO_3 units. The effect of the pH shows that both reactions, contrary to an earlier interpretation [68a–68d], proceed independently of each other and are not coupled (see Fig. 12).

The increase in the rate of zero-order formation of monophosphates at the chain ends is particularly large at pH 10 to 7. Here the weakly acidic terminal groups of the chains are converted into undissociated POH groups. The increase in the rate of first-order formation of metaphosphates is particularly large at pH 3 to 5, at which the non-terminal, strongly acidic "side groups" of the polyphosphates are also converted into undissociated POH groups.

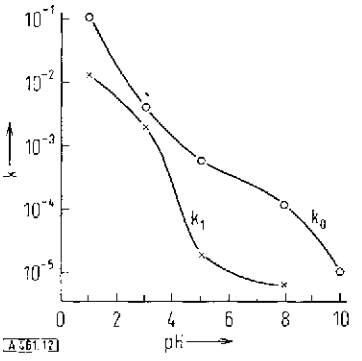


Fig. 12. The variation of the constants k_0 (zero order) and k_1 (first order) with the pH in the degradation of high-molecular weight polyphosphates.

Both reactions are also accelerated by the cations of added salt solutions, but at higher salt concentrations the formation of metaphosphates is accelerated more than the degradation from the chain ends. This is a further indication that the two reactions are not coupled. In general, the higher the ionic charge and the smaller the ionic radius, the more effective are the cations.

It can be seen from the analogous catalytic effect of cations on the hydrolysis of disulfate ions [69] (see Fig. 13) that even ions which are equal in radius and charge, *e.g.* Mg^{2+} and Ni^{2+}, differ in catalytic activity, and that the latter increases with the tendency of the ions to complex formation (*i.e.* the stability constant), *e.g.* with EDTA. The effect of the

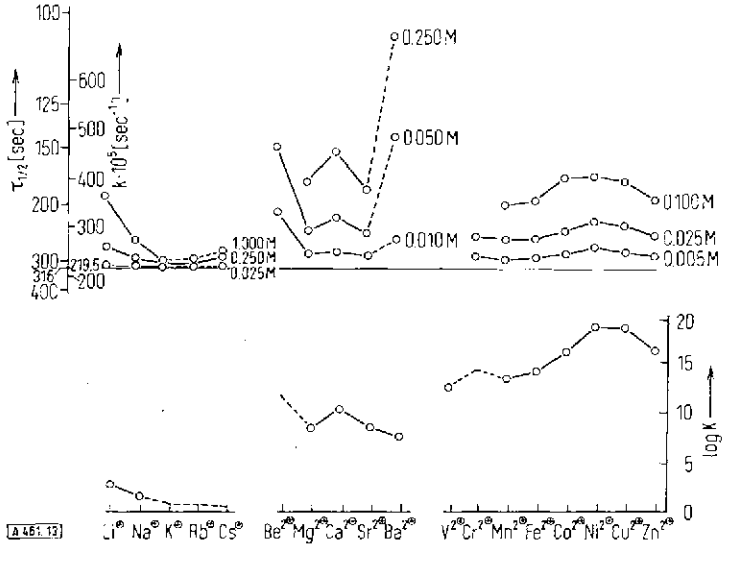
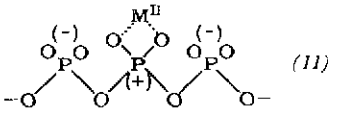


Fig. 13. Above: half-lives $\tau_{1/2}$ and rate constants k for the hydrolysis of 0.01 M solutions of $K_2[S_2O_7]$, catalysed by cations at various concentrations. (The line parallel to the abscissa denotes solutions free from foreign salts.)

Below: the stability constants K of the EDTA complexes of cations. (The dotted lines denote the means of the stability constants of other similar complexes.)

[69] *E. Thilo* and *F. von Lampe*, Chem. Ber. *97*, 1775 (1964).

cations on the degradation of polyphosphates is also due to chelate formation [see Formula *(11)*], as a result of which the P atoms of the PO_4 tetrahedra in question become positive, and hence more ready to combine with PO groups situated elsewhere in the same anion chain, or with OH^- ions or water molecules.

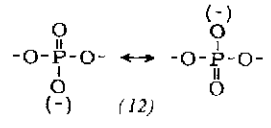


(11)

The fact that cations accelerate the formation of metaphosphates more than the degradation from the chain ends is probably due to the greater ease of chelation within the chains. This is supported by the observation that the cations promote coiling of the chains. For this reason the rate of degradation of polyphosphates also depends on the chain length. Other conditions being equal, the rate of degradation of sodium polyphosphates increases with the chain length, reaching a maximum at about the decaphosphate. The effect of the chain length can no longer be observed when $\bar{n} > 100$ [70]. This is a further indication that the cations must interact with more than one PO_3 group of the anion chain at time.

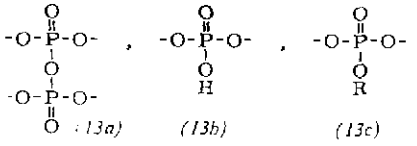
C. Cross-Linked Phosphates

Cross-linked phosphates are obtained by heating a mixture of phosphates, in which the cation:phosphorus ratio is smaller than 1 (*e.g.* by the thermal dehydration of a mixture of dihydrogen monophosphates and free phosphoric acid). The processes involved are complex and depend on the nature of the cation, as well as on the temperature and the water vapor pressure [71]. Even free phosphoric acid is converted into polymers *(5)* with tertiary PO_4 groups, after first forming linear polymers [72] which, unlike the oligophosphates, contain free water and monophosphoric acid [73]. The polymers *(5)* contain a varying number of PO_4 tetrahedra which are



(12)

resonance stabilization



(13a) *(13b)* *(13c)*

no resonance stabilization

linked to other PO_4 tetrahedra through three oxygen atoms. These groups *(13a)*, which also occur to a small extent in Graham's salt and its analogues [74], are easily hydrolysed, since they are not stabilized by resonance, unlike the polyphosphates *(12)* formed from them by hydrolysis. Furthermore, nucleophilic attack on the tertiary PO_4 tetrahedra is favored in comparison with that on the negatively charged PO_4 tetrahedra. The same is true of the free polyphosphoric acids *(13b)* and their esters *(13c)*, in which the P–O–P bonds are again easily cleaved by hydrolysis, more easily in fact than the P–O–R linkages, as is particularly noticeable in the products of the reaction of phosphorus pentoxide (P_4O_{10}) with ether [30c, 75].

D. The Analysis of Condensed Phosphates

The quantitative separation and the accurate quantitative determination of the components of mixtures of condensed polyphosphates is rendered impossible by the ability of the latter to bind cations [76]. The only practicable method is paper chromatography, which was extended to phosphate chemistry by *Ebel* [77] and by *Westman* [78], and which has since been modified [35] for special purposes and quantitative determinations, aided also by the use of ^{32}P [26, 8a, 46f, 46g]. The migrating components have been found to be free acids or acidic anions [79]. Thin-layer chromatography [80] and (for high-molecular phosphates) paper electrophoresis [81] can also be used. Polyvalent cations, however, must first be replaced by alkali metal ions with the aid of ion exchangers if unambiguous results are to be obtained [82]. Quantitative separations, even for preparative purposes, have also been achieved on anion-exchange columns (*e.g.* Dowex IX 10) by eluting with solutions of alkali metal salts [45, 46a, 46b, 83].

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Translated by Express Translation Service, London

[70] *W. Wieker*, Z. anorg. allg. Chem. *313*, 309 (1961).

[71] *E. Thilo* and *A. Sonntag*, Z. anorg. allg. Chem. *291*, 186 (1957); *A. Winkler, H. Hofsäss*, and *E. Thilo, ibid. 306*, 317 (1906).

[72] *K.-H. Jost*, Makromolekulare Chem. *55*, 203 (1962).

[73] *A. L. Huhti* and *P. A. Gartaganis*, Canad. J. Chem. *34*, 785 (1956); *E. Thilo* and *R. Sauer*, J. prakt. Chem. [4] *4*, 324 (1957).

[74] *R. Pfanstiel* and *R. K. Iler*, J. Amer. chem. Soc. *74*, 6059 (1952); *U. P. Strauss et al., ibid. 75*, 3935 (1953); *77*, 1473 (1955); *78*, 3553 (1956); *E. J. Griffith* and *C. F. Callis, ibid. 81*, 833 (1955).

[75] *R. Rätz* and *E. Thilo*, Liebigs Ann. Chem. *572*, 173 (1951); *E. Thilo* and *H. Woggon*, Z. anorg. allg. Chem. *277*, 17 (1954).

[76] *H. Grunze*, Chem. Techn. *9*, 466 (1957).

[77] *J. P. Ebel* and *Y. Volmar*, C. R. hebd. Séances Acad. Sci. *233*, 415 (1951); *J. P. Ebel, ibid. 234*, 621 (1952); Bull Soc. chim. France *20*, 991 (1953).

[78] *A. E. R. Westman* and *A. E. Scott*, Nature (London) *168*, 740 (1951); *A. E. R. Westman, A. E. Scott*, and *J. T. Pedley*, Chem. in Canada *4*, 35 (1952).

[79] *E. Thilo* and *W. Feldmann*, Z. anorg. allg. Chem. *298*, 316 (1959).

[80] *T. Rössel*, Z. analyt. Chem. *196*, 6 (1963); *197*, 333 (1963); *M. Baudler* and *M. Mengel, ibid. 206*, 8 (1964); *M. Baudler* and *F. Stahlmann*, Naturwissenschaften *51*, 57 (1964).

[81] *B. Sansoni* and *L. Baumgartner*, Z. analyt. Chem. *158*, 241 (1957).

[82] *E. Thilo, H. Grunze, G. Hämmerling*, and *G. Werz*, Z. Naturforsch. *11b*, 266 (1956).

[83] *M. Matsuhashi*, J. Biochemistry (Tokyo) *44*, 65 (1957); *H. L. Rothbart, H. W. Weymouth*, and *W. Riemann III*, Talanta *11*, 33 (1964).

[84] *L. Pauling*, J. Amer. chem. Soc. *51*, 1010 (1929).

Pyrolysis of Sodium and Silicon Pentafluorobenzoates [1]

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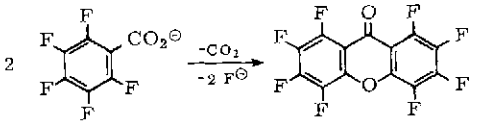
Pyrolysis of sodium pentafluorobenzoate at 275 °C leads to removal of CO_2 and formation of a pale brown powder, from which white needles of composition $C_{13}F_8O_2$ *(1)* with m.p. 250 °C can be isolated in a yield of 35 % by sublimation at 110 °C/10^{-3} mm and recrystallization of the sublimate from benzene. The substance has infrared absorption bands at 1670 ($\nu_{C=O}$), 1645, 1620, 1510, and 1480 cm^{-1} (fluorinated aromatic ring).

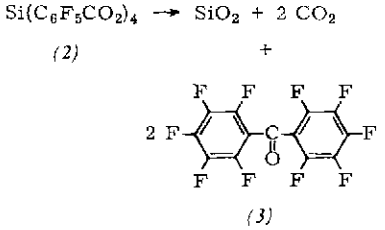


(1)

Its chemical behavior and mass spectrum [2] (molecular ion at m/e = 339.97380 and fragments at m/e = 320.97982, 311.98376, and 292.98926) indicate the structure of an octafluoroxanthone. Compound *(1)* behaves chemically to a large extent analogously to xanthone. In conc. sulfuric acid it affords a yellow solution with a green fluorescence, showing ultraviolet and visible absorption bands at 2630, 3420, and 4200 Å. The positions and structures of these bands correspond to those for xanthone. Dilution with water regenerates compound *(1)* unchanged from its solution in conc. H_2SO_4 or 70 % $HClO_4$. The basicity of the carbonyl group characteristic of 4-pyrones is shown by the ready formation, in anhydrous benzene, of an intensely yellow adduct with $AlBr_3$ that crystallizes from the solution as $C_{13}F_8O_2 \cdot AlBr_3 \cdot C_6H_6$.

Silicon tetrakis(pentafluorobenzoate) *(2)*, m.p. 200 °C, $\nu_{C=O}$ = 1755 cm^{-1}, can be obtained in almost quantitative yield by reaction of silicon tetrachloride with pentafluorobenzoate in boiling anhydrous benzene for 24 hours. It is purified by recrystallization from anhydrous benzene.

When heated at 290 °C it decomposes slowly to yield decafluorobenzophenone *(3)*, $C_{13}F_{10}O$, m.p. 94 °C, $\nu_{C=O}$ = 1720



(2) *(3)*

cm^{-1} with further bands at 1650, 1535, and 1510 cm^{-1} (fluorinated aromatic ring). The yield of pure *(3)* amounts to 80 %. Hitherto this compound was accessible only in poor yield, by chromic acid oxidation of bis(pentafluorophenyl)-methanol [3].

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[1] 2nd communication on Reactions of Metal Halides with Perfluoromonocarboxylic acids. – Part 1: *P. Sartori* and *M. Weidenbruch*, Angew. Chem. *76*, 376 (1964); Angew. Chem. internat. Edit. *3*, 376 (1964).

[2] We thank Dr. *Jonas*, Dr. *Meise*, and Dr. *Waltz* of Farbenfabriken Bayer for determination of the mass spectra.

[3] *J. C. Tatlow*, Brit. Pat. 923 115 (1963); Chem. Abstr. *59*, 9902 g (1963).

Benzylation of Olefins

By Prof. Dr. D. Klamann, Dr. P. Weyerstahl, and Dr. M. Fligge

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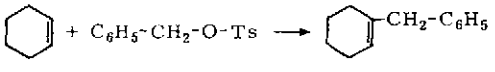
Benzyl *p*-toluenesulfonate can decompose spontaneously and exothermally into *p*-toluenesulfonic acid and resins having the composition $(C_7H_6)_n$ [1]. We were interested in the mode of reaction of compounds of the type $R-CH_2X$ (R = aryl or a heterocyclic group; X = RSO_3– or halogen) in presence of an excess of olefin.

Benzyl *p*-toluenesulfonate (0.2 mole) was refluxed for 8 h with 300 ml of cyclohexane and a catalytic amount of acid, or the mixture was heated without acid in a bomb tube at 120 °C for 3 h; reaction occurred with discoloration and separation of *p*-toluenesulfonic acid. The liquid was decanted from the acid and shaken with sodium hydrogen carbonate solution, the excess of cyclohexane was distilled off in a vacuum, and the residue chromatographed on aluminum oxide (neutral, activity II) in pentane. The eluate was distilled. The main fraction, distilling between 48 and 60 °C at 0.2 mm, consisted of 1-cyclohexylcyclohexene (formed by acid-catalysed dimerization of cyclohexene) together with a 67 % yield of an approximately 8:1 mixture of 1-benzylcyclohexene *(1)* and 3-benzylcyclohexene. Three further products formed in much smaller amounts were not identified.



(1)

A similar mixture was obtained on fission of *endo-exo*-7-phenylnorcarane by *p*-toluenesulfonic acid in cyclohexene at 120 °C.

This benzylation of olefins, which has not previously been observed, can also be carried out with isobutene, 2-methyl-1-pentene, and 2-ethyl-1-hexene. It has not so far been possible to separate the mixtures of isomeric benzylated products.

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German version: Angew. Chem. 77, 1137 (1965)

[1] *F. Drahowzal* and *D. Klamann*, Mh. Chem. *82*, 468 (1951), who cite further references.

Partial Synthesis of Some Cocarcinogens from Croton Oil

By Prof. Dr. E. Hecker, Dr. H. Kuhinyi, Dipl.-Chem. H. U. Schairer, Dipl.-Chem. Ch. v. Szczepanski, and Dr. H. Bresch

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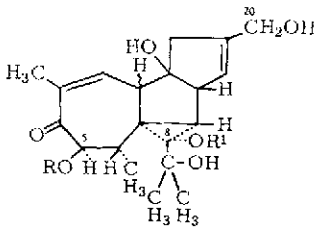
Dedicated to Professor Richard Kuhn on the occasion of his 65th birthday

The eight compounds A1 and B1 to B7 that have been obtained pure from croton oil are toxic, inflammatory, and highly active cocarcinogens; they are fatty acid diesters of the polyfunctional diterpene phorbol for which the structure *(1)* is proposed [1]. Of the three esterifiable hydroxy groups of phorbol, the primary one on C-20 is free in the isolated compounds; the secondary one on C-5 and the tertiary one

on C-8 carry, respectively, a short- and a long-chain fatty acid residue [1]. Thus two series of isomers are possible.



(1), R = R^1 = H

(2), R = H, R^1 = Acetyl; *O*-acetylated at C-20

(3), R = Decanoyl, R^1 = acetyl

(4), R = Lauroyl, R^1 = acetyl

(5), R = Myristoyl, R^1 = acetyl

(6), R = Acetyl, R^1 = H

(7), R = Acetyl, R^1 = decanoyl

(8), R = Acetyl, R^1 = lauroyl

(9), R = Acetyl, R^1 = myristoyl

	Rf [a]	$[\alpha]_D$	νCO [cm⁻¹]	NPAB M.p. [°C]	I.U. [c] [μg/ear]
(3)	0.30	60°	1710	88–89 [b]	0.1
(7)	0.37	47°	1738; 1706	147–149	0.3
(4)	0.32	53°	1710	85–87 [b]	0.2
(8)	0.40	48°	1738; 1704	147–149	0.2
(5)	0.33	47°	1710	85–87	0.1
(9)	0.41	44°	1738; 1704	146–148	0.1

[a] From silica gel HF_{254} (Merck, Darmstadt). Solvent CH_2Cl_2/acetone (3:1), saturated atmosphere.

[b] Light red modification.

[c] Inflammation unit (see ref. [2]).

For the synthesis of 8-*O*-acetyl-5-*O*-acylphorbols, phorbol was converted by partial acetylation with acetic anhydride into phorbol 8,20-diacetate *(2)*, m.p. 181–182 °C, $[\alpha]_D^{26}$ = +78° (0.5 % in dioxane), γmax = 203, 233, 335 mμ, ε_{max} = 12000, 5200, 70 (in ethanol). With long-chain acyl chlorides this diacetate gave the 5,8,20-triesters. Liberation of the primary hydroxyl group by acid-catalysed partial transesterification led to 8-*O*-acetylphorbol 5-decanoate *(3)*, 5-laurate *(4)*, and 5-myristate *(5)*. These compounds, which were homogeneous on thin-layer chromatography, are colorless, non-crystallizing resins whose Rf values and ultraviolet, infrared, and NMR spectra could not be differentiated; they were characterized as their crystalline 4-(4-nitrophenylazo)benzoates (NPAB).

For preparation of 5-*O*-acetyl-8-*O*-acylphorbols, phorbol triacetate was converted by base-catalysed partial transesterification into resinous 5-*O*-acetylphorbol *(6)*, $[\alpha]_D^{25}$ = +128° (*ca.* 2.5 % in dioxane), γ_{max} = 231 and 333 mλ, ε_{max} = 5000 and 70 (CH_3OH). With long-chain acyl chlorides *(6)* gives triesters from which the primary hydroxy group can be liberated by acid-catalysed partial transesterification. 5-*O*-Acetylphorbol 8-decanoate *(7)*, 8-laurate *(8)*, and 8-myristate *(9)* were homogeneous on thin-layer chromatography, forming colorless, non-crystallizing resins whose Rf and $[\alpha]_D$ values as well as ultraviolet, infrared, and NMR spectra could not be differentiated; the same applies to the melting points of their NPAB esters, which gave no mixed m.p. depression.

Three of the synthetic phorbol esters are identical with active components of croton oil: B4 [3] is identical with 5-*O*-acetylphorbol 8-decanoate *(7)*, B7 [3] with 5-*O*-acetylphorbol 8-laurate *(8)*, and A1 [4] with 8-*O*-acetylphorbol 5-myristate *(5)*. Representatives of both series are thus present in croton oil and biologically active.

The partial synthesis of *(5)* has been described earlier [5] and meanwhile confirmed [6].

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Publication deferred until now at the authors' request

[1] *E. Hecker, H. Kubinyi, Ch. v. Szczepanski, E. Härle*, and *H. Bresch*, Tetrahedron Letters *1965*, 1837, and literature cited there.

[2] *E. Hecker*, Z. Krebsforsch. *65*, 325 (1963).

[3] *E. Clarke* and *E. Hecker*, Naturwissenschaften *52*, 446 (1965); Z. Krebsforsch. *67*, 192 (1965).

[4] *E. Hecker, H. Bresch*, and *Ch. v. Szczepanski*, Angew. Chem. *76*, 225 (1964); Angew. Chem. internat. Edit. *3*, 227 (1964); *E. Hecker* and *H. Bresch*, Z. Naturforsch. *20b*, 216 (1965).

[5] *H. Kubinyi*, Dissertation, Universität München, 1964.

[6] *E. R. Arroyo* and *J. Holcomb*, Chem. and Ind. *1965*, 355; *M. Helpern* and *B. L. van Duuren*, Chem. and Ind. *1965*, 943.

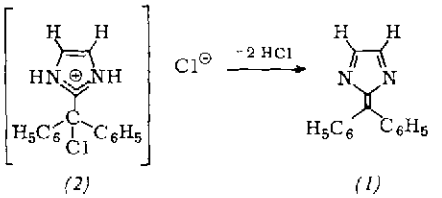
Synthesis of a 1,4-Diazafulvene

By Dr. W. Rohr and Prof. Dr. H. A. Staab

Institut für Organische Chemie
der Universität Heidelberg (Germany)

The dependence of the "aromatic" character of fulvenes on the electron-donating properties of substituents at C-6 of the fulvene system has been intensively studied [1]. However, little is yet known about how a change in the charge distribution in the five-membered ring affects the bonding system of fulvenes. Azafulvenes are of particlar interest in this respect.

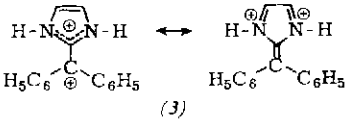
We have prepared 6,6-diphenyl-1,4-diazafulvene *(1)* [2], the first representative in the diazafulvene series, by elimination of HCl from 2-(chlorodiphenylmethyl)imidazolium chloride *(2)* with triethylamine in tetrahydrofuran (65–70 % yield); the product *(1)* is isolated by filtering off the triethylammonium chloride and evaporating the solvent and is recrystallized from tetrahydrofuran. Compound *(2)* was obtained by the action of thionyl chloride on 2-(hydroxydiphenylmethyl)imidazole (m.p. 189–190 °C, prepared from 2-benzoylimidazole and phenylmagnesium bromide in 75–80 % yield).



(2) *(1)*

The product *(1)* forms yellow crystals, m.p. 150–152 °C (decomp.). Its molecular weight was determined mass-spectrometrically as 232. Its NMR spectrum in $CDCl_3$ (tetramethylsilane as internal standard) shows the two five-membered-ring protons as a sharp singlet of intensity 2 at τ = 1.72 and the protons of the two phenyl residues as a multiplet of intensity 10 at τ = 2.52.

The most intense ultraviolet band for *(1)* (λ_{max} = 361 mμ, ε = 18700, in cyclohexane) is at distinctly longer wavelengths than is the corresponding absorption of 6,6-diphenylfulvene [3]. This band is shifted hypsochromically in acetonitrile with a slight decrease in intensity (λ_{max} = 356 mμ, ε = 17400). A second absorption maximum is observed at 241 mμ (ε = 9000, in cyclohexane). In conc. H_2SO_4 compound *(1)* gives the same spectrum as 2-(hydroxydiphenylmethyl)imidazole in the same solvent (λ_{max} = 438 mμ, ε = 36300). We assume that the mesomeric dication *(3)* is present in these solutions.



(3)

With sodium borohydride in tetrahydrofuran/ethanol (5:1), the product *(1)* gives a 75% yield of a compound, m.p. 233 °C, that is identical with the recently prepared 2-(diphenylmethyl)imidazole[4]. When product *(1)* is boiled for 2 h in tetrahydrofuran/water (2:1) it affords 2-(hydroxydiphenylmethyl)imidazole in 72% yield. Addition of the calculated amount of ethereal hydrogen chloride to a solution of product *(1)* in tetrahydrofuran regenerates the starting material *(2)* almost quantitatively.

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[1] Cf., for example, *K. Hafner, K. H. Häfner, C. König, M. Kreuder, G. Ploss, G. Schulz, E. Sturm,* and *K. H. Vöpel,* Angew. Chem. *75*, 35 (1963); Angew. Chem. internat. Edit. *2*, 123 (1963), where further references are given.

[2] In numbering the fulvene system we follow the proposal of Chemical Abstracts.

[3] *E. D. Bergmann* and *Y. Hirshberg,* Bull. Soc. chim. France *17*, 1091 (1950).

[4] *H. A. Staab* and *K. Wendel,* Liebigs Ann. Chem., in the press.

Synthesis of 1,2,3-Triazolo[1,5-a]quinoxalinium and 1,2,3-Triazolo[5,1-c]-benzo-1,2,4-triazinium Salts [1]

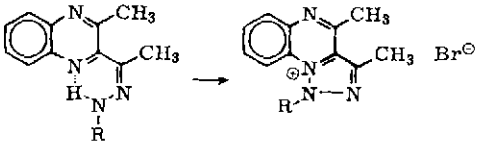
By Dr. A. Messmer and Dipl.-Chem. O. Szimán

Central Research Institute for Chemistry of the Hungarian Academy of Sciences, Budapest (Hungary)

By a generalization of the method of preparation of pyridine-condensed triazolium[2] and tetrazolium[3] salts, 2-acetyl-3-methylquinoxaline phenylhydrazone *(1a)*[4] is converted by four moles of *N*-bromosuccinimide in glacial acetic acid at room temperature into 3,4-dimethyl-1-phenyl-1,2,3-triazolo[1,5-*a*]quinoxalinium bromide *(2a)*. A 1:1 complex, m.p. = 128 °C, of *(2a)* and *N*-bromosuccinimide is first precipitated from the solution. The compound *(2a)* is isolated from this complex by precipitation from nitromethane with diethyl ether.

The analogue *(2b)* is obtained similarly from the *p*-methoxyphenylhydrazone (m.p. = 186 °C).

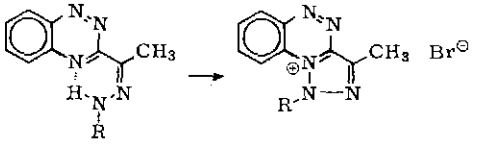
Compounds *(2)* are water-soluble and give 90–95% yields of tetrafluoroborates and perchlorates that crystallize well. The structure of compounds *(2)* corresponds with their elemental analyses and infrared spectra (no NH bands). Sodium dithionite in alkaline solution regenerates the hydrazones *(1)* from the compounds *(2)* in 70% yield.



(1) *(2)*

R	M.p. [°C]	Yield [%]	$BF_4^{\ominus}$-salt m.p. [°C]	$ClO_4^{\ominus}$-salt m.p. [°C]
(2a), C_6H_5	171	60	213	214
(2b), p-CH_3O—C_6H_4	163	92	206	212

Further, the phenylhydrazone *(3a)* and the *p*-methoxyphenylhydrazone *(3b)*, m.p. = 151 °C, of 3-acetylbenzo-1,2,4-triazine[5] are cyclodehydrogenated to 3-methyl-1-phenyl-1,2,3-triazolo[5,1-*c*]benzo-1,2,4-triazinium bromide *(4a)* and the 1-(*p*-methoxyphenyl) derivative *(4b)*, respectively, by *N*-bromosuccinimide under the above-mentioned conditions. The product *(4a)* is precipitated as tribromide, which is converted into the monobromide by boiling ethanol/ether (1:1). Both products *(4)* form tetrafluoroborates and perchlorates that crystallize well.



(3) *(4)*

R	M.p. [°C]	Yield [%]	$BF_4^{\ominus}$-salt m.p. [°C]	$ClO_4^{\ominus}$-salt m.p. [°C]
(4a), C_6H_5	183	30	212	217
(4b), p-CH_3O—C_6H_4	165	52	211	215

Received: September 28th, 1965 [Z 71/894 IE]
German version: Angew. Chem. 77, 1077 (1965)

[1] Part 2 of New Heteroaromatic Azolium Salts. – Part 1: [3].

[2] *R. Kuhn* and *W. Münzing,* Chem. Ber. *86*, 858 (1953).

[3] *A. Messmer* u. *A. Gelléri,* Angew. Chem. *77*, 171 (1965); Angew. Chem. internat. Edit. *4*, 154 (1965).

[4] *F. Sachs* u. *A. Röhmer,* Ber. dtsch. chem. Ges. *35*, 3307 (1902).

[5] *E. Bamberger* and *J. Lorenzen,* Ber. dtsch. chem. Ges. *25*, 3539 (1892).

Synthesis and Properties of Allyl Hydroperoxide

By Dr. H. E. Seyfarth, J. Henkel (deceased), and Prof. Dr. A. Rieche

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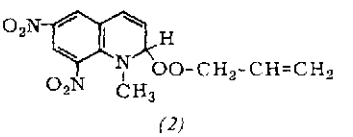
Allyl hydroperoxide *(1)* has been synthesized in preparative quantities by peroxygenation of allylzinc chloride. Very small amounts were previously obtained from allyl methanesulfonate and H_2O_2 by *S. Dykstra* and *H. S. Mosher*[1] who described the substance as very sensitive (synthesis under red light).

Allylzinc chloride is accessible from allylmagnesium chloride and zinc chloride in ether at 25 °C (molar ratio 1:1, 2 hours' stirring under argon). Its 0.3 M solution is saturated with oxygen at −75 °C. Hydrolysis[2] with 2 N HCl liberates the hydroperoxide *(1)* (crude yield 50%) which is found in the ether phase. Extraction with 2 N NaOH and removal of the ether by distillation leads to a liquid product of 98% purity (determined by iodimetric titration).

$$CH_2{=}CH{-}CH_2{-}MgCl \xrightarrow{ZnCl_2} CH_2{=}CH{-}CH_2{-}ZnCl$$

$$\xrightarrow{O_2} CH_2{=}CH{-}CH_2{-}OOZnCl \xrightarrow{H_2O} CH_2{=}CH{-}CH_2{-}OOH \quad (1)$$

Reduction of the product *(1)* with Na_2SO_3 gives allyl alcohol quantitatively. Treatment with 2-ethoxy-1,2-dihydro-1-methyl-6,8-dinitroquinoline, a specific precipitant for hydroperoxides[3], affords 2-allylperoxy-1,2-dihydro-1-methyl-6,8-dinitroquinoline *(2)* as yellow needles, m.p. 101.5–103 °C.



(2)

The hydroperoxide *(1)* is stable below 0 °C but can also be kept for considerable periods at room temperature and is not decomposed to a notable extent in 2 N KOH or 2 N

H_2SO_4 at 0 °C. Heating a drop in a test tube over a free flame leads to detonation; sensitivity to shock is notable only after admixture of a few grains of sand. Addition of bromine affords 2,3-dibromopropyl hydroperoxide (solvent: ether; Br_2 added dropwise at 15 °C). The isomer, 2-bromo-1-bromomethylethyl hydroperoxide, was recently[4] obtained by simultaneous action of oxygen and bromine on allyl bromide. Addition of chlorine to compound *(1)* is also possible.

The hydroperoxide *(1)* is perhaps an intermediate product of the oxygenation of propene to acrolein[5] or glycerol[6]. In accord with this suggestion acrolein can be detected on thermal decomposition of compound *(1)*.

Received: October 1st, 1965 [Z 73/898 IE]
German version: Angew. Chem. 77, 1078 (1965)

[1] *S. Dykstra* and *H. S. Mosher*, J. Amer. chem. Soc. *79*, 3474 (1957).

[2] Hydrolysis of the ethereal solution of $CH_2=CH-CH_2-OOZnCl$ was carried out, in analogy with directions by *H. Hock* and *F. Ernst*, Chem. Ber. *92*, 2716 (1959), by addition of 2 N HCl at −40 °C. In one of several experiments an ether explosion resulted, whose cause may have been acid decomposition of crystalline organozinc peroxy compounds that separated.

[3] *A. Rieche, E. Schmitz*, and *P. Dietrich*, Chem. Ber. *92*, 2239 (1959).

[4] *A. Rieche, M. Schulz*, and *K. Kirschke*, Angew. Chem. *77*, 219 (1965); Angew. Chem. internat. Edit. *4*, 244 (1965).

[5] *J. D. Mullen* and *G. Skirrow*, Proc. Roy. Soc. (London), Ser. A *244*, 312 (1958).

[6] *G. Nettesheim*, German Pat. 1158951; Chem. Abstr. *60*, 6747a (1964).

Synthesis of Pteridine N-Oxides [1]

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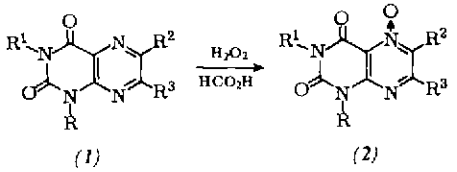
der Technischen Hochschule Stuttgart (Germany)

Pteridine *N*-oxides have so far been obtained only by cyclization of 4-amino-5-nitrosopyrimidines with phenacyl- or acetonyl-pyridinium salts[2]. The product obtained by *G. B. Brown et al.*[3] is probably a 1-hydroxy-6,7-dimethyl-lumazine (analogous to 3-hydroxy-4-pteridinone[4]) rather than a pteridine oxide.

We have found that pteridines can be converted into *N*-oxides by direct oxidation with 30 % H_2O_2 in concentrated formic acid at room temperature. In this way lumazine *(1a)* and its *N*- and *C*-methyl derivatives *(1b)–(1f)* give lumazine 5-oxides *(2a)–(2f)*, which separate either at once or on concentration of the reaction mixture. Yields are between 20 and 70 %.



(1) *(2)*

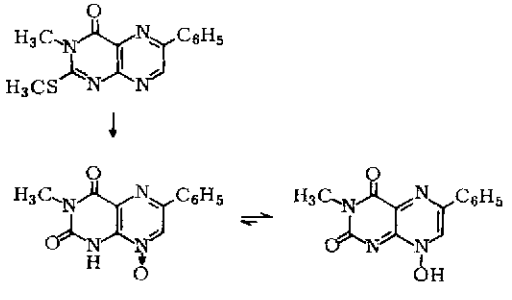
	R	R¹	R²	R³		R	R¹	R²	R³
a)	H	H	H	H	*(f)*	CH_3	CH_3	CH_3	CH_3
b)	CH_3	H	H	H	*(g)*	CH_3	H	C_6H_5	C_6H_5
c)	H	H	CH_3	CH_3	*(h)*	CH_3	CH_3	C_6H_5	H
d)	CH_3	H	CH_3	CH_3	*(i)*	CH_3	CH_3	H	C_6H_5
e)	H	CH_3	CH_3	CH_3					

The structure of the product *(2a)* was proved by rearrangement (refluxing with acetic anhydride for 10 h) to 2,4,6-pteridinetrione. Reduction of *(2a)* by Pt/H_2 gave 5,6,7,8-tetrahydrolumazine which was isolated and characterized as its 5-acetyl derivative. The *N*-oxides are stable to acid hydrolysis (1 N H_2SO_4). Alkaline hydrolysis (1 N NaOH) of *(2d)* and *(2f)* occurs with opening of the pyrimidine ring and affords 5,6-dimethyl-3-methylamino-2-pyrazinecarboxylic acid 1-oxide and 3-methylamino-5,6-dimethyl-2-methylcarbamoyl-pyrazine 1-oxide, respectively. For further characterization the pK_a values and ultraviolet spectra of the *N*-oxides were determined (see Table).

	pK_a (H_2O)	λ_{max} [mμ] [a]				log ε_{max}				pH [b]	Species present [c]	Yield [%]
(2a)	5.34	234	244	270	345	4.26	4.27	3.73	3.84	2.0	N	23
		245	266	(285)	387	4.10	4.23	(3.95)	3.86	8.0	⊖	
(2b)	7.98	239		281	344	4.30		3.77	3.71	6.0	N	40
		245		283	348	4.33		3.89	3.77	11.0	⊖	
(2c)	6.02	239		(276)	342	4.37		(3.67)	3.86	3.0	N	18
		240	267	(285)	380	4.13	4.14	(4.11)	3.89	9.0	⊖	
(2d)	8.51	238		287	349	4.40		3.71	3.84	6.0	N	68
		244		289	353	4.38		3.83	3.88	11.0	⊖	
(2e)	6.15	238		(281)	343	4.44		(3.96)	3.88	3.0	N	28
		(239)	266		382	(4.18)	4.33		3.90	9.0	⊖	
(2f)	−2.67	241		287	351	4.45		3.87	3.83	7.0	N	58
		247			353	4.22			3.86	−4.9	⊕	

[a] In water; values in parentheses denote shoulders. *(2f)*: in 65 % H_2SO_4.
[b] pH at which the spectra were determined.
[c] Species present at the pH given in the preceding column.
N = Neutral molecule; ⊖ = monoanion; ⊕ = monocation.

Steric factors have a strong influence on the formation of *N*-oxides. While 1-methyl-6,7-diphenyl- *(1g)* and 1,3-dimethyl-6-phenyl-lumazine *(1h)* could not be oxidized, 1,3-dimethyl-7-phenyl-lumazine affords the 5-oxide *(2i)* in 65 % yield. In accord with these findings we formulate the oxidation product of 3-methyl-2-methylthio-6-phenyl-4(3*H*)-pteridone as the 8-oxide *(3)* or its tautomer, the 8-hydroxy-derivative *(4)*.



(3) *(4)*

Received: October 4th, 1965 [Z 88/920 IE]
German version: Angew. Chem. 77, 1136 (1965)

[1] Reported at the 3rd Australian Symposium on Heterocyclic Chemistry, August 11th, 1965 in Melbourne (Australia).

[2] *I. J. Pachter, P. E. Nemeth*, and *A. J. Villani*, J. org. Chemistry *28*, 1197 (1963).

[3] *R. M. Cresswell, H. K. Maurer, T. Strauss*, and *G. B. Brown*, J. org. Chemistry *30*, 408 (1965).

[4] *W. B. Wright* and *J. M. Smith*, J. Amer. chem. Soc. *77*, 3927 (1955).

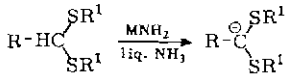
Carbanions of 1,3-Dithianes. Reagents for C–C Bond Formation by Nucleophilic Displacement and Carbonyl Addition

By Prof. Dr. E. J. Corey and Dr. D. Seebach

Department of Chemistry, Harvard University,
Cambridge, Massachusetts (U.S.A.)

The temporary modification of a carbonyl group so that the carbon atom behaves as a nucleophile in displacement and addition reactions would be of great utility in organic

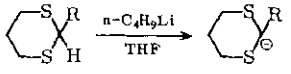
synthesis. A simple way of accomplishing this objective is suggested by the work of *Arens et al.*[1a] which established that mercaptals of type *(1)* can be converted into carbanions *(2)* using alkali metal amides in liquid ammonia. However, these anions are not of general synthetic applicability. For example, the anion *(2)*, R = CH_3, can only be alkylated using an excess of primary halide (30–70 % yield) and does not add onto ketones.



(1) *(2)*

R = H, CH_3, C_6H_5
R^1 = C_2H_5, C_6H_5

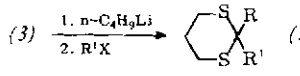
Carbanions of type *(4)* can be generated from dithianes *(3)*[1b,2] by the action of n-butyl-lithium (1 equiv.). As reagents they are superior to the carbanions *(2)*, because of ease of preparation, relative stability, and excellent reactivity especially in those cases where the carbanion carries an alkyl or other electron-repelling-substituent.



(3) *(4)*

A variety of carbanions *(4)* have been generated including R = prim., sec., and tert. alkyl, allyl, benzyl, aryl, and oxygen-containing groups such as $-CH_2CH(OC_2H_5)_2$ and $C_6H_5-CH(O^{\ominus})-$.

The anion *(4)*, R=H, undergoes alkylation in excellent yields (70–90 % of purified product) with a wide variety of alkyl halides (highest yields with iodides). The efficiency of introduction of a second alkyl group is also good, as can be seen in Table 1. Starting from *(3)*, R=H, by two successive



(5)

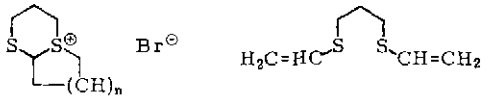
Table 1.

R	R'X	Yield of *(5)* [%]	B.p. (bath temp.) [°C/mm]
CH_3	i-C_3H_7I	84	60/0.3
CH_3	$C_6H_5CH_2Br$	90	113/0.08
CH_3	$ClCH_2CON(C_2H_5)_2$	50	undist. oil
t-C_4H_9	i-C_3H_7I	45	
n-C_5H_{11}	n-$C_5H_{11}Br$	82	100/0.05
n-C_5H_{11}	i-C_3H_7Br	85	84/0.03
n-C_5H_{11}	geranyl-Br	80	undist. oil
C_6H_5	i-C_3H_7Br	90	m.p. 50.5–51.5 °C
H	$(C_2H_5O)_2CHCH_2Br$	77	115/0.3

additions of butyl-lithium and alkyl halide, two alkylations can be performed in a single reaction mixture without isolation of intermediates to give 2,2-dialkyldithianes in good yields, *e.g.* 70 % yield for *(5)*, R=R'=i-C_3H_7, using *(3)*, R=H, and isopropyl iodide.

Although the alkylation reaction fails with some halides, *e.g.* cyclohexyl iodide, due to competing elimination, the tendency for elimination is surprisingly low with other halides, *e.g.* $(C_2H_5O)_2CHCH_2Br$, which normally lead to much elimination with carbanionic reagents.

One or two bromide ions may be displaced from 1,3-dibromopropane or 1,4-dibromobutane by the carbanion *(4)*, R=H, depending on the relative amounts used; with equivalent amounts the sulfonium bromides *(6)* are obtained and, interestingly, *(6a)* undergoes internal elimination with base to form *(7)* cleanly[3].



(6a), n = 1
(6b), n = 2

(7)

The carbanions *(4)* also react readily with 1,2-oxides to form mercaptals of β-hydroxy ketones or -aldehydes, *e.g.* *(8)*, from styrene oxide and *(4)*, R=CH_3, (70 % yield). Compound *(8)* is an undistillable oil which yields benzylideneacetone on hydrolysis and dehydration.

(8) *(9)*

(10) *(11)*

Ketones and aldehydes combine with anions of type *(4)* generally and in good yields to give mercaptals *(9)* of α-hydroxy aldehydes and -ketones (Table 2). The products of

Table 2.

(4), R =	Aldehyde or ketone	Yield of *(9)* [%] [a]	B.p. (bath temp.) [°C/mm] (m.p. [°C])
H	propionaldehyde	80	–
H	benzaldehyde	91	(70.5–71.6)
H	cyclopentanone	70	113/0.02
H	cyclohexanone	85	145/0.2
H	benzophenone	80	(136–136.5)
CH_3	cyclohexanone	80	165/1.2
CH_3	benzophenone	83	(136–137.5)
n-C_5H_{11}	benzophenone	78	(94–95.5)
i-C_3H_7	benzophenone	52	(144–145.2)

[a] The yields given are generally those obtained in the first experiment and are not necessarily optimal.

addition of *(4)*, R=H, to ketones can be dehydrated either by treatment with *p*-toluenesulfonic acid in benzene or by sequential reaction with thionyl chloride and potassium t-butoxide to give ketene mercaptals *(10)*.

Imines are also susceptible to addition as shown by the formation of *(11)*, m.p. 102.5–103.8 °C, from benzylideneaniline and *(4)*, R=CH_3, in 70 % yield.

The conversion of dithianes to carbonyl compounds can be accomplished by a variety of procedures[4].

On reaction of the anions *(4)* with oxygen and subsequent hydrolysis carboxylic acids R–CO_2H are formed[5].

Preparation of the carbanions (4) from 1,3-dithianes:

A 0.2–0.5 M solution of the dithiane at −30 °C under nitrogen is stirred and treated with one equivalent of 1.5 M n-butyl-lithium in hexane at the rate of 3–5 ml/min. The mixture is stirred at −30 to −20 °C for 1.5 h for *(3)*, R=H, CH_3, C_2H_5, i-C_3H_7, n-C_5H_{11}, C_6H_5, or 8 h for *(3)* R=t-C_4H_9. The clear, colorless solutions thus obtained can be stored at −20 °C under N_2 for at least three weeks. The content of anion *(4)* can be checked by treatment with deuterium oxide followed by NMR analysis of the isolated [2-D]-dithiane.

2,2-Diisopropyl-1,3-dithiane by sequential alkylation of 1,3-dithiane:

To a solution containing 30 mmoles of the anion *(4)*, R=H, in tetrahydrofuran at −5 °C were added 5.60 g (33 mmoles) of isopropyl iodide, and the mixture was maintained at 0 °C for 14 h under nitrogen. The resulting solution of 2-isopropyl-1,3-dithiane was treated at −30 °C with 35 mmoles of n-butyl-lithium in hexane and after 1.5 h 5.85 g (35 mmoles) of isopropyl iodide were added. After a reaction period of 70 h at 0 °C under nitrogen the reaction mixture was poured into three times its volume of water, acidified to pH 5–6 and extracted with five portions (30 ml each) of pentane. After washing successively with 3 % aqueous sodium bisulfite, 5 % aqueous KOH, and water the extract was dried (K_2CO_3) and concentrated to give 5.82 g (95 %) of a nearly colorless oil which contained 15 % of 2-isopropyl-1,3-dithane and 85 % of 2,2-diisopropyl-1,3-dithiane (NMR analysis). Fractionation through a small (5 cm) column gave 4.30 g (70 %) of pure 2,2-diisopropyl-1,3-dithiane *(5)*, R=R'=i-C_3H_7, b.p. 95 °C/0.5 mm, n_D^{25} = 1.5392.

Received: October 5th, 1965 [Z 75/901 IE]
German version: Angew. Chem. *77*, 1134 (1965)

[1a] *J. F. Arens et al.*, Rec. Trav. chim. Pays-Bas *78*, 663 (1959); *81*, 1009 (1962). – See also *S. Oae, W. Tagaki*, and *A. Ohno*, Tetrahedron *20*, 427 (1964); *W. E. Truce* and *F. E. Roberts*, J. org. Chemistry *28*, 961 (1963).

[1b] The open-chain anions *(2)* can be prepared in the same way; when R = alkyl, however, the presence of a tert. amine, *e.g.* triethylenediamine, is necessary. The product of the reaction of *(2)*, R = CH_3, R^1 = C_6H_5, with benzophenone was obtained in this way in 75 % yield, m.p. 153–155 °C.

[2] 1,3-Dithiane *(3)*, R=H, was prepared in excellent yield by slow addition of a mixture of dimethoxymethane and 1,3-propanedithiol in chloroform to a solution of boron fluoride etherate in chloroform at reflux. The other dithianes were made by the general procedure reported for 1,3-dithiolanes by *R. M. Roberts* and *Ch.-Ch. Cheng*, J. org. Chemistry *23*, 963 (1958).

[3] See *F. Weygand* and *H. Daniel*, Chem. Ber. *94*, 3145 (1961), for an analogy.

[4] *J. English, Jr.* and *P. H. Griswold, Jr.*, J. Amer. chem. Soc. *67*, 2039 (1945) and references cited therein; *F. Weygand* and *H. J. Bestmann*, Chem. Ber. *90*, 1230 (1957); *F. Weygand, H. J. Bestmann*, and *H. Ziemann*, *ibid. 91*, 1040 (1958).

[5] *B. W. Erickson*, unpublished experiments in these Laboratories.

Synthesis of 1,n-Dicarbonyl Derivates Using Carbanions from 1,3-Dithianes

By Prof. Dr. E. J. Corey and Dr. D. Seebach

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The preceeding note[1] reports the utility of bisthiocarbanions of type *(1)* as reagents for displacement and addition reactions at electrophilic carbon atoms to form derivatives of aldehydes and ketons. This communication deals with the application of these carbanions to the synthesis of 1,2-, 1,3-, and other dicarbonyl derivatives.

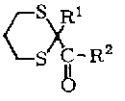
Treatment of the anions *(1)* of 1,3-dithianes[1] with CO_2 at −70 °C affords the mercaptals *(2)* of α-keto carboxylic acids in 70–75 % yield. With a large excess of ethyl chloroformate (instead of CO_2) at −70 °C the ethyl carboxylates *(3)* are obtained [yields: *(3a)* 60 %, *(3b)* 78 %] which can be saponified ($CH_3OH/H_2O/KOH$) to the dithianecarboxylic acids.

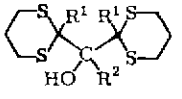
(1)

(2a), R^1 = CH_3, R^2 = CO_2H, m.p. 133–135 °C
(2b), R^1 = t-C_4H_9, R^2 = CO_2H, m.p. 98.5–99 °C
(3a), R^1 = CH_3, R^2 = $CO_2C_2H_5$
(3b), R^1 = $CH_2C_6H_5$, R^2 = $CO_2C_2H_5$
(4), R^1 = CH_3, R^2 = CHO

Reaction of *(1)*, R^1=CH_3, with one equivalent of dimethylformamide or a large excess of ethyl formate at ca. −10 °C leads to the dithioketal *(4)* of α-oxopropionaldehyde (m.p. of the 2,4-dinitrophenylhydrazone of *(4)*: 167.5–168.5 °C). The yield is 50–60 %. *N,N*-Dimethylacetamide, however, does not react with *(1)*, R^1 = CH_3, under similar conditions, and this seems to be true for higher homologues in general.

Monomercaptals *(5)* of 1,2-diketones can be made from anions of type *(1)* and carboxylic acid derivatives. In some cases, but not generally, esters are satisfactory starting materials. Thus, the reaction of *(1)*, R^1=CH_3, (2 equiv.) with ethyl cyclohexanecarboxylate gives *(5a)* in 60 % yield, whereas the reaction with ethyl benzoate under the same conditions leads to the dimercaptal *(6a)*, m.p. 156.5–158 °C, in 95 % yield. The results obtained in a particular case depend on the relative reactivities of the starting ester and the ketone derivative *(5)* and the tendency of this derivative to undergo enolate formation *vs.* addition in further reaction with the anion *(1)*. The synthesis of *(5b)* is not feasible by reaction of *(1)*, R^1=CH_3, with ethyl acetate even when the anion is added slowly to a thirty-fold excess of the ester. The chief product is invariably the 2:1 adduct *(6b)*. However, the 1:1 adduct *(5b)* can be obtained in about 50 % yield by slow addition of the anion *(1)*, R^1=CH_3, to excess acetyl chloride at −70 °C. Presumably the zinc or cadmium salts of *(1)* would be more satisfactory reagents for the synthesis of structures of type *(5)* from acid chlorides and this point is under investigation. The reaction of nitriles with the lithium salts *(1)* produces the monomercaptals *(5)* usually without complication; for example, *(5d)* was readily obtained (80 % yield) from the anion *(1)*, R^1=CH_3, and benzonitrile at low temperatures.



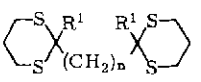


(5a), R^1 = CH_3, R^2 = C_6H_{11}
(5b), R^1 = CH_3, R^2 = CH_3
(5c), R^1 = H, R^2 = CH=CH-C_6H_5
(5d), R^1 = CH_3, R^2 = C_6H_5

(6a), R^1 = CH_3, R^2 = C_6H_5
(6b), R^1 = CH_3, R^2 = CH_3
(6c), R^1 = H, R^2 = CH=CH-C_6H_5

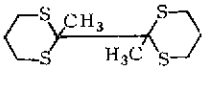
With α,β-unsaturated carbonyl compounds reaction occurs preferentially by 1,2- rather than 1,4-addition. For example, ethyl cinnamate and *(1)*, R^1=H, (in equimolar amounts) afford a mixture of *(5c)* (m.p. 99–100 °C) and a 1:2 adduct *(6c)* (m.p. 176.5–177.5 °C). Alkylation of carbanions *(1)* by ketals of α- and β-halocarbonyl compounds[1] [*e.g.* $XCH_2CH(OR)_2$] represents an approach to 1,3- and 1,4-dicarbonyl structures.

Alkylation reactions furnish another route to derivatives of 1,n-dicarbonyl compounds. The 1,6-diketone derivatives *(7a)* and *(7b)* were prepared from 1,4-dibromobutane in 84 and 89 % yield, respectively, and the 1,5-diketone derivative *(7c)* was obtained from 1,3-dibromopropane (66 % yield).



(7a), R^1 = H, n = 4, m.p. 102.5–103.5 °C
(7b), R^1 = CH_3, n = 4, m.p. 108.5–109 °C
(7c), R^1 = H, n = 3, m.p. 101.5–102 °C

Finally, carbanions of type *(1)* undergo coupling under the influence of oxidizing agents such as 1,2-dibromomethane, Cu(II), or iodine to afford 1,2-dicarbonyl derivatives such as *(8)*, m.p. 184–186 °C.



(8)

2-Methyl-2-benzoyl-1,3-dithiane (5d):

To a cold (−78 °C) solution of 10 mmoles of the lithium derivative *(1)*, $R^1=CH_3$, in tetrahydrofuran[1] was added with stirring 1.06 g (10 mmoles) of benzonitrile. The resulting bright orange mixture was kept at −78 °C for 40 min, after which the bath was removed and stirring was continued for an additional 40 min. The reaction mixture was then poured onto ice and extracted with ether. The extracts were washed with dilute base, dried over Na_2SO_4 and concentrated to give 2.22 g (95 %) of crude imine which was hydrolysed with 150 ml of 4 % hydrochloric acid at 70 °C for 45 min. The product, which partially separated as colorless crystals, was removed by extraction with ether. After washing, drying, and concentration the extract yielded 1.95 g (82 %) of *(5d)*, m.p. 97.8–98.7 °C. After recrystallization from methanol the m.p. is 98.4–98.8 °C.

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German version: Angew. Chem. 77, 1135 (1965)

[1] *E. J. Corey* and *D. Seebach*, Angew. Chem. 77, 1134 (1965); Angew. Chem. internat. Edit. 4, 1075 (1965).

Diazomethylphosphine Oxides

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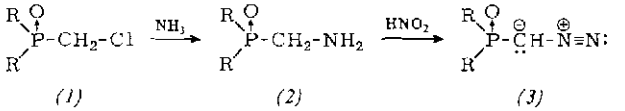
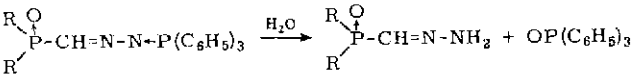
The first preparation of diazomethylphosphine oxides *(3)* has been achieved by the following reactions:



(1) *(2)* *(3)*

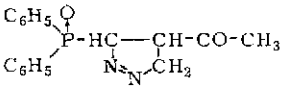
For synthesis of the intermediates *(2)*, methanolic solutions of the chloromethyl compounds *(1)* were saturated with NH_3 at 0 °C and heated for 5 h in an autoclave at 130 °C. The residues were taken up in chloroform and extracted several times with dilute sulfuric acid. The compounds *(2)* were precipitated from the extracts by alkali and recrystallized several times from benzene/ether. Their conversion into *(3)* was effected by adding sodium nitrite to their solutions in glacial acetic acid, with ice-cooling, whereupon the diazomethylphosphine oxides separated. Thus, *P,P*-dibenzyl-*P*-diazomethylphosphine oxide *(3)*, R = C_7H_7, m.p. 99 °C, was formed immediately in 90 % yield from *P*-aminomethyl-*P,P*-dibenzylphosphine oxide *(2)*, R = C_7H_7, m.p. = 112 °C, and 1 mole of sodium nitrite in glacial acetic acid; *P*-diazomethyl-*P,P*-diphenylphosphine oxide *(3)*, R = C_6H_5, m.p. = 56 °C, was obtained analogously in 70 % yield from *P*-aminomethyl-*P,P*-diphenylphosphine oxide *(2)*, R = C_6H_5, m.p. = 101 °C. Both the diazomethyl compounds are very stable and intensely yellow. On addition of hydrochloric acid to their methanol solutions they are converted into the chloromethylphosphine oxides *(1)*, and they react with triphenylphosphine to give phosphazines *(4)* which crystallize from the solution.



(4) *(5)*

These products *(4)* are hydrolysed when heated with 80 % ethanol, affording the phosphinylformaldehyde hydrazones *(5)* which, after removal of the alcohol, are separated by means of chloroform/water from the triphenylphosphine oxides that are formed simultaneously.

Of preparative interest are the addition reactions of the diazomethylphosphine oxides to unsaturated compounds, which lead to phosphine oxides of the pyrazoline series not accessible in other ways. For instance, by warming *P*-diazomethyl-*P,P*-diphenylphosphine oxide *(3)*, R = C_6H_5, with methyl vinyl ketone or dimethyl maleate in dioxane or toluene, removal of the solvent in a vacuum, and recrystallization of the residue from methanol we obtained the pyrazolines *(6)*, m.p. = 169 °C, and *(7)*, m.p. 153 °C, in about 70 % yield.



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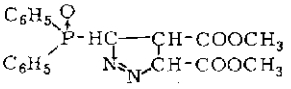

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Synthesis and Properties of 1,4,5,8-Anthradiquinone

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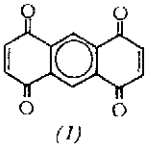
1,4,5,8-Anthradiquinone *(1)*, which is of interest in connection with M.O. calculations of redox potentials of quinones[1] is obtained in good yield by shaking a dioxane solution of 1,4,5,8-anthratetrol with freshly precipated silver oxide and calcium sulfate (as drying agent) for a short time. Small



(1)

amounts of 5,8-dihydroxy-1,4-anthraquinone formed at the same time can be removed chromatographically (chloroform/ethyl acetate, neutral silica gel).

The constitution of the diquinone *(1)* (yellow needles from dioxane/cyclohexane; decomp. at 170 °C) follows from elemental analysis, the ultraviolet spectrum (λ_{max} = 353 mμ; ϵ_{max} = 3750 in dimethylformamide), the NMR spectrum (2 singlets at −7.22 and −8.80 ppm, relative intensity 2:1[2]), and the simple infrared spectrum (strong bands at 1667, 1600, 1271, 1124, and 849 cm^{-1} in KBr). The compound *(1)* has a higher redox potential (+736 mV in 90 % acetic acid containing 3 % of dimethylformamide) than 1,2,5,6-anthradiquinone[3], decomposes in aqueous alkali (in contrast to the 1,2,5,6-diquinone), and reacts readily with nucleophiles. Repeated treatment with aziridine and subsequent dehydrogenation with silver oxide affords 2,7-di- and 2,6,7-tri-aziridino-1,4,5,8-anthradiquinone (proof of structure by elemental analysis and NMR spectroscopy).

On oxidation with *one* equivalent of silver oxide, 1,4,5,8-anthratetrol, which is accessible by alkaline hydrolysis of its acetate[4] with exclusion of air, affords 5,8-dihydroxy-1,4-anthraquinone[5] (colorless leaflets from butanol; decomp. at 300 °C) as main product. By oxidation of 1,4,5-anthratriol (yellow prisms from acetone; decomp. at 230 °C), accessible from its acetate[4], with silver oxide in acetone we obtained 5-hydroxy-1,4-anthraquinone (red needles from chloroform/ethyl acetate; decomp. at 220 °C).

Received: October 11th, 1965 [Z 87/919 IE]
German version: Angew. Chem. 77, 1137 (1965)

[1] *M. G. Evans, J. Gergely*, and *J. de Heer*, Trans. Faraday Soc. *45*, 312 (1949); *S. Weckherlin* and *P. Boldt*, unpublished work.

[2] In deuteriochloroform. Internal standard: tetramethylsilane = 0 ppm.

[3] *P. Boldt*, Naturwissenschaften *51*, 137 (1964).

[4] *H. Brockmann* and *G. Budde*, Chem. Ber. *86*, 432 (1953).

[5] *Y. Lepage*, Bull. Soc. chim. France *1963*, 1141.

Trifluoroacetates of Silicon, Germanium, and Tin [1]

By Dr. P. Sartori and Dipl.-Chem. M. Weidenbruch

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Treatment of silicon tetrachloride with trifluoroacetic acid in anhydrous benzene (250 h at 70 °C, molar ratio 1:2), followed by removal of all the substances distilling up to 100 °C/760 mm and fractional distillation of the residue in a vacuum, affords silicon tetrakis(trifluoroacetate) *(1)*, b.p. 51 °C/1 mm[2], in 25 % yield. There remains a residue, also in 25 % yield, of a highly viscous, colorless liquid that cannot be distilled without decomposition, even in a high vacuum; on the grounds of analysis ($Si:CF_3COO$ = 1.0:2.0), insolubility in proton-inactive solvents, and extremely low volatility, the structure of a polymeric silicon oxide bis(trifluoroacetate) must be ascribed to this compound; molecular-weight determinations were not possible because of the insolubility and involatility of the substance.

When heated for a short time at 200 °C under dry nitrogen, compound *(1)* yields hexakis(trifluoroacetoxy)disiloxane *(2)*, b.p. 120 °C/1 mm, with loss of trifluoroacetic anhydride:

$$2\ Si(OCOCF_3)_4 \xrightarrow{\Delta} [Si(OCOCF_3)_3]_2O + (CF_3CO)_2O$$

(1) *(2)*

On account of the low reactivity of the metal-halogen linkage the trifluoroacetates of germanium and tin cannot be prepared by direct reaction of their tetrahalides with trifluoroacetic acid. These trifluoroacetates are obtained in *ca.* 25 % yield on reaction of germanium or tin tetrachloride with mercury(II) trifluoroacetate in anhydrous trifluoroacetic acid at 0 °C for 8 h. After separation from mercury(II) chloride, germanium tetrakis(trifluoroacetate) *(3)* can be isolated by fractional distillation in a vacuum, forming a colorless liquid of b.p. 20 °C/0.1 mm; this product *(3)* decomposes slowly even at room temperature, with removal of trifluoroacetic anhydride and formation of solid polymeric germoxanes. For isolation of tin tetrakis(trifluoroacetate) *(4)*, m.p. 112 °C, the mercury(II) chloride is filtered off and the liquid concentrated at 20 °C/15 mm until copious crystallization occurs, and the crystal mass is filtered off with exclusion of air; fractional sublimation at 70 °C/10^{-3} mm then affords *(4)* as pure white crystals.

A further route to the compound *(4)* consists of fission of tetraphenyltin by trifluoroacetic acid at 40 °C. The small yield (7 %) in this and the preceding reaction is ascribed to simultaneous formation of a stannoxane. Although the analogous treatment of tetraphenylgermanium with trifluoroacetic acid alone gives no appreciable yield, reaction in anhydrous benzene at 80 °C gives triphenylgermanium trifluoroacetate quantitatively; this can be purified by sublimation at 120 °C/10^{-3} mm and then forms white needles of m.p. 122 °C.

Largely non-polar linkages in the structure M–O–CO can be assumed for all the trifluoroacetates of the fourth main group of the Periodic System, including the well-known lead tetrakis(trifluoroacetate)[3], because of their volatilities and the high-frequency carbonyl absorptions [$\nu_{C=O}$ = 1815 (Si), 1770 (Ge), and 1750 (Sn) cm^{-1}].

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German version: Angew. Chem. *77*, 1138 (1965)

[1] Part 3 of Reactions of Metal Halides with Perfluoromonocarboxylic acids. – Part 2: *P. Sartori* and *M. Weidenbruch*, Angew. Chem. *77*, 1076 (1965); Angew. Chem. internat. Edit. *4*, 1072 (1965).

[2] *P. Sartori* and *M. Weidenbruch*, Angew. Chem. *76*, 376 (1964); Angew. Chem. internat. Edit. *3*, 376 (1964).

[3] German Published Patent Application 1094462 (Dec. 8th, 1960/Oct. 28th, 1958), E. I. du Pont de Nemours & Co.

Stereospecific Synthesis of D-Hydroxynitriles and Optically Active Ethanolamines

By Dr. W. Becker, H. Freund, and Prof. Dr. E. Pfeil

Chemisches Institut der Universität Marburg (Germany)

In the presence of the enzyme D-hydroxynitrile lyase (4.1.2.10)[1] aldehydes and hydrocyanic acid afford D-hydroxynitriles of high optical purity in excellent yields.

D-(+)-*Mandelonitrile*: 40 ml (42 g; 0.4 mole) of benzaldehyde and 80 mg of D-hydroxynitrile lyase are placed in a 1000 ml measuring vessel and the mixture is made up to 980 ml with 0.05 M 50 % alcoholic acetate buffer (pH 5.4). The liquid is covered with a layer (20 ml; 14 g; 0.52 mole) of anhydrous hydrocyanic acid, and the whole is shaken and then kept until the optical rotation is constant (*ca.* 20 min). The D-(+)-mandelonitrile is removed from the aqueous alcoholic layer by shaking with chloroform. After drying and evaporation of the extraction medium in vacuum there remains 51 g of a clear, pale yellow oil of specific rotation $[\alpha]_D^{20} = +39°$ (c = 5, $CHCl_3$). This solidifies to colorless crystals in a refrigerator. The crude product has an optical purity of 90 % and is obtained in 96 % yield.

Aldehyde used	Yield of crude D-hydroxynitrile [%]	$[\alpha]_D^{20}$ of crude product
Benzaldehyde	96	+39.0° (c=5, $CHCl_3$)
m-Methylbenzaldehyde	100	+25.9° as oil
p-Methylbenzaldehyde	98	+30.0° (c=5, benzene)
m-Hydroxybenzaldehyde	94	+21.5° (c=5, CH_3OH)
m-Methoxybenzaldehyde	96	+32.0° (c=5, $CHCl_3$)
Heliotropine	98	+39.5° (c=5, $CHCl_3$)
Thiophene-2-carbaldehyde	88	+38.9° (c=5, $CHCl_3$)
Furfural	85	+30.6° as oil
Crotonaldehyde	69	−22.0° (c=5, $CHCl_3$)
Acetaldehyde	28	+8.2° (c=5, $CHCl_3$)
Propanal	45	+14.0° (c=5, $CHCl_3$)
n-Butanal	88	+6.7° (c=5, $CHCl_3$)
iso-Butanal	84	+3.2° (c=5, $CHCl_3$)
n-Pentanal	86	+6.5° (c=5, $CHCl_3$)

The syntheses can be made continuous if the enzyme is adsorbed on a high-molecular carrier (*e.g.*, ECTEOLA cellulose) and the product is placed in a column. The enzyme is stable in the form of the enzyme-carrier complex that is insoluble in the reaction medium (water or aqueous alcohol according to the solubility of the aldehyde)[2].

Substituted optically active ethanolamines can be obtained from the dextrorotatory D-hydroxynitriles by reduction with $LiAlH_4$ in ether.

R–CH(OH)–CH_2–NH_2 *(1)*	Yield [%]	$[\alpha]_D^{20}$ (c=5, $CHCl_3$)
(1), R = Phenyl	66	−71°
(1), R = *p*-Tolyl	80	−32°
(1), R = *O,O'*-Methylene-3,4-dihydroxyphenyl	50	−50°
(1), R = 2-Thienyl	73	−35°
(1), R = 2-Furyl	68	−28°

Received: October 12th, 1965 [Z 84/918 IE]
German version: Angew. Chem. *77*, 1139 (1965)

[1] Preparation: *W. Becker, U. Benthin, E. Eschenhof*, and *E. Pfeil*, Biochem. Z. *337*, 156 (1963); Angew. Chem. *75*, 93 (1963); *W. Becker* and *E. Pfeil*, Naturwissenschaften *51*, 193 (1964).

[2] German Pat. Appl. No. P 36473 IVb/120 (April 7th, 1965); inventors: *W. Becker* and *E. Peil*.

Preparation of 1,2-Disubstituted Vinylsulfonium Salts and Alkyl Vinyl Sulfides, and of Ethynylsulfonium and Ethynylselenonium Salts

By Priv.-Doz. Dr. J. Gosselck, Dipl.-Chem. L. Béress, Dipl.-Chem. H. Schenk, and Dipl.-Chem. G. Schmidt

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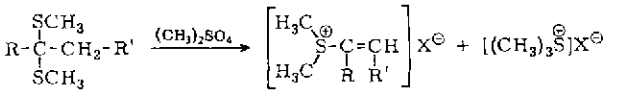
We have found a simple approach to dialkylvinylsulfonium salts disubstituted at the 1,2-positions of the vinyl group in the reaction of dimethyl dithioacetals *(1)* with an excess of acid-free dimethyl sulfate. In the reaction conditions used (1–2 h at 90–100 °C), alkylating cleavage of the thioacetals occurs, with formation of an equimolar mixture of dimethylvinylsulfonium methyl sulfate *(2)* and trimethylsulfonium methyl sulfate *(3)*. The yields of *(2)* amount to 60–80 % [1]. The products *(2)* are isolated by washing the reaction mixture several times with anhydrous ether, dissolving the residue in water, and precipitating the salts *(2)* with picric acid, perchloric acid, or sodium tetraphenylborate [2]. The salts *(3)* then remain in solution.



(1) *(2)* *(3)*

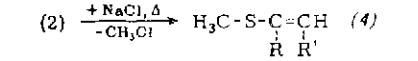
$X^{\ominus} = CH_3SO_4^{\ominus}$

	R	R'	Analysed as	M.p. [°C]
(2a)	Methyl	1-Pyridyl	Picrate	152
(2b)	Phenyl	*p*-Nitrophenoxy	Picrate	199
(2c)	Methyl	2,4-Dinitrophenyl	Perchlorate	178
(2d)	Phenyl	Phenyl	Picrate	161
(2e)	*p*-Nitrophenyl	*p*-Nitrophenyl	Picrate	184
(2f)	Phenyl	$-COOC_2H_5$	Tetraphenylborate	134–135
(2g)	β-Naphthyl	$-COOC_2H_5$	Picrate	138–139

Methylation of methyl vinyl sulfides by dimethyl sulfate under the above conditions also leads to dialkylvinylsulfonium salts *(2h)–(2l)* (yield 60–80 %).

	R	R'	Analysed as	M.p. [°C]
(2h)	H	Phenyl	Picrate	127
(2i)	Phenyl	Benzoyl	Picrate	150
(2k)	Benzoyl	*p*-Chlorophenyl	Methyl sulfate	158
(2l)	Benzoyl	*p*-Nitrophenyl	Perchlorate	202

In contrast to the stable trimethylsulfonium salts *(3)*, the dialkylvinylsulfonium salts *(2)* are very reactive. If their aqueous solution is boiled for 10–15 min with aqueous hot-saturated NaCl solution, removal of methyl chloride leads smoothly to the 1,2-disubstituted methyl vinyl sulfides *(4)*, which are isolated by extraction with ether and distillation or crystallization (yields 40 to 70 %).

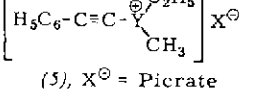


(4), R	R'	B.p. [°C/mm] (M.p. [°C])
p-Nitrophenyl	*p*-Nitrophenyl	(214)
Phenyl	2-Pyridyl	(176) [a]
Phenyl	$-COOC_2H_5$	117–119/0.01
p-Nitrophenyl	$-COOC_2H_5$	(59–60)
p-Chlorophenyl	$-COOC_2H_5$	127–128/1.5×10^{-5}
α-Naphthyl	$-COOC_2H_5$	(102–103)
p-Phenylene	$-COOC_2H_5$	(108)
p-Pyridyl	$-COOC_2H_5$	(67–68)
2-Pyridyl	$-COOC_2H_5$	(157–158) [b]
Phenyl	*p*-Nitrophenoxy	(75)
Phenyl	Phenylthio	142/0.01
Phenyl	Phenyl	130/0.01

[a] As *N*-methyl perchlorate. [b] As picrate.

Methyl vinyl sulfides *(4)* are also obtained directly from the thioacetals *(1)* and dimethyl sulfate by heating them only to 40–50 °C, extracting the solution with ether, and destroying the excess of alkylating agent with ammonia.

Alkylation of methyl phenylethynyl sulfide or selenide with triethyloxonium fluoroborate without a solvent gave the colorless, very hygroscopic ethynylsulfonium and ethynylselenonium salts *(5)*, which were isolated as picrates.



(5), $X^{\ominus}$ = Picrate

(5), Y	M.p. [°C]	$\nu_{C\equiv C}$ [cm^{-1}]
S	100	2195
Se	89	2150

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German version: Angew. Chem. 77, 1140 (1965)

[1] Exceptionally, the yield of *(2a)* was only 30 %.

[2] When sodium tetraphenylborate is used, separation from *(3)* by fractional crystallization from acetonitrile is necessary.

Ethynylation with Vinylsulfonium Salts

By Priv.-Doz. Dr. J. Gosselck, Dipl.-Chem. L. Béress, Dipl.-Chem. H. Schenk, and Dipl.-Chem. G. Schmidt

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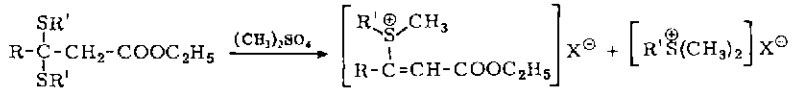
On warming alkyl dithioacetals *(1)* of β-oxocarboxylic acids in an excess of acid-free dimethyl sulfate at 90–100 °C we obtained an equimolar mixture of the dialkylvinylsulfonium methyl sulfate *(2)* and the trialkylsulfonium methyl sulfates *(3)* [1].



(1) *(2)* *(3)*

$X^{\ominus} = CH_3SO_4^{\ominus}$

Addition of an excess of alkali to an aqueous solution of such a dialkylvinylsulfonium salt *(2)* furnishes, even at 0 °C, the corresponding acetylenecarboxylic ester *(4)*, with loss of dialkyl sulfide; the esters are readily hydrolysed to the acids under the reaction conditions, whereas the trialkylsulfonium salts are stable under these conditions.

(2) $\xrightarrow[0°C]{\text{Aqueous alkali}}$ R-C≡C-COOC$_2$H$_5$ + CH$_3$SR'

(4)

+ H$_2$O + CH$_3$SO$_4$Na

R	M.p. [°C]	Yield of acid [%] based on (1)
Phenyl	136–137	80
4-Nitrophenyl	203–204	70
3-Nitrophenyl	143–144	50
4-Chlorophenyl	192–193	75
α-Naphthyl	140–141	55
β-Naphthyl	145–146	77
2-Thienyl	139–140	25

Double ethynylation can also be achieved by this process. Thus the bis(methyl thioacetal) of terephthaloyldiacetic ester gives *p*-phenylenedipropiolic acid

HOOC–C≡C–C$_6$H$_4$–C≡C–COOH

(decomp. 280 °C) in 65 % yield. *m*-Phenylenedipropiolic acid (m.p. 209 °C; yield 70 %) was obtained in the same way.

Received: October 13th, 1965 [Z 85b/924 IE]
German version: Angew. Chem. 77, 1141 (1965)

[1] Cf. *J. Gosselck, L. Béress, H. Schenk*, and *G. Schmidt*, Angew. Chem. 77, 1140 (1965); Angew. Chem. internat. Edit. 4, 1080 (1965).

Trimethylsilyl as Protecting Group for Nitrogen in Organometallic Syntheses Involving Halogenoanilines

By Prof. Dr. W. Broser and Dipl.-Chem. W. Harrer

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The amino hydrogen atoms of aniline can be relatively easily replaced by trimethylsilyl groups[1]:

$$\text{Ar-NH}_2 \xrightarrow[\text{or 2 n-C}_4\text{H}_9\text{Li}]{\text{2 C}_6\text{H}_5\text{Li}} \text{Ar-NLi}_2 \xrightarrow[-2\ \text{LiCl}]{\text{2 TMS-Cl}} \text{Ar-N(TMS)}_2$$

TMS = $(CH_3)_3Si$

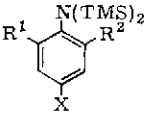
Since the halogen atoms of halogenoanilines are not replaced if stoichiometric amounts of the lithium reagent are used, and since the trimethylsilyl groups can be easily removed by hydrolysis, the latter groups are suitable for use as protecting groups in organometallic syntheses involving halogenoanilines. Thus the following compounds can be synthesized in 80–85 % yield by dropping the organometallic reagent (2 moles) into an ethereal solution of the halogenoaniline (1 mole), then adding a mole of trimethylsilyl chloride, replacing the ether by means of ligroin, adding a second mole (+ 20 % excess) of trimethylsilyl chloride, and refluxing the mixture for 8–10 h:

p-bromo-*N,N*-bis(trimethylsilyl)aniline *(1a)*, a yellow oil, b.p. 86–87 °C/1 mm;

4-bromo-2-methoxy-*N,N*-bis(trimethylsilyl)aniline *(1b)*, a colorless oil, b.p. 99–100 °C/1 mm; and

4-bromo-2,6-dimethoxy-*N,N*-bis(trimethylsilyl)aniline *(1c)*, colorless crystals, b.p. 112–113 °C/1 mm; m.p. = 73 °C.

The halogen of compounds *(1a)–(1c)* can also be replaced by lithium, if metallic lithium or n-butyl-lithium in ether under nitrogen at 25–35 °C is used. The products *(2a)–(2c)* resemble phenyl-lithium in chemical behavior. For instance, addition of an ethereal solution of *(2a)–(2c)* slowly to a rapidly stirred suspension of solid carbon dioxide in ether at −80 °C affords the lithium benzoates *(3a)–(3c)*, from which the corresponding *p*-aminobenzoic acids are obtained on removal of the protecting groups (short heating with dilute mineral acid or 10 % acetic acid). The lithium benzoates *(3a)–(3c)* are converted by trimethylsilyl chloride in boiling ligroin into the trimethylsilyl esters *(4a)–(4c)* [*(4a)*: b.p. 129–131 °C/1 mm, *(4b)*: 134–135 °C, 1 mm, *(4c)*: 136–137 °C/1 mm; pale yellow, viscous oils that crystallize



(1), X = Br
(2), X = Li
(3), X = COOLi
(4), X = COOTMS

(a), $R^1 = R^2 = H$
(b), $R^1 = H$, $R_2 = OCH_3$
(c), $R^1 = R^2 = OCH_3$

slowly]. On treatment of the lithio derivatives *(2a)–(2c)* with diethyl carbonate in boiling ether and subsequent hydrolysis with dilute hydrochloric acid at 40–60 °C, the corresponding triarylmethanol derivatives are formed. Further, all the *m*-methoxylated parafuchsins have been synthesized by combinations of the compounds *(2a)–(2c)* with the esters *(4a)–(4c)*.

Received: October 13th, 1965 [Z 79/905 IE]
German version: Angew. Chem. 77, 1139 (1965)

[1] *U. Wannagat, C. Krüger*, and *H. Niederprüm*, Z. anorg. allg. Chem. 314, 82, 89 (1962).

Chloroformylation of α-Pyrrolones

By Prof. Dr. K. E. Schulte, Doz. Dr. J. Reisch, and U. Stoess

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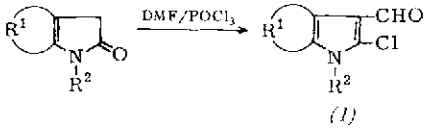
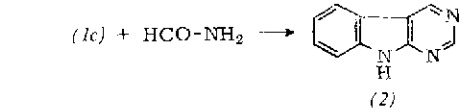
α,β-Unsaturated β-chloroaldehydes can be prepared by chloroformylation[1,2] of isocyclic ketones. We found that α-pyrrolones also undergo this reaction, affording the corresponding chloroaldehydes *(1)* in 50–60 % yield (for products see the Table).



(1)

	R^1	R^2	M.p. [°C]
(1a)	$-(CH_2)_4-$	$-H$	162
(1b)	$-(CH_2)_4-$	$-C_6H_5$	156
(1c)	$-(CH)_4-$	$-H$	223–225

A solution of 0.02 mole of the pyrrolone in 40 ml of chloroform is added dropwise at 0–10 °C to a Vilsmeier reagent prepared from 0.06 mole of dimethylformamide and 0.05 mole of phosphorus oxide chloride. The mixture is heated for 5–6 h at the boiling point. After removal of the solvent by distillation, the residue is treated with ice-water, neutralized, and extracted with chloroform. The organic phase is dried and freed from solvent, and the residue is recrystallized from alcohol.



(2)

Compounds *(1)* can also be used for preparation of condensed heterocycles. For instance, 9*H*-pyrimido[4,5-*b*]indole *(2)* (m.p. 235–237 °C, yield 80 %) is formed when 2-chloroindole-3-carbaldehyde *(1c)* is heated for several hours in an excess of formamide.

Received: October 14th, 1965 [Z 78/904 IE]
German version: Angew. Chem. 77, 1141 (1965)

[1] *Z. Arnold* and *J. Zemlicka*, Proc. chem. Soc. (London) *1958*, 227; Coll. czechoslovak. chem. Commun. *24*, 2385 (1959).

[2] *W. Ziegenbein* and *H. Franke*, Angew. Chem. *71*, 573 (1959).

Thiophenes from 5-Oxo Derivatives of 1-Alkynes

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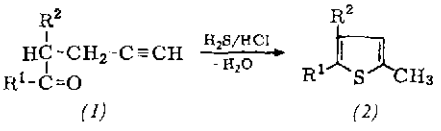
β-Dicarbonyl compounds in the 1-alkyne series can yield furans by intramolecular ring closure[1]. *Baumann* and *Fromm*[2] obtained thioketones by treating ketones with H_2S and HCl, and *Mitra*[3] found that β-dicarbonyl compounds can be converted into monounsaturated thiols if hydrogen sulfide is passed into their alcoholic solution previously saturated with hydrogen chloride. In similar conditions thiophenes *(2)* are obtained from 5-oxo derivatives *(1)* of 1-alkynes (for products see Table).



(1) *(2)*

	R^1	R^2	B.p.[°C/mm Hg]	n_D (at °C)	Yield [%]
(2a)	CH_3	$CO_2C_2H_5$	108–109/8	1.5152 (20)	69
(2b)	C_6H_5	$CO_2C_2H_5$	129–130/2	1.5833 (21)	65
(2c)	CH_3	C_6H_5	109/1.5	1.6044 (19)	50
(2d)	C_6H_5	H	(M.p. 49 °C)		71

0.3 mole of H_2S is passed at −20 °C, and then 1 mole of HCl at between −20 and −10 °C, into a solution of 0.1 mole of the unsaturated ketone in about 100 ml of ethanol. After several hours at room temperature the solvent is removed and the mixture is fractionated in a vacuum.

Received: October 14th, 1965 [Z 77/903 IE)
German version: Angew. Chem. 77, 1141 (1965)

[1] *K. E. Schulte*, *J. Reisch*, and *A. Mock*, Arch. Pharmaz. *295*, 627 (1962).

[2] *E. Baumann* and *E. Fromm*, Ber. dtsch. chem. Ges. *28*, 598 (1895).

[3] *S. K. Mitra*, J. Indian chem. Soc. *10*, 71, 491 (1933).

On the Existence of Metal Carbonyl Carbene Complexes

By O. S. Mills and Dr. A. D. Redhouse[1]

Department of Chemistry, University of Manchester, England

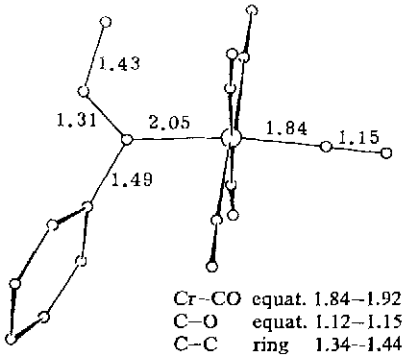
In a recent paper[2], *Fischer* and *Maasböl* have described the preparation of complexes of stoichiometry $(CO)_5W(RCOCH_3)$ *(1)*, where $R=CH_3$ or C_6H_5. From a study of infrared and proton magnetic resonance spectra the possibility that *(1)*, $R=CH_3$, was methoxymethylcarbene-pentacarbonyltungsten was considered.

We have analysed, by x-ray diffraction, single crystals of *(1)*, $R=C_6H_5$, and also of the corresponding chromium complex[3]. We find that the compounds are isomorphous, with the following unit cell dimensions:

	$(CO)_5W(C_6H_5COCH_3)$	$(CO)_5Cr(C_6H_5COCH_3)$
a	10.00 Å	9.91 Å
b	21.90 Å	21.70 Å
c	6.45 Å	6.34 Å
β	96° 12′	96° 35′
Z	4	4
Space group	Cc	Cc

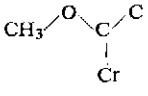
The analysis of these complexes is complicated since the symmetry of the heavy atoms alone corresponds to the higher symmetry of space group C2/c with the metal atoms in special positions on two-fold axes. The pseudo-symmetry introduced into the resulting electron density calculation corresponds to the superimposition of the molecule and its two-fold rotation image.

Crystals of both complexes yielded relatively few diffraction spots, consistent with large thermal vibrations. The structure of the chromium complex was determined from 565 three-dimensional data collected on precession photographs taken with molybdenum Kα radiation. The structure as given in



the figure clearly shows that the molecule does correspond to a "carbene-metal complex". The structure shows the following features:

(i) The phenyl group is roughly perpendicular to the



plane so that the π-electron system of the phenyl group presumeably does not interact with the empty p orbital on the carbene carbon atom. The carbene-phenyl distance (1.49 ± 0.03 Å) corresponds to bonding between two sp^2 hybridized carbon atoms.

(ii) The carbene – oxygen and methyl-oxygen distances (1.31 ± 0.02 Å and 1.43 ± 0.03 Å, respectively) are similar to those found in methyl esters of carboxylic acids.

(iii) The individual Cr–CO distances do not differ from the average (1.88 Å) by more than one standard deviation (0.03Å)
(iv) The Cr-carbene distance (2.05 ± 0.03 Å) is significantly longer than the Cr–CO distances.

(v) The normal to the "carbene plane", *i.e.* the direction of the empty p-orbital, does not align parallel to a principal axis of the Cr octahedron. Indeed, it lies at approximately 45 ° to the x,y axes (with the carbene carbon on the z axis). This arrangement could be caused by steric requirements.

Received: October 22nd, 1965 [Z 93/915 IE]
German version: Angew. Chem. 77, 1142 (1965)

[1] Presented to the Second International Symposium on Organometallic Chemistry, Madison (U.S.A.), September 1st, 1965.

[2] *E. O. Fischer* and *A. Maasböl*, Angew. Chem. *76*, 645 (1964); Angew. Chem. internat. Edit. *3*, 580 (1964).

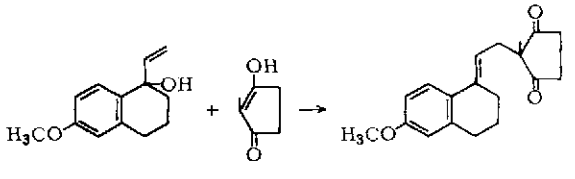
[3] We wish to thank Professor *Fischer* and Dr. *Maasböl* for the preparation of the chromium complex at our request for this analysis.

The Condensation of 6-Methoxy-1-vinyl-1,2,3,4-tetrahydro-1-naphthol with 2-Methylcyclopentane-1,3-dione

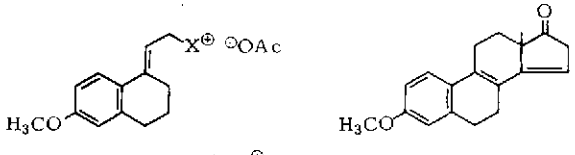
By C. H. Kuo, M. Sc., Dr. D. Taub, and Dr. N. L. Wendler

Merck Sharp & Dohme Research Laboratories,
Rahway, New Jersey (U.S.A.)

The condensation of *(1)* with *(2)* to give *(3)* has achieved considerable importance recently in the total synthesis of estrone and related substances. The condensation, as reported, is effected in hot alcoholic media in the presence of strong bases[1], but proceeds at best in only fair yield (50–60 %).



(1) *(2)* *(3)*



(4), $X^{\oplus}$ = $-S-C(NH_2^{\oplus})NH_2$

(5), $X^{\oplus}$ = $-\overset{\oplus}{P}(C_6H_5)_3$

(6)

We have found that this condensation does not occur in the presence of a mole of base and is, in fact, catalysed by acid and by the 1,3-dione *(2)*. Thus, when *(1)* and *(2)* are warmed together in alcohol solution coupling to give *(3)* occurs smoothly in 65–70 % yield. This finding suggested an ion-pair intermediate arising from acid-base interaction of *(2)* and *(1)*, respectively. In pursuance thereof it was found that *(1)* in acetic acid in the presence of thiourea produced the crystalline thiuronium salt *(4)* in nearly quantitative yield (m.p. 125–127 °C; λ_{max} = 275 mμ, ε = 19500 in methanol). The latter, in turn, coupled with *(2)* in aqueous solution at room temperature to yield crystalline *(3)* in 80–85 % yield.

The reaction of *(1)* and *(2)* (pK_a 4.5) is essentially unaffected by triphenylphosphine, although *(1)* itself in acetic acid solution (pK_a 4.7) rapidly forms a stable but non-crystalline salt *(5)* (λ_{max} = 270 and 276 mμ, ε = 13000 and 13500 in methanol) with triphenylphosphine[2]. From this it would follow that the ion-pair involved in the coupling of *(1)* and *(2)* is intimate in character.

Finally it was observed that *(1)* and *(2)* in acetic acid-xylene (1:2) at 120 °C afford 8,14-bisdehydroestrone methyl ether *(6)* in one operation in 60–65 % yield.

Received: October 25th, 1965 [Z 96/916 IE]
German version: Angew. Chem. *77*, 1142 (1965)

[1] *I. N. Nazarov, S. N. Ananchenko,* and *I. V. Torgov,* Izv. Akad. Nauk S.S.S.R., Otdel. khim. Nauk *1959*, 103; *S. N. Ananchenko* and *I. V. Torgov,* Dokl. Akad. Nauk S.S.S.R. *127*, 553 (1959); Tetrahedron Letters *1963*, 1553; *T. B. Windholz, J. F. Fried,* and *A. A. Patchett,* J. org. Chemistry *28*, 1092 (1963); *G. H. Douglas, J. M. H. Groves, D. Hartley, G. A. Hughes, B. J. McLoughlin, J. Siddal,* and *H. Smith,* J. chem. Soc. (London) *1963*, 5072; *T. Miki, K. Hiraga,* and *T. Asako,* Proc. chem. Soc. (London) *1963*, 139; *D. J. Crispin* and *J. S. Whitehurst, ibid. 1963*, 22.

[2] Cf. *H. Freyschlag, H. Grassner, A. Nürrenbach, H. Pommer, W. Reif,* and *W. Sarnecki,* Angew. Chem. *77*, 277 (1965); Angew. Chem. internat. Edit. *4*, 287 (1965)

CONFERENCE REPORTS

Conference of North-West German Chemistry Lecturers

The conference took place on June 11th and 12th, 1965 at Clausthal-Zellerfeld (Germany). A total of 74 papers was read partly in three parallel sessions. To avoid duplication, the following review contains abstracts of only those papers whose contents have not yet been published or submitted for publication. The abstracts are arranged in alphabetical order of authors' names. A subject index to this Report is on p. 1097 of this issue.

1

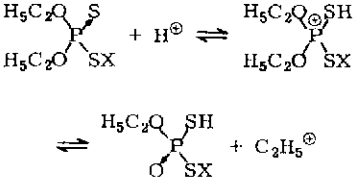
Thermal Decomposition of Zinc Dialkyldithiophosphates

E. Baumgarten and *H. Luther,* Clausthal-Zellerfeld (Germany)

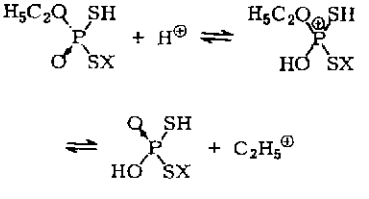
Zinc dialkyldithiophosphates are used, *inter alia*, in lubricants as oxidation and corrosion inhibitors. To obtain an insight into their mode of action, we have investigated their thermal decomposition kinetically. It was found from thermo-gravimetric measurements and from gas-chromatographic and infrared spectroscopic analyses that zinc dialkyldithiophosphates decompose in an autocatalytic reaction. An initial reaction, the nature of which is not yet elucidated, is followed by several steps catalysed by acidic compounds formed as intermediates, for which the following scheme is proposed (X = metal).

A. Formation of Alkyl Ions

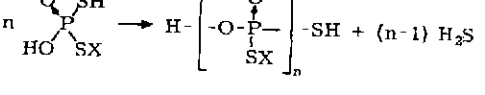
1. Decomposition of the diester



2. Decomposition of the monoester



B. Decomposition of the monometal dithiophosphate



C. Recombination steps

1. Formation of olefin

$$C_2H_5^{\oplus} \rightleftharpoons H_2C{=}CH_2 + H^{\oplus}$$

2. Formation of mercaptan and dialkyl sulfide

$$C_2H_5^{\oplus} + H_2S \rightleftharpoons C_2H_5\text{-}\overset{\oplus}{\underset{H}{\overset{H}{S}}} \rightleftharpoons C_2H_5\text{-}SH + H^{\oplus}$$

$$C_2H_5^{\oplus} + C_2H_5\text{-}SH \rightleftharpoons C_2H_5\text{-}\overset{\oplus}{\underset{H}{S}}\text{-}C_2H_5 \rightleftharpoons (C_2H_5)_2S + H^{\oplus}$$

The volatile decomposition products (dialkyl sulfides, mercaptans, olefins, hydrogen sulfide) arise in approximately the calculated amounts.

2

Separation of Enzymes of Pancreatic Fluid

W. Berndt and *W. Thorn*, Hamburg (Germany)

Rabbit pancreatic fluid, dialysed against 5×10^{-3} M phosphate buffer was chromatographed on DEAE-cellulose with 0.005 M phosphate buffer (pH 8.0). Lipase, procarboxypeptidase-K_1, trypsinogen, and chymotrypsinogen were eluted as cationic proteins with the solvent, followed by amylase. The separation of trypsinogen, still containing procarboxypeptidase-K_2, and chymotrypsinogen, was effected by gradient elution (phosphate buffer, pH 8.0, 0.005 M → 0.2 M). The other enzymes eluted with the solvent front were fractionated on CM-cellulose.

The enzymes of the pancreatic juice of the cat precipitate easily at low salt concentrations. Procarboxypeptidase, trypsinogen, and in particular lipase precipitate on dialysis against 5×10^{-3} M tris(hydroxymethyl)aminomethane buffer (pH 8.0). In this case, because of the necessary high salt concentration, ion-exchange chromatography is less suitable. Gel filtration on Sephadex G-100 (0.1 M tris buffer, pH 7.2, containing 1 M NaCl) gave a sharp separation of lipase, procarboxypeptidase, chromotrypsinogen + trypsinogen, trypsin inhibitor, and amylase. Under these conditions, the molecular weights of the procarboxypeptidase and trypsin inhibitor are about 57,000 and 8000. Lipase, with a molecular weight of about 100,000, migrated with the solvent front. A molecular weight of 24,500 was found for trypsinogen and chymotrypsinogen. Less pronounced separation effects are found with Sephadex G-200.

Characteristic species-dependent differences were observed on electrophoresis on cellulose acetate foils in 0.056 M veronal buffer (pH 8.6). The pancreatic juices of cats and rabbits were separated into several fractions.

3

Resonance of 1,2-Dithiacyclopenten-3-ones

F. Boberg, Hannover (Germany)

Infrared carbonyl bands and dipole moments provide information about electron displacements in 1,2-dithiacyclopenten-3-ones. The direction of the C–O bond moment can be determined by comparing the moments of halogenated 1,2-dithiacyclopentenones (Cl in the 4- and 5-positions). 4-Chloro-5-amino-1,2-dithiacyclopenten-3-ones possess extraordinarily high moments (up to 10 D), ascribed to the importance of the resonance structures with nitrogen as electron donor and oxygen as electron acceptor. The structures of the benzoylation products [1] of 4-chloro-5-anilino-1,2-dithiacyclopenten-3-one are confirmed by the dipole moments.

[1] *F. Boberg*, Liebigs Ann. Chem. *681*, 178 (1965).

4

Microwave Spectrum and Structure of $(CH_3)_3C{-}C{\equiv}C{-}Cl$ [1]

H. K. Bodenseh, R. Gegenheimer, J. Mennicke, and *W. Zeil*, Kiel (Germany)

Rotational transitions of the following compounds have been measured (isotopes in natural abundance):

$(CH_3)_3C{-}C{\equiv}C{-}^{35}Cl$, $(CH_3)_3C{-}C{\equiv}C{-}^{37}Cl$, $(CH_3)_3C{-}C{\equiv}{}^{13}C{-}^{35}Cl$; $(CH_3)_3{}^{13}C{-}C{\equiv}C{-}^{35}Cl$, and $(CH_3)_2({}^{13}CH_3)C{-}C{\equiv}C{-}^{35}Cl$.

Lines of $(CH_3)_3C{}^{13}C{\equiv}C{-}^{35}Cl$ are only 0.2–0.5 Mc/s from the ^{12}C lines of the compounds $(CH_3)_3C{-}C{\equiv}C{-}^{35}Cl$ and $(CH_3)_3C{-}C{\equiv}C{-}^{37}Cl$, since the corresponding C-atom is very close to the center of gravity of the molecule, and they could therefore not be found. Because of the large number of excited vibrational states, every rotational transition gives very many lines. The absorption line corresponding to the vibrational ground state was determined by intensity comparisons at various temperatures. The following distances could be calculated directly from the measured rotational constants: $r_{\equiv C-Cl} = 1.638$ Å; $r_{\overline{C-C\equiv C}-} = 2.671$ Å. Even on the assumption of a short triple-bond distance of 1.205 Å, a value of only 1.466 Å is obtained for the length of the sp^3-sp single bond. This is about 0.03 Å less than in the analogous compounds t-butylacetylene and t-butyl cyanide [2]. No accurate information could be obtained on the position of the methyl C-atoms, since the lines of the transitions with $K_{-1} = 0$ and $K_{-1} \geqslant 2$ of the asymmetric molecules $(CH_3)_2({}^{13}CH_3)C{-}C{\equiv}C{-}^{35}Cl$ form an irresolvable group, and of the two lines with $K_{-1} = 1$, the one at higher frequency is masked by lines of excited vibrational states of the group mentioned, whereas the one at lower frequency could not be detected with certainty because of its low intensity.

[1] Previous investigations: *W. Zeil* et al., Z. Naturforsch. *15a*, 1011 (1960).

[2] *L. Nugent, D. Mann*, and *D. Lide*, J. chem. Physics *36*, 965 (1962).

5

Alkali-Metal Thioferrates(III)

W. Bronger, Münster (Germany)

$RbFeS_2$ and $CsFeS_2$ [1] were first prepared, by a process known from the preparation of $KFeS_2$ [2], by the reaction of iron powder with a mixture of sulfur and rubidium and cesium carbonates, respectively, at 800 °C in an atmosphere of nitrogen, followed by purification with water. $NaFeS_2$ could not be obtained pure in this way, but could be so obtained by the reaction of iron powder with Na_2S_2 and sulfur at 800 °C under nitrogen. The compounds are produced as analytically pure, well-formed needle-shaped crystals with metallic luster.

For $RbFeS_2$, X-ray investigations on single crystals showed a structure isotypical with that of $KFeS_2$ [3] (space group C_{2h}^6-$C_{c/2}$; lattice constants $a = 7.22$ Å, $b = 11.70$ Å, $c = 5.42$ Å, $\beta = 112.0°$). For $CsFeS_2$, a hitherto unknown rhombic type of structure was found (space group D_{2h}^{25}-Immm; lattice constants $a = 7.13$ Å, $b = 11.92$ Å, $c = 5.42$ Å).

In the previously known alkali-metal thioferrates(III), the Fe atoms are surrounded tetrahedrally by the S atoms.

The tetrahedra are always linked through edges, so that relatively short Fe-Fe distances occur. In the $KFeS_2$ type, the alkali-metal ions have a coordination number of 8 with respect to the sulfur, and in $CsFeS_2$ they have a coordination number of 10.

Between 90 and 700 °K, $KFeS_2$, $RbFeS_2$, and $CsFeS_2$ have a slight, substantially temperature-independent paramagnetism, which indicates pronounced Fe-Fe interactions. Mixed crystals of the composition $K(Fe_{1-x}Al_x)S_2$ with $x \leq 0.08$ show a transition to normal paramagnetism, the Fe-Fe interactions being perturbed.

[1] *W. Bronger*, Naturwissenschaften *7*, 158 (1965).

[2] *K. Preis*, J. prakt. Chem. *107*, 12 (1869); *R. Schneider*, ibid. *108*, 16 (1869).

[3] *J. W. Boon* and *C. H. MacGillary*, Rec. trav. chim. *61*, 910–920 (1942).

6

Quantitative Separation of RNA and DNA Structural Units on Cation-Exchangers

E. W. Busch and *N. Takriti*, Hamburg (Germany)

The cation-exchanger Dowex 50W, X 4 (400 mesh, Na^+ form) was used. On a column 60 cm long (diameter 1 cm) it was possible to separate the ribomononucleotides with the exception of thymidine and uridine monophosphates from the deoxyribomononucleotides. With a 10^{-3} M HCl solution and 10^{-2} M NaCl, or an ammonium formate buffer (pH 3.0, 0.05 M NH_3), the nucleotides were eluted in the sequence thymidine, guanosine, deoxyguanosine, cytidine, deoxycytidine, adenosine, and deoxyadenosine monophosphates. The small elution volumes (averaging about 15 ml) of individual substances were surprising. A small part (about 10 % of the amount added) of the purine derivatives of deoxyribose phosphate was hydrolysed on the column at room temperature. For quantitative determinations, it was therefore necessary to cool the column to 10 °C.

With a column 20 cm long, it was possible to separate the bases thymine, hypoxanthine, guanine, cytosine, methylcytosine, 6-methylaminopurine, and adenine with an ammonium formate buffer (pH 3.5, 0.06 M NH_3) and 0.35 M NaCl. The process is suitable for quantitative determination of the bases in acid hydrolysates of the DNA from mammalian organs in contrast to the well-known Cohn method, in which 2 N HCl is used as eluent.

The corresponding nucleosides can be separated with the same arrangement, except that the ammonium formate buffer has a lower pH (3.1).

It was possible to separate a mixture of bases and nucleosides on a column 50 cm long. The individual substances appeared in the sequence uridine, thymine, hypoxanthine, guanosine, cytidine and guanine (together), adenosine, cytosine, methylcytosine, adenine. The eluent consisted of an ammonium formate buffer (pH 3.5, 0.06 M NH_3) and 0.35 M NaCl. Cytine and guanine were distinguished photometrically by measurements at two different wavelengths.

7

Representation of Diffusion Coefficients by Melting Parameters

G. Döge, Braunschweig (Germany)

The temperature-dependence of self-diffusion coefficients is frequently described by the Arrhenius relation

$$D = D_0 \exp(-A/RT)$$

A rule, first found for liquid metals, that the constant A in this equation is proportional to the Gibbs free energy at the melting point, also applies to liquid alloys, liquid rare gases, and compounds whose molecules are approximately spherical and not highly polar. The proportionality factor is about 1.3. For the above substances and at low pressures, the coefficient of self-diffusion D_{Tm} at the melting point T_m is between 1.5×10^{-5} and 2.0×10^{-5} cm² sec^{-1}. This range is not greater than the error of most measurements in the liquid phase.

The Arrhenius relation can be rewritten in terms of D_{Tm} and T_m:

$$D = D_{Tm} \cdot \exp[(A/R)(T_m^{-1} - T^{-1})]$$

With this equation, it is possible to calculate very satisfactorily the unknown self-diffusion coefficients of the class of substances mentioned.

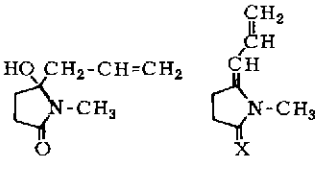
Theoretical consideration of this rule leads to the assumption that liquid phase at the melting point is to be regarded as a corresponding state. Reduction of the diffusion data of liquids to critical constants does not lead to a relation applicable to different classes of substances.

8

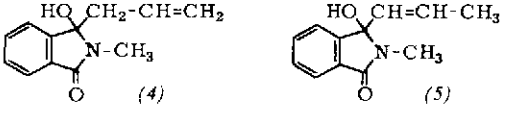
Anomalous Reactions of Imides with Grignard Compounds

W. Flitsch and *R. Heidhues*, Münster (Germany)

With excess of allylmagnesium bromide, cyclic imides form basic products that have not so far been obtained in the pure state. To elucidate the reaction, equimolar amounts of imides and Grignard compounds were allowed to react, and definite primary products of the reaction were obtained. Of these, the 2-allyl-2-hydroxy-1-methyl-5-pyrrolidone *(1)* arising from *N*-methylsuccinimide eliminates water on heating with the formation of 1-methyl-2-propenylidene-5-pyrrolidone *(2)*. This can be reduced to the pyrrolidine *(3)* with $LiAlH_4$.



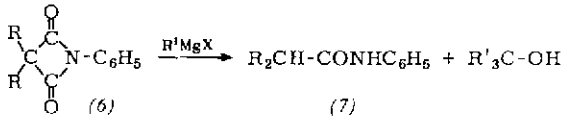
(1) *(2)*, X = O; *(3)*, X = H_2



(4) *(5)*

The 1-allyl-1-hydroxy-2-methyl-3-oxo-2,3-dihydro-1*H*-isoindole *(4)* formed from *N*-methylphthalimide does not, however, split out water but isomerizes on heating to *(5)*.

Malonimides *(6)* react with Grignard compounds with the formation of monocarboxylic anilides *(7)*:



(6) *(7)*

9

Investigations on Tetrathiopercarbonic Acid

G. Gattow and *J. Wortmann*, Göttingen (Germany)

The stoichiometric amount of gaseous HCl was passed slowly into a suspension of $(NH_4)_2CS_4$ in dimethyl ether cooled to about −78 °C. The liquid phase was filtered at about −78 °C

and the dimethyl ether was distilled off in vacuum. A yellow compound having the composition H_2CS_4 crystallized. The fact that this was not a solution of sulfur in H_2CS_3 was shown by investigations on the H_2CS_3/S system, by comparison of the infrared spectra and the spectra in the visible and ultraviolet regions, and by paper-chromatographic analysis. H_2CS_4 melts at −36 °C; the heat of fusion is 2.7 ± 0.5 kcal/mole. By determining the H_2S pressure over H_2CS_4 (isoteniscopic method) the enthalpy of formation of tetrathiopercarbonic acid was determined as $\Delta H_f = +9.7 \pm 0.8$ kcal/mole. In aqueous solution, H_2CS_4 decomposes according to first-order kinetics with a half-life of 14 sec at 0 °C. The acid dissociation constants at 0 °C were found to be $K_1 = 2.89 \times 10^{-4}$ and $K_2 = 1.4 \times 10^{-8}$. It can be concluded from the results that tetrathiopercarbonic acid must be formulated as SC(SSH)(SH).

10

Substrate Supply and Inhibition of the Metabolism of Rabbit Heart Perfused In Situ

G. Gercken and *P. Hürter*, Hamburg (Germany)

Because of the multiplicity of substances that the heart takes up from the flowing blood, it is difficult to determine the significance of individual substrates for cardiac metabolism. We have perfused rabbit hearts in the heart-lung preparation with a simplified blood consisting of washed and dialysed bovine erythrocytes in phosphate Ringer solution with 3 % of Haemaccel [*]. The effects of individual substrates supplied and of metabolism inhibitors on the function and metabolism of the heart were determined by the pressure-volume work and the content of ATP, ADP, AMP, creatine phosphate, inorganic phosphate, glycogen, glucose, glucose-1-phosphate, glucose-6-phosphate, fructose 1,6-diphosphate, dihydroxyacetone phosphate, lactate, and pyruvate in the muscle. The heart was kept capable of functioning by glucose, pyruvate, and fatty acids, in contrast to mannose, fructose, and metabolites of the citric acid cycle. If no nutrient was supplied, acute heart failure set in at an ATP content of 75 % and a creatine phosphate content of less than 50 % of the normal figure. A similar decrease in the glycogen content with a reduction in the energy-rich phosphate compounds was found with insufficiencies after disturbance of the oxidative metabolism (CO and KCN poisoning). Here, however, glycogen can be degraded only to lactic acid. After poisoning with NaF or monoiodoacetate, the hearts failed with a normal glycogen content and a concentration of energy-rich phosphate compounds reduced as with other insufficiences. Monoiodoacetate increased the concentration of dihydroxyacetone phosphate and fructose diphosphate to 100 and 50 times the normal values, respectively. The insufficiency due to inhibition of glycogenolysis indicates that the substrate chain phosphorylation in the cytoplasm is important for the contraction. The various insufficiencies due to inadequate availability of energy are in contrast with the insufficiency due to inhibition of the contractile proteins in which the energy-rich phosphate compounds and the glycogen increase above their normal amount.

[*] Behringwerke AG., Marburg (Germany).

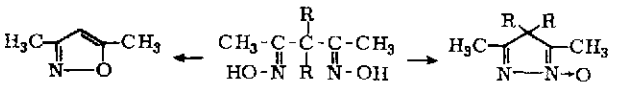
11

4H-Pyrazole N-Oxides from 1,3-Dioximes

H. Gnichtel and *H. Schönherr*, Berlin (Germany)

We have investigated the formation of heterocycles from the dioximes of acetylacetone *(1a)* and 3,3-dimethyl- *(1b)* and 3,3-diethylacetylacetones *(1c)*.

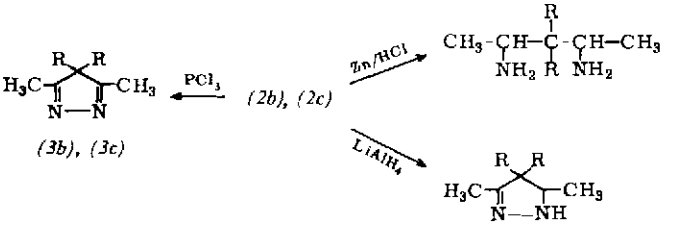
The action of thionyl chloride in liquid SO_2 on *(1a)* gives 3,5-dimethylisoxazole *(2a)*, while *(1b)* and *(1c)* gives 3,4,4,5-



(2a) *(1)* *(2b), (2c)*

(a), R = H; *(b)*, R = CH_3; *(c)*, R = C_2H_5

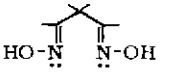
tetramethylpyrazole 1-oxide *(2b)* and 3,5-dimethyl-4,4-diethylpyrazole 1-oxide *(2c)*, respectively. In the reaction of *(1b)*, 3,4,4,5-tetramethylpyrazole *(3b)* and *N*-methyl-*N'*-acetylaminoisobutyramide were isolated as by-products. The *N*-oxide *(2c)* forms a very hygroscopic hydrochloride, the hydroxyl band of which is at 2100 cm^{-1}. The high dipole moment (6.8 D) is in harmony with the hypsochromic displacement of the ultraviolet absorption with increasing dielectric constant of the solvent.



(3b), (3c) *(2b), (2c)*

The presence of a 4*H*-pyrazole *N*-oxide is also proved by the deoxygenation of *(2b)* and *(2c)* with PCl_3 to the pyrazoles *(3b)* and *(3c)*, respectively. In contrast to other cyclic nitrones, the reduction of *(2b)* or *(2c)* with $LiAlH_4$ leads to pyrazoline.

The formation of *(2b)* and *(2c)* permits the conclusion that the dioximes *(1b)* and *(1c)* exist in the α-form *(4)*.



(4)

12

Resorption and Metabolism of cis-Octadec-12-enoic Acid in Man and Rat

G. Grimmer, Hamburg (Germany)

cis-Octadec-12-enoic acid is possibly a biosynthetic precursor of the octadeca-9,12-dienoic acids (*e.g.* linoleic acid).

Some hours after the administration of *cis*-octadec-12-enoic acid triglyceride to an experimental subject, samples of intestinal lymph and blood were taken and the lipids were isolated from them. After separation into cholesterol esters, triglycerides, phosphatides, and free fatty acids, the fatty acid composition of these fractions was determined by gas chromatography. Besides unchanged *cis*-octadec-12-enoic acid in all the fractions, the content of the octadecadienoic acids in all fractions with the exception of the phosphatides increased in the first 3 hours after the administration of the cis-octadec-12-enoic acid triglyceride. Six hours after the administration of the triglyceride, the content of octadecadienoic acids had fallen below the initial value. If, on the other hand, the experimental subject was given linoleic acid, the concentration of the octadecadienoic acids increased further even after six hours.

By oxidative degradation, it was possible to identify the bulk (85 %) of the octadecadienoic acid which occurred in the triglyceride fraction after the administration of *cis*-octadec-12-enoic acid as linoleic acid.

After the feeding of [^{14}C]-*cis*-octadec-12-enoic acid triglyceride to rats, approximately the same specific activities were found in the cholesterol esters, triglycerides, and free fatty acids, but only a quarter of this figure in the phosphatides. Under these

conditions the specific activity of the dienoic acids is only slightly less than that of the monoenoic acids (unchanged *cis*-octadec-12-enoic acid). It was found, however, that the dienoic acids consisted of equal parts of unlabeled linoleic acids (from the depot fat) and strongly labeled octadeca-12,15-dienoic acid. Consequently, *cis*-octadec-12-enoic acid is not a precursor of linoleic acid in the rat. In contrast to previous ideas, the second double bond is introduced nearer to the methyl end than to the carboxyl end of the acid.

13

Comparison of Calculated and Measured Line Intensities in X-Ray Fluorescence Analysis

K. H. Grothe and *G. Krause*, Hannover (Germany)

In the calculation of the intensity of X-ray fluorescence lines, monochromatic exciting radiation is generally assumed. For more accurate calculations, therefore, the intensity distribution of the Bremsspectrum of a tungsten tube was determined, including the characteristic lines.

The spectrum was subdivided into 600 equal, almost monochromatic sections, and for each of these sections the intensities of the K lines of cobalt and nickel were calculated with all correction factors taken into account. The sum of all the part-intensities gives the total fluorescence intensity. The calculations were carried out for mixtures of cobalt and nickel (Co:Ni = 0.01:1 to 60:1).

Although the strong tungsten lines in the exciting spectrum were only slightly below the cobalt and nickel absorption edges, the fluorescence lines were 50 % excited by the Bremsspectrum. Even regions of the Bremsspectrum with very much shorter wavelengths than the absorption edges still contributed considerably to the excitation.

It was possible to determine the secondary excitation of the cobalt line by the Kβ line of Ni by comparing the measured intensities with those in the calculation of which the secondary excitation was not taken into account. It amounted to about 8 % for a cobalt-nickel ratio of 1:1 and about 20 % for higher concentrations of nickel. This method is generally applicable to the determination of the secondary excitation.

14

New Phases Near the Composition $NbO_{2.5}$)

R. Gruehn, *D. Bergner*, and *H. Schäfer*, Münster (Germany

With M = (Nb^{IV}, Nb^{V}) and (Nb^{V}, W^{VI}) ten independent phases are observed in the range from $MO_{2.4}$ to $MO_{2.6}$; the numerous modifications of Nb_2O_5 are not included in this number.

The Nb/O system was investigated with an arrangement with which the heterogeneous equilibrium could be measured simultaneously. At 1300 °C, Nb_2O_5 or NbO_2 was heated in definite mixtures of H_2O and H_2 (method A). Under these conditions, all the NbO_x phases mentioned below can be obtained.

The narrow phase $NbO_{2.482}$ and the homogeneity region $NbO_{2.479-2.467}$ are available by chemical transport (method B) as well as by method A [1, 2]. Compounds of the same type arise in the heating of mixed precipitates (method C) in the TiO_2-Nb_2O_5 system [1]. The upper phase boundary at $MO_{2.479 \pm 0.001}$ is identical with the compound $TiNb_{24}O_{62}$ ($MO_{2.480}$) the structure of which was determined by *Roth* and *Wadsley* [3a]. The high stability of the lower phase boundary $MO_{2.467}$ is surprising; this can be obtained as (Nb^{IV}, Nb)$O_{2.467}$ (methods A, B), (Ti^{IV}Nb)$O_{2.467}$ (method C), and by heating the oxide mixture (method D) as (Al, Nb)$O_{2.467}$[4], (Ga, Nb)$O_{2.467}$ and (Fe^{III}, Nb)$O_{2.467}$.

Method A gives two other phases: $NbO_{2.453}$, which is identical with *Norin*'s $Nb_{22}O_{54}$ ($NbO_{2.454}$) [5], and $NbO_{2.460-2.466}$. The latter gives Guinier diagrams very similar to those of the new compound (Nb, W)$O_{2.506-2.512}$ (method D). The upper limits of the two phases possibly correspond to the members of a new structurally related series $M_{3n+2}O_{8n-1}$ with n = 10 and n = 13.

As the lowest phase, $NbO_{2.417}$(I) arises at 1100 °C and $NbO_{2.417}$(II) at 1300 °C by method A; both can also be obtained by method B [1].

In the Nb_2O_5/WO_3 system (method D), we found a further new compound (Nb,W)$O_{2.567}$. The Guinier diagram shows a close relationship to the neighboring phases (Nb,W)$O_{2.538}$ and (Nb,W)$O_{2.589}$, the structures of which were determined by *Roth* and *Wadsley* [3b]. However, (Nb,W)$O_{2.567}$ is obviously not to be assigned to one of the structural series $M_{3n+1}O_{8n+1}$ and $M_{4n+3}O_{11n}$ to which these and other phases belong [3b].

The composition of the phase (Nb,W)$O_{2.653 \pm 0.005}$ (method D, 1000–1100 °C) differs from the ratio $Nb_2O_5 \cdot WO_3 (= MO_{2.667})$. A previously described "$Nb_2O_5 \cdot WO_3$" [6] should probably be described as (Nb,W)$O_{2.653}$. The corresponding (Ta, W)$O_{2.653}$ has also been found.

[1] *R. Gruehn* and *H. Schäfer*, Naturwissenschaften *50*, 642 (1963).

[2] *H. Schäfer*, *R. Gruehn*, *F. Schulte*, and *W. Mertin*, Bull. Soc. chim. France *1965*, 1161.

[3] *R. S. Roth* and *A. D. Wadsley*, Acta Cryst. *18*, 724 (1965) (a); *19*, 26, 32, 38, 42 (1965) (b).

[4] This phase corresponds to the "(Al, Nb)$O_{2.46}$" of *G. K. Layden*, J. Amer. Cer. Soc. *46*, 506 (1963).

[5] *R. Norin* and *A. Magnéli*, Naturwissenschaften *47*, 354 (1960); also personal communication from *R. Norin*.

[6] *L. I. Fiegel*, *G. P. Mohanty*, and *I. H. Healy*, J. chem. Engng. Data *9*, 365 (1964).

15

Mass-Spectrometric Sequence Analysis of Acetylated Peptides of Aromatic Amino Acids

H. Grützmacher, Hamburg (Germany)

In the mass spectra of simple aliphatic *N*-acetylpeptides, aminoacylium or iminium ions are formed preferentially by cleavage of the CO–NH or the –CHR–CO– bonds. These reactions can be explained by the removal of an electron from the electron-rich peptide group on electron impact. Aromatic systems are also readily ionized by electron impact. When phenylalanine, tyrosine, tryptophan, or histidine is present in the petide chain, the positive charge in the molecule ion can also be taken over by the aromatic side-chain, which leads to the frequent formation of "side-chain" ions $Ar-CH_2^{\oplus}$. The intensity of the lines due to these ions is particularly high with an *N*-terminal position of the aromatic amino acid. It increases in the sequence phenylalanine < histidine < tyrosine < tryptophan. The same sequence is found from the mass spectra of simple amino acid derivatives. The relative intensities of the otherwise common aminoacylium and iminium ions decrease in the same sequence. A second reaction typical of the mass spectra of the *N*-acetylpeptides of aromatic amino acids is the elimination of the amino group together with the adhering acyl residue as a neutral amide molecule from the molecular and fragment ions.

The nature and the position of the aromatic amino acid in the peptide can be determined from the mass number of these characteristic ions.

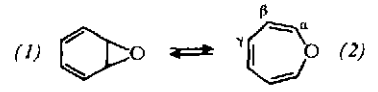
16

NMR-Spectroscopic Investigations of the Kinetics of the Benzene Oxide-Oxepin Equilibrium

H. Günther, Köln (Germany)

Oxepin [1] exhibits a proton-resonance spectrum at room temperature which agrees neither with the structure of benzene oxide *(1)* nor with the valence-tautomeric monocyclic

structure *(2)*. The absorption of the γ-, β-, and α-protons at 3.9, 4.4, and 4.8 τ and the temperature-dependent changes of the spectrum are however satisfactorily explained by the assumption of a valence-tautomeric equilibrium *(1)* ⇌ *(2)* with comparable concentrations of the two forms.



The existence of valence-tautomerism has now been confirmed by NMR measurements in CF_3Br/pentane (2:1) between −87 and −127 °C. After broadening of all the signals, an incipient splitting of the α-proton signal is observed at *ca.* −113 °C. At −127 °C, the spectrum corresponds to a superposition of the spectra of the two compounds. On the basis of the intensity ratio found, the following assigment was made:

$$\tau^{\alpha}_{(1)} = 6.0;\ \tau^{\beta}_{(1)} = 3.7;\ \tau^{\gamma}_{(1)} = 3.7;\ \tau^{\alpha}_{(2)} = 4.3;\ \tau^{\beta}_{(2)} = 4.3;\ \tau^{\gamma}_{(2)} = 3.7.$$

The relative chemical shift between the α-protons in *(1)* and *(2)* is 100.8 ± 5.1 cps. The mole fractions of the two forms are obtained from the intensity ratios of the signals below the coalescence temperature and from the chemical shift of the α-protons in the averaged spectrum ($\nu^{\alpha} - p_{(1)}\nu^{\alpha}_{(1)} + p_{(2)}\nu^{\alpha}_{(2)}$) above −110 °C, and the equilibrium constants are obtained from $K = p_{(2)}/p_{(1)}$. The temperature-dependence of K gives the heat of the reaction *(1)* → *(2)* as $\Delta H^{\circ} = 1.7 \pm 0.4$ kcal/mole. The life-time $\tau_{(1)}$ of benzene oxide was determined from the half-width of the α-proton signal in the region of slow exchange below the coalescence temperature and of fast exchange above −110 °C. The line width was corrected for field inhomogeneity and spin-spin coupling with the β-protons. Using 10 measured points, the Arrhenius equation gives an activation energy of $E_a = 9.1 \pm 0.8$ kcal/mole and a frequency factor $A = 2.5 \times 10^{14}$ for the reaction *(1)* → *(2)*. For the reverse reaction $E_a = 7.2 \pm 1.0$ kcal/mole and $A = 1.3 \times 10^{12}$. The ratio of the frequency factors gives the entropy change for the reaction *(1)* → *(2)* as $\Delta S^{\circ} = 10$ cal. deg.$^{-1}$ mole^{-1}.

[1] *E. Vogel, W. A. Böll,* and *H. Günther,* Tetrahedron Letters *1965*, 609.

17

Sulfophthalein Ethers

H. Haeussler, Seelze (Germany)

Alcoholic solutions of some sulfophthaleins bleach on long standing, owing to the formation of ethers. This reaction has been investigated with Phenol Red as an example, using *Stahl*'s gradient thin-layer technique [1].

Phenol Red first forms the yellow monomethyl ether and then a colorless dimethyl ether in the sultone form. The sultone dissolved in dioxane migrates to the solvent front on a thin-layer plate. At pH 1.7, it forms the pink cation when the developed plate is dried. Above pH 2, the sultone adds on water when the starting spot is dried, to form the dimethyl ether of the carbinol form; partial hydrolysis to the monomethyl ether also occurs. If the sultone is applied in methanolic solution, above pH 8 the trimethyl ether of the carbinol form is formed as well, by the addition of methanol to the sultone of the dimethyl ether.

Phenol Red reacts with higher alcohols in a substantially similar manner. The reaction rate decreases considerably with increasing chain length. However, the dimethyl ether of Phenol Red adds alcohols instantaneously. This reaction is proposed for the identification of alcohols, because of the distinct R_f-values of the mixed trialkyl ethers formed. The dimethyl ether also reacts instantaneously with ammonia and with primary and secondary amines.

Alcoholic solutions of Chlorophenol Red, Bromophenol Red, and Thymol Blue also form ethers readily. On the other hand, solutions of Bromophenol Blue and Bromocresol Green are stable on storage.

[1] *E. Stahl,* Chem. Ing. Techn. *36*, 942 (1964); Angew. Chem. internat. Edit. *3*, 784 (1964).

18

Acid-Catalysed Rearrangements of N-Halogenoguanidines

A. Heesing, H. Schulze, and *U. Wernicke,* Münster (Germany)

The thermal stability of alkylated *N*-chloroguanidines depends markedly on the position of the alkyl groups. Symmetrically disubstituted guanidines give the most stable *N*-halogeno derivatives. Explanation of this effect is difficult because of the large number of possible isomers and tautomers.

Arylguanidines can be converted into *N*-halogeno compounds only if oxidation to intensely colored quinoid by-products is inhibited by substitution. This oxidation does not take place with arylated amides, ureas, and amidines.

On thermal decomposition of *N*-halogenoguanidines, most of the guanidine is re-formed; in addition, alkyl and arylalkyl side-chains are split off as aldehydes or acids. Chlorinations in the sense of a thermally induced Orton rearrangement [1] play no part.

Aralkylated *N*-chloroguanidines rearrange almost instantaneously in concentrated sulfuric acid to products chlorinated in the nucleus. Trapping experiments show the intermolecular character of the rearrangement. The high velocity and the high *o*/*p* ratio show that the reaction takes place through Cl^+ (or the protonated *N*-chloroguanidine). The reaction therefore corresponds only formally to the Orton rearrangement.

The same isomer ratio (*o*:*m*:*p* = 7: *ca.* 0:3) is obtained in the chlorination of alkylguanidines with other *N*-chloro compounds (*e.g.*, *N*-chlorosuccinimide, -phthalimide, and -acetamide) in concentrated sulfuric acid. The guanidinium group, which is separated by one or two CH_2 groups from the phenyl group, thus exerts no directing effect on the substitution despite its charge. *N*-Phenyl-*N*-methylguanidine also gives also gives very little of the *meta* isomer in the rearrangement of its *N'*-chloro-derivative and in the chlorination with the very active *N*-chloro-*N'*-butylguanidine (*o*:*m*:*p* = 1:1:4). The reactions are significantly slower. The small amount of *o*-isomer must be ascribed to the repulsion of the attacking cation by the charge of the guanidinium group. The small extent of the *m*-directing effect, which is surprising when compared with all other positively charged first substituents that have so far been investigated [2], can be explained by mesomerism between the phenyl and the guanidine groups, as a result of which the phenyl residue is made negative in the *o*- and *p*-positions.

[1] *E. D. Hughes* and *C. K. Ingold,* Quart. Rev. (chem. Soc., London) *6*, 35 (1952).

[2] *J. H. Ridd* and *J. H. P. Utley,* Proc. chem. Soc. (London) *1964*, 24.

19

Reactions of Alkylaluminum Compounds with Diazomethane

H. Hoberg, Mülheim/Ruhr (Germany)

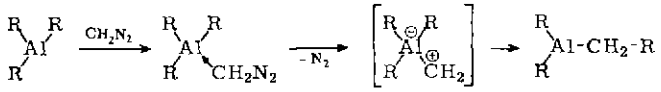
The action of CH_2N_2 at room temperature on organoaluminum compounds R_2AlX (X = R,H, halogen, or OR) gives rise to the evolution of N_2. Reactions are rapid when X = Cl, Br, or I, the corresponding halogenomethylaluminum compounds $R_2Al\text{-}CH_2X$ being formed [1]. When X = H or R, the products *(1)* are immediately produced.

$$R_2AlX + 3m\ CH_2N_2 \longrightarrow Al\text{-}(CH_2)_{m_1}\text{-}R\ (CH_2)_{m_2}\text{-}R\ (CH_2)_{m_3}\text{-}X + 3m\ N_2$$

(1), $m_1 + m_2 + m_3 = 3m$

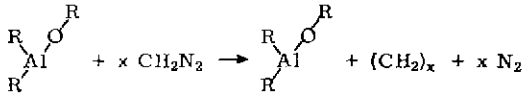
Aluminum compounds with X = H are more reactive with respect to diazomethane than those with X=R, whereas those with X = CH_3 react less readily than those with X = CH_2–R. This agrees with the situation in the reaction between 1-alkenes and the corresponding Al compounds [2]. With diazomethane, R_2AlX with X = F or OR forms exclusively polymethylene with slow elimination of N_2. CH_2N_2 does not react at room temperature with dialkyl-*N*-dialkylaminoaluminum $R_2Al\text{-}NR_2$. The same applies to salt-like organoaluminates, *e.g.* $Na[Al(C_2H_5)_4]$.

While the formation of compounds *(1)* is explained by the intermediate formation of an "inverse Al-ylide" *(2)*, the



(2)

formation of polymethylene must be regarded as a catalytic reaction of the organoaluminum compounds.



[1] *H. Hoberg*, Liebigs Ann. Chem. *656*, 1, 15 (1962).

[2] *K. Ziegler, H. G. Gellert, K. Zosel, E. Holzkamp, J. Schneider, M. Söll*, and *W. R. Kroll*, Liebigs Ann. Chem. *629*, 121 (1960).

20

Coordination Chemistry of Organometallic Compounds of Group IVb Elements

F. Huber, Aachen (Germany)

8-Hydroxyquinoline (HOx) reacts with R_2PbHal_2 in alcoholic solution on addition of NH_3 to give yellow, crystalline dioxinates $R_2Pb(Ox)_2$ (R = CH_3, decomp. p. > 135 °C; C_2H_5, decomp. p. > 120 °C; n-C_4H_9, decomp. p. > 120 °C; C_6H_5, decomp. p. > 167 °C), while on addition of water, crystalline, yellow complexes of the composition $R_2PbHal(Ox)$ precipitate, which can be recrystallized from methanol. Analogous compounds arise when alcoholic solutions of HOx and R_2PbA_2 (A = NO_3; carboxylate) are mixed. Some representatives of this new kind of compound $R_2MX(Ox)$ have also been prepared with M = Sn and Ge (see Table).

	R	X	Decomp. p. > °C
$R_2PbX(Ox)$	CH_3	CF_3CO_2	190
	C_2H_5	Br	110 m.p.
	n-C_4H_9	Cl	122
		CH_3CO_2	180
	C_6H_5	Cl	187
		NO_3	228
		$C_2H_5CO_2$	212
		$ClCH_2CO_2$	204
		CF_3CO_2	240
$R_2SnX(Ox)$	CH_3	Cl	157 m.p.
	n-C_4H_9	Cl	50
		CH_3CO_2	142
	C_6H_5	Cl	147 m.p.
$R_2GeX(Ox)$	C_6H_5	Cl	34

Molecular weight determinations show that some of these compounds (particularly the halogenooxinates) are monomeric in solution, while others are polymeric. In agreement with the result of conductivity measurements, this excludes a salt-like structure $[R_2M(Ox)]X$ with a coordination number of 4; it is assumed that in the monomeric compounds the metal has a coordination number of 5 and in the polymers a coordination number of 6.

In the dioxinates $R_2M(Ox)_2$ [$(C_6H_5)_2Ge(Ox)_2$, decomp. p. > 140 °C has also been prepared] and in the benzoylacetonates [*e.g.* $(C_6H_5)_2Pb(Bzac)_2$, m.p. 160 °C], as in the donor-acceptor complexes $R_2MX_2{\cdot}2D$ (*e.g.* D = pyridine) there is a coordination number of 6 (prepared for the first time: M = Pb; R = C_2H_5, n-C_4H_9, C_6H_5 [1]; X = Cl, Br; – M = Sn; R = n-C_4H_9, C_6H_5; X = Cl, CH_3COO; D/2 = 1,10-phenanthroline, 2,2′-dipyridyl; – M = Ge; R = n-C_4H_9, C_6H_5; X = Cl; D/2 = 1,10-phenanthroline). The tendency of R_2PbX_2 to form coordination compounds is more pronounced than was previously assumed. The reaction of R_4Pb (R = CH_3, C_2H_5, C_6H_5) with dry SO_2 gives $R_2Pb(SO_2R)_2$, a sulfinate which is insoluble in all the usual solvents and is, on the basis of infrared spectra, a coordination polymer with sixfold-coordinated Pb.

[1] $(C_6H_5)_2PbCl_2$·phenanthroline and $(C_6H_5)_2PbCl$ 2,2′-dipyridyl have recently also been prepared by *K. Hills* and *M. C. Henry*, J. organomet. Chemistry *3*, 159 (1965).

21

Metabolite Content and Function of the Substrate-Free Perfused Rabbit Brain

P. Hürter and *G. Gercken*, Hamburg (Germany)

According to *Geiger et al.* [1], cat's brain remains capable of functioning on artificial perfusion with nutrient-free solution for more than one hour. This raises the question of what materials are degraded when glucose is not available for the production of energy.

We have investigated the influence of a substrate deficiency on the rabbit brain with the help of an arrangement in which the head, separated from the circulation of the body, was perfused with a Sigma-pump. The natural blood flow was then completely prevented, and the circulation was independent of regulation by the brain centers. The perfusion solution used was a simplified blood consisting of bovine erythrocytes and phosphate Ringer solution with the addition of Haemaccel. The contents of adenosine triphosphate, creatine phosphate, glycogen, glucose, and lactate were determined enzymatically in brain tissue taken after various times, and were fixed in liquid air. With a low supply of glucose (1 mmole/l of the perfusion solution), spontaneous electric potentials of the brain were also recorded after 60 min from the beginning of perfusion. The contents of ATP and creatine phosphate in the brain remained unchanged. On the other hand, with complete absence of glucose, the functioning of the brain ceased after about 7 min. After 10 min the intracellular content of free glucose was only 0.3 µmole/g of fresh tissue and after 30 minutes 0.05 µmole/g. The concentration of energy-rich phosphate compounds had already fallen after only 10 minutes. Within 30 minutes, the ATP content fell from 2.0 to 0.32 µmole/g of fresh tissue and the content of creatine phosphate from 2.1 to 0.29 µmole/g. In contrast to experiments on oxygen deficiency [2], the glycogen content of the brain with substrate deficiency and a sufficient supply of oxygen fell only slowly. Since the signs of an energy deficit appeared even in the first few minutes, under these conditions the rate of degradation of glycogen is obviously not sufficient to cover the lack of free glucose.

[1] *A. Geiger, J. Magnes*, and *R. S. Geiger*, Nature (London) *170*, 754 (1952).

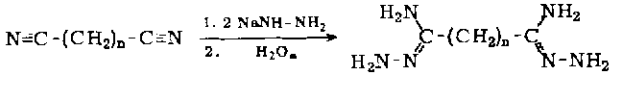
[2] *W. Thorn, H. Scholl, G. Pfleiderer*, and *B. Müldener*, J. Neurochem. *2*, 150 (1958).

22

Uses of Sodium Hydrazide for the Synthesis and Degradation of Organic Compounds

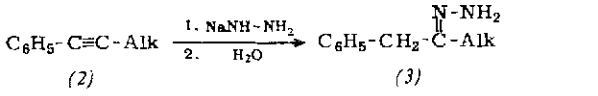
Th. Kauffmann, L. Bán, W. Burkhardt, E. Rauch, and J. Sobel, Münster and Darmstadt (Germany)

The hitherto unknown diamidrazones *(1)*, which undergo interesting polymerization reactions, are obtained conveniently and in good yield by treating the corresponding dinitriles in boiling ether with sodium hydrazide in the presence of free hydrazine. Under conditions (excess of sodium hydrazide without the addition of hydrazine, ether at 0 °C) which lead almost quantitatively to amidrazones in the case of mononitriles, aliphatic dinitriles remain substantially unaffected.



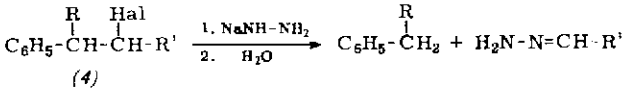
(1)

With alkyl groups other than CH_3 (for which metallation takes place), acetylenes *(2)* react with sodium hydrazide in boiling ether to give good yields of hydrazones *(3)* from which the corresponding ketones, amines, and azines can be conveniently prepared.



(2) *(3)*

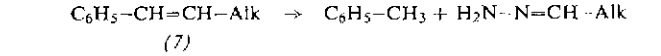
Halides of type *(4)* (Hal = Cl, Br, I; R and R′ = H or alkyl) are split by sodium hydrazide in boiling diethyl or diisopropyl ether. As a rule, the yields of toluene are higher than 75%. On the other hand, halides of types *(5)* and *(6)* give only a small amount of toluene in corresponding reactions. Here the main reaction is the substitution of the halogen by hydrogen [halides *(5)*] or by the hydrazino group [halides *(6)*].



(4)

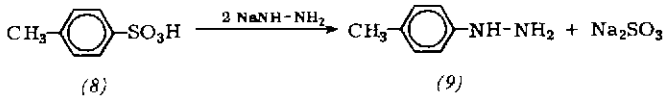
(5) *(6)*

In the splitting of ethylenes *(7)* with sodium hydrazide [1], in accordance with *M. S. Newman*'s "rule of six" [2], the rate of decomposition fails suddenly when the unbranched alkyl residue, extended from 4 to 5 and more C-atoms, is capable of sterically screening the olefinic double bond.



(7)

Aromatic sulfonic acids are smoothly converted into the corresponding arylhydrazines by treatment with sodium hydrazide in ether at 35 °C. Thus *p*-toluenesulfonic acid *(8)* gives *p*-tolylhydrazine *(9)* in 98% yield; since no *m*-tolylhydrazine forms, the substitution takes place by the addition/elimination mechanism. This surprising reaction opens up a new route to arylhydrazines.



(8) *(9)*

[1] *Th. Kauffmann*, Angew. Chem. *76*, 214 (1964); Angew. Chem. internat. Edit. *3*, 349 (1964).

[2] *M. S. Newman* in: Steric Effects in Organic Chemistry. Wiley, New York 1965, p. 206.

23

Reactions of Trithiocarbonic Acid

B. Krebs and *G. Gattow*, Göttingen (Germany)

Trithiocarbonic acid $SC(SH)_2$ is a versatile reagent for the introduction of the CS_3 group: because of its ready decomposition into H_2S and CS_2, it is often a preparatively more convenient substitute for H_2S in the preparation of R^1-S-R^2 bonds (R^1,R^2 = inorganic or organic groups) or for the preparation of inorganic sulfides sensitive to hydrolysis. The reaction of $SC(SH)_2$ with mono- or polyfunctional halogen compounds takes place particularly smoothly.

In particular, the following compounds have been prepared by the reaction of stoichiometric amounts in chloroform or benzene:

1. chemically very stable, yellow to orange-brown solid polymers of uniform composition $(CS_3)_n$ and $(CS_{2.5})_n$ (n = 8 to 12) by the reaction of $SC(SH)_2$ with Br_2 or from Na_2CS_3 + S + thiophosgene [1];

2. 1,3-dithiolan-2-thione-4,5-dione $C_3O_2S_3$ in the form of lustrous red crystals by the reaction of $SC(SH)_2$ with oxalyl chloride [2];

3. dimeric thiomalonic anhydride $(C_3H_2O_2S)_2$ as colorless crystals by reaction with malonyl chloride;

4. thiosuccinic anhydride $C_4H_4O_2S$ from $SC(SH)_2$ and succinyl chloride;

5. a yellow, chemically very stable polymer of composition $(S-CO-CH=CH-CO)_n$ (n = 4 or 5) from $SC(SH)_2$ and fumaroyl dichloride;

6. a very stable, yellow polymer insensitive to hydrolysis, of uniform composition $[SP(C_{0.5}S_{1.5})_3]_n$ from PCl_5 and $SC(SH)_2$, as well as a similar compound from $SC(SH)_2$ and PCl_3;

7. solid white addition compounds $BX_3 \cdot SC(SH)_2$ stable below −20 °C by the reaction of the boron halides BF_3, BCl_3, and BBr_3 with $SC(SH)_2$; and

8. Al_2S_3 by the reaction of $SC(SH)_2$ with $AlCl_3$.

Other new products were obtained in the reaction of $SC(SH)_2$ with Se_2Cl_2, $SeCl_4$, and BrCN at low temperatures. The compounds prepared were characterized by chemical, infrared spectroscopic, and X-ray methods.

[1] *B. Krebs* and *G. Gattow*, Z. anorg. allg. Chem. *338*, 225 (1965).

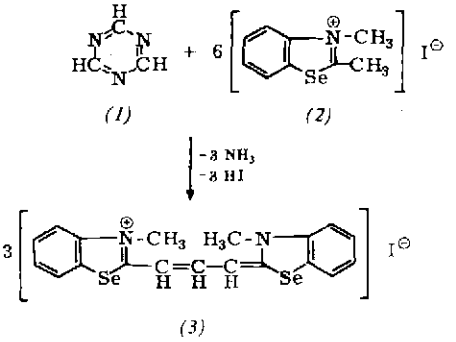
[2] *B. Krebs* and *G. Gattow*, Angew. Chem. *75*, 978 (1963); Angew. Chem. internat. Edit. *2*, 618 (1963).

24

Ring Opening of 6-Membered Heterocycles by Nucleophilic Reagents

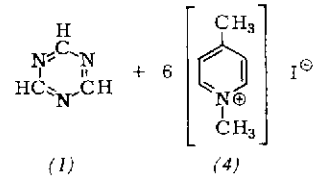
A. Kreutzberger, Münster (Germany)

1,3,5-Triazine *(1)* and 2,3-dimethyl-1,3-benzoselenazolium iodide *(2)* in anhydrous pyridine give bis[methylbenzoselenazole-(2)]-trimethinecyanine iodide *(3)* in a smooth reaction and with good yield. In contrast to the condensation of *(2)* with orthoformic ester, the 1,3,5-triazine method permits the use of lower temperatures and shorter reaction times.

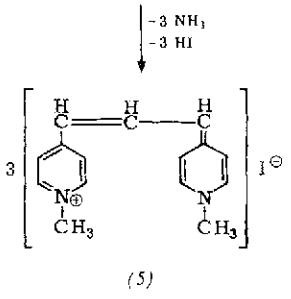


(1) *(2)* *(3)*

This method is also applicable to quarternary bases which cannot be condensed with orthoformic ester. While *N*-methyl-γ-picolinium iodide *(4)* reacts with chloroform only in the presence of a large excess of caustic potash and with strong heating, with 1,3,5-triazine it forms bis-[1-methyl-pyridine-(4)]-trimethinecyanine iodide *(5)* even on moderate heating of the reaction mixture.



(1) *(4)*



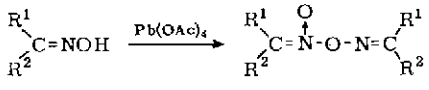
(5)

25

The Oxidation of Aromatic and α,β-Unsaturated Oximes with Lead Tetraacetate

H. Kropf, Hamburg (Germany)

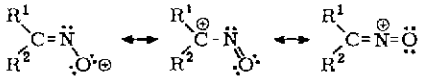
Whereas the reaction of aliphatic and alicyclic oximes with lead tetraacetate gives *gem*-acetoxynitrosoalkanes or their dimers [1], these can be detected only for a very short time or not at all in the oxidation of aromatic and α,β-unsaturated oximes. In solvents such as ether, tetrahydrofuran, benzene, and methyl chloride, in addition to the carbonyl compounds, the corresponding oxime anhydride *N*-oxides *(1)* are obtained [2].



(1)

Examples: α- or β-benzaldoxime → benzaldoxime anhydride *N*-oxide; α- or β-cinnamaldoxime → cinnamaldoxime anhydride *N*-oxide; α- or β-furfuraldoxime → furfuraldoxime anhydride *N*-oxide; benzophenone oxime → benzophenone oxime anhydride *N*-oxide; benzil α- or β-dioxime → diphenylfuroxan.

The formation of these compounds is explained as a trapping reaction of the mesomeric cations *(2)* arising as primary products by unconverted oxime.



(2a) *(2b)* *(2c)*

Since in no case were sterically individual isomers isolated after the oxidation of unsymmetrically substituted oximes, in particular of aldoximes, participation of the limiting structure *(2c)* cannot be excluded.

The carbonyl compound corresponding to the oxime used probably arises from the *gem*-acetoxynitrosoalkane formed as an intermediate *via* a *gem*-diacetoxy compound. This is also indicated by the appearance of nitrous gases in the reaction in glacial acetic acid, in which it was also not possible to detect any oxime anhydride *N*-oxide. Benzaldoxime anhydride *N*-oxide can be disproportionated with HCl/glacial acetic acid to the oxime and the nitroso compound.

[1] *D. C. Iffland* and *G. X. Criner*, Chem. and Ind. *1956*, 176; *H. Kropf* and *R. Lambeck*, unpublished work.

[2] Some of these compounds have also been prepared from the oximes with nitrous gases, nitrous acid, Na hypochlorite, or I_2/Na_2CO_3, and have been called oxime peroxides: *J. L. Smith*, Chem. Rev. *22*, 239 (1938); *J. H. Boyer* and *H. Alul*, J. Amer. chem. Soc. *81*, 4237 (1959).

26

Coordination Polymers of Dialkylphosphinic Acids

W. Kuchen and *H. Hertel*, Aachen (Germany)

Phosphinic acids occur in metal complexes in various ways as bridge ligands. The dialkyldithiophosphinato complexes $[R_2PSS]_2M$ of Zn(II), Cd(II), and Hg(II) are associated through ligand bridges. The corresponding Zn(II)-complexes of the acids $(C_2H_5)_2PSSeH$ and $(C_2H_5)_2PSeSeH$ exhibit a slight association in benzene solution. On the other hand, molecular weights of up to about 15,000, depending on the pretreatment of the preparations, have been found for the dialkylphosphinate complexes $[R_2POO]_2Co$ ($R = C_3H_7$, C_4H_9) in benzene. Coordination polymers also arise in the reaction of diethyldithiophosphinic acid or its sodium salt with metal carbonates or the corresponding halides in organic solvents:

$$\begin{matrix} 2\ (C_2H_5)_2PSOH + MCO_3 \\ \text{or} \\ 2\ (C_2H_5)_2PSONa + MX_2 \end{matrix} \xrightarrow[-\ 2\ NaX]{-H_2O,\ \ CO_2} [(C_2H_5)_2PSO]_2M$$

The colorless bis(diethylthiophosphino)-zinc(II) and the corresponding deep blue Co(II) complex are powders which melt without decomposition and dissolve in organic solvents after previous swelling. On evaporation, their very viscous benzene solutions leave smooth highly adherent films. Osmometric molecular weight determinations in benzene have shown a marked concentration-dependence of the molecular weights; for example, the molecular weight of the Zn complex varies between 3000 and 12,000 (at 10–65 g/l, 25 °C). A molecular weight of 60,000 (± 20%) was found for the Co complex with a Zellophan-600 membrane, which proved to be permeable to small amounts of low-molecular weight components of the polydisperse substance. The reduced viscosities, which increase strongly with increasing concentration of the benzene solutions of the two complexes, and also the concentration- and temperature-dependences of the molecular weights, indicate that weakly aggregated threadlike molecules are present.

27

Structure and Thermodynamics of Molten Halides

H. Kühnl, Giessen (Germany)

When halides of multivalent metals are dissolved in molten alkali-metal halides, halogeno complex ions are formed. Information on the coordination and association of the dissolved salts is given by a comparison of the liquidus lines on the alkali-metal chloride side of the phase diagram with curves calculated theoretically. The latter were obtained by a method due to *Flood* and *Urnes* [1] based on the Temkin model of salt melts.

According to this model, in melts of KCl the chlorides of bivalent Cr, Mn, Fe, Co, Cu, Zn, Cd, and Mg form complexes of the type $[MCl_4]^{2-}$. On the other hand, $TiCl_2$ and VCl_2 associate to form complicated mixtures of polynuclear complex ions. Solutions of $TiCl_3$, VCl_3, $CeCl_3$, and $PuCl_3$ in a KCl melt show that the chlorides of the trivalent ions are present predominantly as $[MCl_6]^{3-}$ complexes. $AlCl_3$ and $FeCl_3$ are

exceptions; with these substances the existence of ions of the type $[M_2Cl_8]^{2-}$ must be assumed.

Analogous statements apply to solutions in molten RbCl. Because of the higher charge density of the Na^+, lower mean coordination numbers are obtained in a melt of NaCl than in molten KCl or RbCl.

The influence of the composition of mixed melts of alkali-metal halides, sometimes with added alkaline-earth metal halides, on the enthalpies of solution of $FeCl_2$ and $FeBr_2$ was investigated by EMF measurements. In this case the solvent can be described by the mean charge density of the cations or anions. A bend in the plot of the enthalpy of solution against cation charge density indicates that in solutions of $FeCl_2$, complex anions change into cationic units at a charge density of 1.2.

A change in the mean charge density of the anions in solutions of $FeBr_2$ in bromide melts affects the excess Gibbs free energy of solution 10–15 times more strongly than a corresponding change in the cations, since the Fe^{2+} ions are affected by the anions from the first coordination sphere and by the cations of the second coordination sphere.

[1] *H. Flood* and *S. Urnes*, Z. Elektrochem. *59*, 834 (1955).

28

Metabolite Content and Protein-Synthesizing Capacity of Cat Pancreas Before and After Interruption of the Circulation for Two Hours

F. Liemann and *W. Berndt*, Hamburg (Germany)

We have investigated the synthesis of protein in cat pancreas as a function of the energy metabolism. For this purpose, the protein synthesis was stimulated by infusion of the hormones pancreozymin and secretin, and, with continuation of the infusion, the flow of blood through the gland was interrupted for 2 hours. The metabolites of the energy metabolism and the protein synthesis were determined before the infusion, after 2 hours of infusion, after interruption of the circulation for 2 hours, and 2 hours after restoring the circulation. The results show: 1) the infusion brings about a considerable increase in the rate of metabolism, 2) the ADP-content of the pancreas is not increased after interruption of the circulation for 2 h; 3) the cellular components responsible for the synthesis of protein withstand an interruption of the circulation for 2 h; 4) after interruption of the circulation, less protein is secreted per unit time, but it contains all enzymes in the same ratio as before.

29

New Compounds of the $CaFe_2O_4$ Type

Hk. Müller-Buschbaum, Münster (Germany)

Compounds of the composition $M^{2+}M_2^{3+}O_4$ (where M^{2+} is, for example, Mg, Ca, Sr, Ba, and M^{3+} is Sc, Y, La) have been obtained in a plasma furnace above 2000 °C in well-crystallized form. So far, $CaSc_2O_4$, SrY_2O_4, and $MgSc_2O_4$ have been investigated by X-ray analysis. The compounds, which are colorless, stable to air, and soluble in hot mineral acids, crystallize orthorhombically in the space group D_{2h}^{16}-Pnam and are isotypical with $CaFe_2O_4$ [1, 2] (lattice constants $CaSc_2O_4$: a = 9.65, b = 11.20, c = 3.16 Å; SrY_2O_4: a = 10.08, b = 11.91, c = 3.40 Å; $MgSc_2O_4$: a = 9.51, b = 10.83, c = 3.11 Å). M^{3+} is always surrounded octahedrally by oxygen, whereas M^{2+} has six O-neighbors in the form of a trigonal prism with other O-particles arranged over the prism surfaces, two of these belonging to the coordination sphere [3]. The distribution of metal in $MgSc_2O_4$, which no longer corresponds to $CaSc_2O_4$, is remarkable. Calculations of structure factors and $(F_o - F_c)$ syntheses show that Mg and Sc are statistically distributed over the metal positions. This result is in accord with the mean distances between the positions of M^{3+} and oxygen, which are smaller than the sum of the ionic radii (2.10 Å instead of 2.14 Å), or the mean Sc^{3+}–O distances in other scandium compounds. The prismatic environment present for the M^{2+} particles is "too large" for the relatively "small" Mg^{2+} ions. It is true that this discrepancy is moderated by partial replacement of the Mg by Sc particles, but it is not eliminated. $MgSc_2O_4$ must therefore, in contrast to the metallates $CaSc_2O_4$ and SrY_2O_4, be regarded as a mixed oxide.

Distance calculations on compounds of the $CaFe_2O_4$ type show that the $[M^{3+}{}_2O_4]^{2-}$ anion skeleton is immobile and rigid. The existence of such compounds therefore depends strongly on the size of the cation. The margin for the existence of stable compounds with small M^{2+} ions is greater than that for stable compounds with large cations. The fact that it has not so far been possible to prepare $CaSc_2O_4$ is due to this effect.

The holes for the M^{2+} ions become greater with increasing size of the octahedra of M^{3+} ions. However, the compound BaY_2O_4 can be prepared because of the larger $[Y_2O_4]^{2-}$ skelton as compared with Sc.

[1] *P. M. Hill, H. S. Peiser*, and *J. R. Rait*, Acta Crystallogr. *9*, 981 (1956).

[2] *B. F. Decker* and *J. S. Kasper*, Acta Crystallogr. *10*, 332 (1957).

[3] *Hk. Müller-Buschbaum* and *H. G. Schnering*, Z. anorg. allgem. Chem. *336*, 295 (1965).

30

Colloid Chemical Investigations on Asphaltenes

H. J. Neumann, Braunschweig (Germany)

Asphaltenes are bituminous substances which are soluble in carbon disulfide and insoluble in paraffins. For analytical determination, they are precipitated by the addition of a 40-fold volume of standard gasoline or n-pentane. The asphaltenes have been separated completely from various petroleum oils by four-stage ultrafiltration. Like the petroleum resins, they are dispersed colloidally in the crude oils. Since they precipitate on the addition of a large excess of (non-polar) paraffins, but remain colloidally dispersed on the addition of (slightly polar) naphthenic, aromatic, or chlorinated hydrocarbons, and precipitate together with other substances with more highly polar non-solvents (*e.g.* diethyl ether, ethyl acetate, acetone, isopropanol), the precipitations cannot be explained simply by solubility considerations. The asphaltenes are polydisperse, spherical, resoluble, oleophilic micellar colloids which are solubilized in the naphthenic hydrocarbons of petroleum oils. The addition of large amounts of paraffinic hydrocarbons abstract their solubilizing agents by dilution, and they coagulate. Such a precipitation of polydisperse colloids is unsuitable as an analytical method, since the solubility depends on the amount of the substrate and the past history of the sol. The asphaltenes contain almost all the inorganic constituents of the petroleum oils, and almost all the polar groups (carboxyl, aldehyde, and phenolic groups). These polar groups are responsible for aggregation to micelles (dipole forces). Hydrocarbon residues responsible for the solvation of the micelles are turned outwards. If such micelles arrive at water-oil boundaries, the molecules are oriented in such a way that the polar groups are turned towards the water, and the hydrocarbon residues project into the oil phase. This irreversibly destroys the micelles, and mechanically stable surface skins form, which stabilize water-in-oil emulsions. These emulsions can be broken by colloids dissolved in the aqueous phase and possessing a hydrophilic and an oleophilic end. This is important for secondary recovery and for the demulsifying of the emulsions obtained. Breaking the emulsion by destruction of the boundary skin brings about a reduction in viscosity.

31

Chemical Problems of Lead Poisoning

H. Rüssel, Hannover (Germany)

In order to elucidate the question of the binding of lead to liver constituents in chronically lead-poisoned cattle and sheep, liver homogenates were analysed, with the following results: 1) The lead is non-dialysable and is therefore bound to high-molecular weight substances. 2) With physiological saline, the lead passes partially into the solution and is included in the substances stable up to 80 °C. These consist of ferritin or ferritin-like compounds. 3) Lead contained in cattle liver is more than 50% insoluble in neutral aqueous solution. By solubility experiments with acids and complexing agents, it was possible to show the linkage of this lead component to iron-containing compounds. These differ from hemosiderin by their solubility in phenol, and are probably iron hydroxide-protein colloids with different particle sizes.

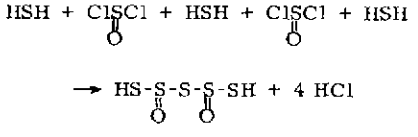
32

Synthesis of Sulfane Oxides

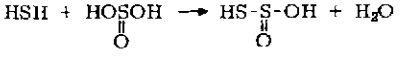
P. W. Schenk, W. Kretschmer, R. Ludwig, R. Steudel, and *M. Töpert*, Berlin (Germany)

Sulfane oxides are chain-like sulfur compounds of the type $H(S_2O)_xSH$. The structure follows from the synthesis, for which three routes have been found:

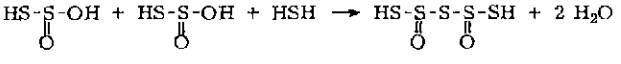
1. Condensation of $SOCl_2$ with H_2S in ether at −10 °C:



2. Polycondensation of thiosulfurous acid, which is formed from H_2S and H_2SO_3 in organic solvents at low temperatures and can be isolated[1]:

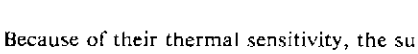


Further condensation takes place spontaneously, and in the presence of H_2S occurs according to the scheme



H_2S and SO_2 in CCl_4 at −10 °C give a yellow precipitate of the composition S:O:H ≈ 2.6:1:0.5. Even without an organic solvent, the liquid compounds give a poly(sulfane oxide) at −65 °C. SO_2Cl_2 (in CCl_4/ether at −10 °C) can also be used instead of SO_2, being reduced by H_2S to SO_2, after which the components of the Wackenroder reaction are again present together.

3. Careful hydrolysis of S_2Cl_2 in CCl_4/dioxane at −10 °C leads to a poly(sulfane oxide) of the composition S:O:H ≈ 2.6:1:1.0. The primary product is probably again thiosulfurous acid:



Because of their thermal sensitivity, the sulfane oxides often contain more sulfur than the value corresponding to the ideal formula. They decompose above 70 °C with vigorous evolution of gases; in vacuum S_2O is evolved as well as SO_2.

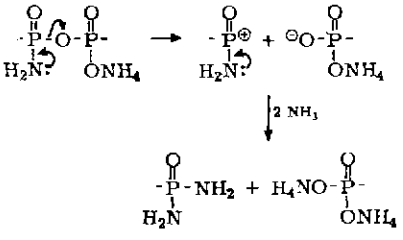
[1] *P. W. Schenk* and *R. Ludwig*, Z. Naturforsch. *20b*, 809 (1965).

33

The Ammonolysis of Diphosphorus Pentoxide

P. W. Schenk and *K. Scheffler*, Berlin (Germany)

Hexagonal-rhombohedral P_4O_{10} (H-form) and anhydrous liquid ammonia do not react with one another at atmospheric pressure. In the presence of small amounts of water or ammonium chloride (of the order of a few ppm), on the other hand, a reaction sets in which has been followed by measuring the proton magnetic resonance and by analysis of the reaction products insoluble in liquid ammonia. Water is not consumed in the reaction – on the contrary, its content in the liquid ammonia increases during the ammonolysis. While the ammonolysis of the H-form of P_4O_{10} takes place rapidly, the orthorhombic modifications of phosphorous pentoxide do not react, or react only very slowly, with liquid ammonia. The first step of the ammonolysis is the addition of an NH_4^+ ion to the oxygen of the $\geqslant P{=}O$ group. Subsequently NH_3 is added to the phosphorus atom, which has become positive. The main products of the reaction were found to be phosphoric triamide, ammonium phosphorodiamidate, and various ammonium oligophosphoroamidates, by one- and two-dimensional thin-layer chromatography. No diammonium phosphoromonoamidate is produced. The sizes and intensities of the spots in the chromatogram were compared with those from solutions of known concentrations. The yields of the ammonolysis products are independent of the water content of the liquid ammonia, provided that this is between 10^{-4} and *ca.* 8%. The directive influence of the NH_2 group leads to an accumulation of NH_2 groups on the same phosphorus atom:



34

Investigations on Triarylphosphines with Substituents of the Second Kind

G. P. Schiemenz, Kiel (Germany)

According to the classification of organic groups into (+M) and (−M) substituents, phosphine phosphorus should be classed as an electron donor while, if it is desired to retain the octet rule, the phosphorus in aromatic phosphine oxides and sulfides should exert no mesomeric effect. Ultraviolet spectra show, however, that the phosphorus in tris-(*p*-dimethylaminophenyl)phosphine, and its oxide and sulfide, and in similar compounds, probably through d-orbital participation, behaves as a (−M) substituent [1]. This finding is opposed by no convincing evidence of a 3p-donor effect of the phosphine phosphorus. The electronic effect of the phosphine phosphorus has been investigated by several independent methods on triarylphosphines $(C_6H_5)_2PC_6H_4A$ with electron-accepting substituents (A = COOH, $COOCH_3$, $CONH_2$, $CON(CH_3)_2$, $COCH_3$, CHO, CN, NO_2) in the *p*-position to the phosphorus, in which the conditions for a p-orbital participation should be particularly favorable. The pK values of the acids, and hence the Hammet constants, and the ν(C=O) frequencies, show that with respect to a phenyl residue having weak acceptor substituents in the *p*-position (A = COOH,

$COOCH_3$, $CON(CH_3)_2$, $COCH_3$, disturbed by strong intermolecular interactions in the amides) and also with respect to the unsubstituted phenyl residue, the phosphine phosphorus always behaves as a weak, and the phosphine oxide and sulfide phosphorus as a relatively strong, (−M) substituent. Intensification of the (−M) effect of *p*-substituents (A = CHO, CN, NO_2) diminishes the acceptor effect of the phosphorus in the phosphine oxides and sulfides, while the phosphine phosphorus behaves in the aldehyde as a substituent without an M effect (by NMR spectroscopy: position of the signal of the formyl proton), but in the nitrile [IR-spectroscopy: position and intensity of $\nu(C\equiv N)$] and in the nitro compound [by IR-spectroscopy: position of $\nu_{as}(NO_2)$] as a (+M) substituent having donor properties of the magnitude of a methyl group. On the other hand, the $(C_6H_5)_2N$ group is always a strong electron-donor and the phosphonium phosphorus is still a fairly strong acceptor even with respect to a *p*-nitrophenyl residue.

Consequently, both donor properties of the phosphine phosphorus and the earlier postulated reversal of the M-effect in phosphine phosphorus have been experimentally confirmed. If the measured effect is regarded as the difference between a 3d-acceptor and a 3p-donor effect, the difference between the phosphines and the phosphine oxides and sulfides (with pure 3d-orbital participation) leads to a considerable 3p-orbital participation also for those phosphines in which an acceptor effect results. The idea of an acceptor effect of phosphine phosphorus, together with a recalculation of the electronegativity of sp^2 carbon, allows for the first time an explanation of the well-known fact that the phosphorus in aromatic phosphines forms the negative end of the P–C partial dipole. The special role of the phosphorus in the series of the triaryl compounds of group Va elements and the deficient tendency of the elements of the 2nd octet to form p_π to p_π double bonds is also possibly due to d-orbital participation.

[1] *G. P. Schiemenz*, Angew. Chem. *77*, 593 (1965); Angew. Chem. internat. Edit. *4*, 603 (1965).

35

Investigations on the Constitution of Hydroxo Complexes [1]

H. G. v. Schnering, Münster (Germany)

$Na[Zn(OH)_3]$ contains discrete planar $[Zn(OH)_3]$ groups linked to one another in pairs by strong hydrogen bonds (tetragonal needles; a = 10.86, c = 5.35 Å; D_{4H}^{13}) [2, 3].

$Na_2[Cu(OH_4)]$ shows the (4+2) coordination typical of Cu^{2+}. The plane $[Cu(OH)_4]$ groups are not completely isolated, since the OH^- particles of the complex ion should be regarded as more distant partners of neighboring Cu-atoms (orthorhombic; a = 6.75, b = 6.78, c = 9.02 Å; D_2^4; marked pseudosymmetries.

$Ba_2[Zn(OH)_6]$ contains isolated $[Zn(OH)_6]$ groups with a markedly distorted quasi-octahedral (4+2) coordination for Zn. This is a deformed K_2PtCl_6 structure, the deformation of which is obviously not due to hydrogen bonds but to the diminution in the size of the "holes" for the Ba particles (monoclinic; a = 6.11, b = 6.37, c = 10.46 Å, β = 125.7°; C_{2h}^5) [3].

According to the powder diagrams, $Ba_2[Cu(OH)_6]$ is isotypical with $Ba_2[Zn(OH)_6]$ (a = 6.09, b = 6.50, c = 10.45 Å, β = 126.0°) [3].

$Ba_2[Mg(OH)_6]$ is isostructural with $Ba_2[Zn(OH)_6]$ and $Ba_2[Cu(OH)_6]$, and is therefore a true complex compound. It crystallizes pseudotetragonally, with a' = 8.72 and c' = 8.49 Å, in a distorted K_2PtCl_6 lattice. The exact symmetry of the anisotropic "octahedral" crystals is still not quite certain because of high pseudo-symmetries.

In the preparation of $NaSn(OH)_3$ (orthorhombic needles with a = 14.55, b = 16.79, c = 5.89 Å; D_2^4), a complete rearrangement in about 48 hours of this phase into a different, morphologically very similar phase was observed (monoclinic needles; with a = 17.35, b = 8.23, c = 22.20 Å, β = 101°). It is difficult to decide by analysis whether this is a second form of $NaSn(OH)_3$ or a compound containing less water.

The infrared spectra of the complex hydroxides are disturbed by the small amounts of carbonate always present. Nevertheless, they show characteristic absorptions in the region from 700–1200 cm^{-1}. Comparisons of hydroxides and fluorides of the same type of formula gave an increment of 13 cm^3/mole for the space requirement of the OH^- group. Otherwise, there are hardly any examples of isostructural pairs of compounds.

A calculation in which the electrostatic potential profiles in the environments of proton-bearing particles were determined gives very satisfactorily the positions of the H-atoms if the positions of the other particles are known [3]. The process was checked on a number of compounds with known positions of the hydrogen [LiOH, $Ca(OH)_2$, $AlO(OH)$, KH_2PO_4].

[1] The samples were prepared according to *R. Scholder* et al., cf. Z. anorg. allg. Chem. *241*, 76 (1939); *216*, 138 (1934); *215*, 355 (1933); *317*, 113 (1962); *216*, 176 (1933).

[2] *H. G. Schnering*, Naturwissenschaften *48*, 665 (1961).

[3] *H. G. Schnering*, Habilitation thesis, Universität Münster, 1963.

36

Raman Spectra of Colored Crystal Powders Obtained by Excitation with Laser Radiation

B. Schrader and *M. Stockburger*, Dortmund (Germany)

The red radiation of the ruby (6943 Å) and the He-Ne gas lasers (6328 Å) is suitable for the excitation of Raman frequencies. The spectra of colored fluorescing and light-sensitive substances, in which the customary excitation by Hg-lines is unsuccessful, are particularly interesting. Colored substances are generally solid at room temperature and often sparingly soluble. They were investigated as layers of powder or as polycrystalline tablets. The radiation leaving the rear (unirradiated) side of the sample was observed. The unshifted scattered radiation was greatly weakened by twofold reflection at an interference filter of narrow bandwidth with practically no weakening of the Raman radiation. Raman lines in the neighborhood of the exciting lines were therefore still observable. The amount of substance required was 10 to 50 mg.

Colorless substances can also be excited by laser radiation. Here however, as the energy balance shows, the Hg low-pressure lamp is superior to the He-Ne and the ruby lasers. The argon laser with a radiation output of 350 mw at each of the wavelengths 4880 and 5145 Å is highly promising as a universal source of Raman lines, but it is still too expensive.

37

Comparative Investigations on the Stability of the Hexabalogenotechnetates(IV) and -rhenates(IV)

K. Schwochau, Köln (Germany)

We have determined complex-formation constants and ligand-exchange rates of the hexachloro- and hexabromotechnetates(IV) and -rhenates(IV). The formation constants k_6, determined by potentiometric measurements of the equilibrium concentration of the free ligand ions in 3 M $HClO_4$ at 15.0 °C, were 4.6×10^4 for $[TcCl_6]^{2-}$, 2.2×10^6 for $[ReCl_6]^{2-}$, 3.8×10^3 for $[TcBr_6]^{2-}$, and 1.8×10^5 l/mole for $[ReBr_6]^{2-}$. The constants of the Tc complexes are smaller than those of the corresponding Re complexes by a factor of about

50. The greater stability of the halogenorhenates can be explained qualitatively by their different ligand field stabilization energies.

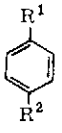
To measure the rates of exchange, the complex ions were labeled with ^{36}Cl or ^{82}Br. Here again, the chloro- and bromotechnetates were found to be considerably more labile; their exchange rates are approximately 20 and 50 times larger, respectively, than those of the analogous Re compounds. The activation energies of the exchange reactions were found to be 28.4 kcal/mole for $[TcCl_6]^{2-}$, 30.3 for $[ReCl_6]^{2-}$, 22.8 for $[TcBr_6]^{2-}$, and 27.5 for $[ReBr_6]^{2-}$.

38

C_{26}-Hydrocarbons as Model Substances for Lubricating Oils

P. Studt, Berlin (Germany)

The following hydrocarbons were prepared:



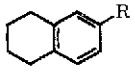
(1), $R^1 = -C_2H_5$, $R^2 = -C_{18}H_{37}$
(2), $R^1 = -C_4H_9$, $R^2 = -C_{16}H_{33}$
(3), $R^1 = -C_6H_{13}$, $R^2 = -C_{14}H_{29}$
(4), $R^1 = -C_8H_{17}$, $R^2 = -C_{12}H_{25}$

(5), $R^1 = R^2 = -C_{10}H_{21}$

(6), $R^1 = R^2 = -HC(CH_3)(C_8H_{17})$

(7), $R^1 = R^2 = -HC(C_3H_7)(C_6H_{13})$

Compounds *(6)* and *(7)* contain two equivalent asymmetric C-atoms. From *(6)* it was possible to isolate the racemate in pure form by fractional crystallization. It was impossible to separate *(7)* into the racemic and meso-forms. Catalytic hydrogenation of compounds *(3)* *(5)* and subsequent fractional crystallization gave the *trans*-disubstituted cyclohexane derivatives.



(8), $R = -C_{16}H_{33}$

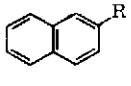
(9), $R = -CH(C_5H_{11})(C_{10}H_{21})$

(10), $R = -CH_2-CH(C_5H_{11})(C_8H_{19})$

(11), $R = -(CH_2)_2-CH(C_5H_{11})(C_8H_{17})$

(12), $R = -(CH_2)_4-CH(C_5H_{11})(C_6H_{13})$

(13), $R = -(CH_2)_5-CH(C_5H_{11})(C_5H_{11})$



(14), $R = -C_{16}H_{33}$

(15), $R = -CH(C_5H_{11})(C_{10}H_{21})$

(16), $R = -(CH_2)_5-CH(C_5H_{11})(C_5H_{11})$

The compounds with unbranched side chains are crystalline substances at room temperature, but have low melting points. Branching of the side-chains leads to a marked lowering of the melting points (so that the compounds are liquid at room temperature), to a lowering of the boiling points, and to an increase in the viscosities, branching in the vicinity of the ring system having a particularly marked effect. The boiling points can be explained qualitatively on the basis of a steric effect: branching hinders the mutual approach of the molecules and leads to a decrease in the cohesion energy and therefore to a lowering of the boiling point. The marked influence of the structure on viscosity cannot yet be satisfactorily explained. It is striking that a decrease in the cohesion energy runs parallel with an increase in viscosity.

39

Separation and Detection of Glucuronides

N. Takriti and *W. Thorn*, Hamburg (Germany)

Formation of glucuronides occupies the foremost position among the possibilities available to an organism for the conversion of sparingly soluble substances belonging to the body or foreign to it into a more soluble form capable of secretion. The properties of the glucuronides are substantially determined by the properties of the aglycones. The development of a generally applicable method of determination has hitherto been prevented by the variability of the aglycones. In most cases, one of the components has been determined after hydrolytic splitting of the glucuronides.

We have separated mixtures of glucuronides without hydrolysis by means of ion-exchange and thin-layer chromatography. Model substances and samples of urine with and without the addition of model substances could be separated on silica gel with chloroform/methanol/glacial acetic acid (8:1:1) as the eluent. A spraying reagent used consisted of anisaldehyde conc. sulfuric acid/glacial acetic acid (100:2:1). The method was demonstrated on pregnanediol glucuronide. Good separation of the urine components is achieved in a short time without hydrolysis or previous purification. 5β-Pregnane-3α,20α-diol glucuronide is readily identified as a blue spot.

40

Oxidation Reactions of α-Substituted Thiocarboxamides

W. Walter, *K.-D. Bode*, and *P. Hell*, Hamburg (Germany)

The oxidation of α-ketothioamides with hydrogen peroxide leads to stable thioamide *S*-oxides only in the case of primary thioamides; α-ketothioamides substituted on the nitrogen are oxidatively desulfurized, the *S*-oxide stage being passed through very rapidly. The stability of the *S*-oxides of amides of purely aliphatic or purely aromatic thiocarboxylic acids is affected substantially less by substitution on the nitrogen.

Tertiary compounds are the only series in which thiourethanes give no *S*-oxides [1].

The reaction of thioamides with sulfenyl chlorides also takes place with electrophilic attack on the sulfur and leads to unsymmetrical disulfides. The thioamides which give no *S*-oxides also react in this way.

[1] *W. Walter* and *K.-D. Bode*, Liebigs Ann. Chem. *681*, 64 (1965).

41

Investigations in the Titanium/Hydrogen System

G. Wedler and *H. Strothenk*, Hannover (Germany)

The phase diagram of the titanium/hydrogen system is known above 300 °C. The heats of reaction have generally been determined from the temperature-dependence of the absorption isotherms and occasionally from heats of combustion. The figures have a pronounced scatter even at the same composition of the system. Direct calorimetric measurements of the heat of reaction are not yet available.

In order to determine the ranges of existence of the individual phases and heats of reaction at 273 °K, titanium films about 150 Å thick, vapor-deposited in ultrahigh vacuum were investigated. These films could be charged with hydrogen at

room temperature, even at an equilibrium pressure of $< 10^{-5}$ mm, up to a composition of $TiH_{1.9}$.

With very small amounts of hydrogen, the differential heats of absorption amount to 35 kcal/mole of hydrogen, but they fall sharply with increasing concentration of hydrogen and reach a minimum of 22 kcal/mole of H_2 at $TiH_{0.06}$. From about $TiH_{0.3}$ upwards, they are almost independent of the hydrogen concentration with an average value of 27.5 kcal/mole of H_2.

The electrical resistance of the titanium films first increases with increasing content of hydrogen, the increase being 2.4% with respect to the resistance of the pure titanium film at $TiH_{0.07}$. When the hydrogen concentration is increased further, the resistance decreases, first linearly and then faster, being only 64% of the value for the pure titanium film at $TiH_{1.9}$.

The ranges of existence of the individual phases can be determined from the behavior of the electrical resistance. The upper limiting concentration of the hexagonally close-packed α-phase is found in $TiH_{0.07}$, and the lower limiting concentration of the face-centered cubic γ-phase in $TiH_{0.6}$. The intermediate range is characterized by a linear relationship between hydrogen concentration and electrical resistance.

Consequently, in the range of existence of the pure α-phase the differential heats of absorption fall sharply with increasing hydrogen content, while in the region of the γ-phase they depend only slightly on the hydrogen concentration.

42

Preparation and Reactions of Chloro(chloromethyl)dimethylgermane

M. Wieber and *C. D. Frohning*, Marburg (Germany)

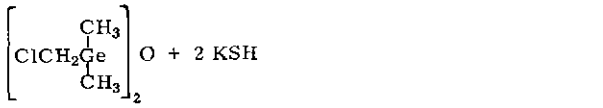
Chloro(chloromethyl)dimethylsilane $(ClCH_2)(CH_3)_2SiCl$ is a starting material for the synthesis of siloxanes with functional groups. The analogous germanium compound has been prepared in accordance with Equations (a)–(c):

$$Ge + 3\,CH_3Cl \rightarrow CH_3GeCl_3 + C_2H_6 \quad (a)$$

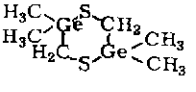
$$CH_3GeCl_3 + CH_2N_2 \rightarrow CH_3(CH_2Cl)GeCl_2 + N_2 \quad (b)\ [1]$$

$$CH_3(CH_2Cl)GeCl_2 + LiCH_3 \rightarrow (CH_3)_2(CH_2Cl)GeCl + LiCl \quad (c)$$

For reaction (a), a method has been evolved to obtain pure methylgermanium trichloride with a yield of 70% (based on the germanium used). The reaction of the dichlorochloromethylmethylgermane with methyl-lithium according to Eq. (c) takes place with a yield of about 50% at −30 °C.



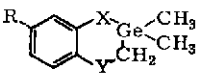
(1)



(2)

Hydrolysis of the chlorochloromethyldimethylgermane gives 1,3-bis(chloromethyl)tetramethyldigermoxane *(1)* which, in turn, can be converted with potassium hydrogen sulfide into 2,2,5,5-tetramethyl-2,5-digerma-1,4-dithiane *(2)*.

The reaction of chloro(chloromethyl)dimethylgermane with aromatic 1,2-diols in the presence of triethylamine as hydrogen chloride acceptor gives binuclear germanium-containing heterocycles having the structure *(3)*.



(3)

X = Y = O, R = H, CH_3
X = Y = S, R = CH_3
X = O, Y = NH, R = H

[1] *D. Seyferth* and *E. G. Rochow*, J. Amer. chem. Soc. *77*, 907 (1955).

43

Phosphorus, Antimony, Sulfur, and Selenium Compounds in the Liquid-Liquid Extraction of Transition-Metal Ions

M. Ziegler, Göttingen (Germany)

Substituted onium compounds $[R_nM]X$ *(1)*, substituted amides $(R_2N)_3MO$ *(2)* and substituted oxides R_nMO *(3)* (M = P, Sb, S, or Se) are suitable for the liquid-liquid extraction of the transition metals. Phosphoric hexamethyltriamide $[(CH_3)_2N]_3PO$ (PHT) gives the crystalline coordination compounds:

$Fe(SCN)_3 \cdot 3(PHT)$ *(4)*	$Th(NO_3)_2 \cdot (PHT)$
$Zn(SCN)_2 \cdot 2(PHT)$ *(5)*	$BiCl_4 \cdot 2(PHT)$
$VO(SCN)_2 \cdot 2(PHT)$	$FeCl_3 \cdot (PHT)$ *(6)*
$UO_2(NO_3)_2 \cdot 2(PHT)$	

Iron can be separated from various transition metals and zinc in the form of compound *(4)*. Zinc isolated in the form of compound *(5)* can be determined volumetrically with EDTA. Iron extracted in the form of compound *(6)* can be determined photometrically in amounts of from 5 μg upwards. Tetraphenylantimonates *[(1), M = Sb]* permit the selective extraction of small amounts of molybdate and the extraction and photometric determination of iron *via* the ferron complex.

Among the substituted sulfoxides *[(3), M = S]*, dibenzyl sulfoxide permits the extraction and photometric determination of small amounts of iron as $Fe(SCN)_3 \cdot 3\,OS(CH_2\text{-}C_6H_5)_2$. With thioxane (thiox), palladium can be extracted and photometrically determined in the form of $Pd(thiox)_2Cl_2$. Triphenylsulfonium salts *(1)*, M = S, permit the selective extraction of $[Co(SCN)_4]^{2-}$.

Diphenyl selenoxide permits the selective extraction of rhodium as $RhCl_3 \cdot 3\,OSe(C_6H_5)_2$, and triphenylselenonium salts permit the isolation of small amounts of ReO_4^-.

[VB 946/260 IE]
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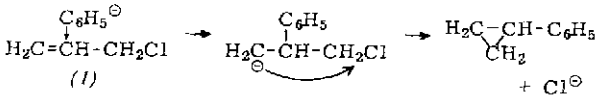
SELECTED ABSTRACTS

A new synthesis of phenylcyclopropanes is reported by *S. Wawzonek, B. Studnicka, H. J. Bluhm,* and *R. E. Kallio*. Addition of phenyl-lithium onto allyl chloride in ether yields allylbenzenes plus phenylcyclopropanes in a ratio which depends on the substitution of the allyl chloride, *e.g.* 13:87, 19:81, and 40:60 for addition onto allyl chloride *(1)*, crotyl chloride, and 1-chloro-5,5,7,7-tetramethyl-2-octene, respectively. The cyclopropanes can be isolated after oxidation of the olefins with potassium permanganate. The reaction is proba-



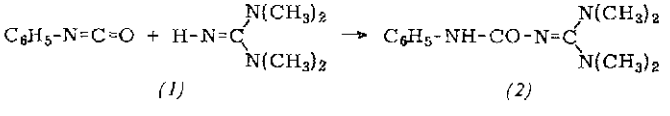
(1)

bly equivalent to an S_N2' reaction in which the phenyl carbanion attacks at the β-carbon atom instead of at the γ-carbon. The resultant anion undergoes an intramolecular reaction with elimination of the chloride ion. / J. Amer. chem. Soc. *87*, 2069 (1965) / – Ma. [Rd 361/570 IE]

The chemical shifts and the π-electron densities of ring protons in aromatic nitrogen heterocycles were compared by *A. H. Gawer* and *B. P. Dailey*. The π-electron densities were calculated using the SCF–MO method of *Roothaan*. The compounds studied were pyridine, the diazines, quinoline, isoquinoline, and the 1,2-, 1,3-, 1,4-, 1,5-, and 2,3-diazanaphthalenes. The chemical shifts and the calculated electron densities correspond only approximately; particularly large differences are observed with the protons attached to the carbon atoms next to the nitrogens. Factors which contribute to these irregularities are the influence of the low molecular symmetry on the calculated electron densities, the magnetic anisotropy due to the lone pair of electrons on the nitrogen, and the interaction of δ- and π-electrons. / J. chem. Physics *42*, 2658 (1965) / –Hz. [Rd 362/571 IE]

The spin multiplicity of difluorocarbene is discussed by *J. Heicklen, N. Cohen,* and *D. Saunders* in connection with the rate constants of its reaction with ethylene, tetrafluoroethylene, and oxygen. CF_2 made by photolysis from C_2F_4, CF_2HBr, CF_2Br_2, or CF_2N_2 is in the singlet state, but CF_2 made by a glow discharge from CF_4 or by the reaction of C_2F_4 with atomic oxygen was recognized to be in the triplet state because of its much faster rates of reaction. The singlet state is probably of lower energy than the triplet state. / *J.* physic. Chem. *69*, 1774 (1965) / –Hz. [Rd 363/572 IE]

The catalytic effect of 1,1,3,3-tetramethylguanidine on the polymerization of isocyanates was studied by *J. T. Gerkegan* and *R. W. Roth*. Tetramethylguanidine *(1)* is a better catalyst than triethylamine or 1,4-bisdimethylaminobutane but is less active than diazobicyclooctane (based on equal concentrations). It combines with phenyl isocyanate to form the urea derivative *(2)*, which also has good catalytic properties. Com-

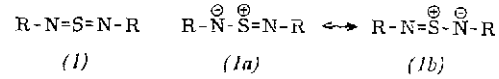


(1) *(2)*

pound *(1)* exerts two functions during the preparation of polyurethanes. Apart from its catalytic effect on the isocyanate reaction, some of it is incorporated into the polyurethane. Thus, in contrast to the t-amine catalysts, it does not remain unchanged in the polymers. / J. appl. Polymer Sci. *9*, 1089 (1965) / –Hl. [Rd 380/589 IE]

α-Phenylethylpotassium as initiator for the polymerization of styrene leads, according to *S. S. Yen*, to almost monodisperse polystyrene (M_w/M_n = 1.06). When chain termination by a proton occurs, no foreign end groups are introduced, for the initiator is identical with the repeating unit of polystyrene. The reaction of polystyrylpotassium with 1,2,4,5-tetrakis-chloromethylbenzene was used to produce a "star" branched polystyrene which also had a very narrow distribution of molecular weights (M_w/M_n = 1.05). The lengths of the rays of the stars can be readily controlled by the ratio of monomer to starter taken. The sedimentation pattern in the ultracentrifuge gives a direct indication of the high uniformity of the branched polystyrene. / Makromolekulare Chem. *81*, 152 (1965) / –Hl. [Rd 325/534 IE]

A new synthesis of stable aliphatic sulfur diimines *(1)* is described by *D. H. Clemens, A. J. Bell,* and *J. L. O'Brien*. If the group R in *(1)* is a bulky t-alkyl group, the sulfur diimines can be obtained from the t-alkylamines and SCl_2, which yield a condensation product $(RNS)_x$ which is then heated in vacuum. Sulfur di-t-butylimine, b.p. 60–62 °C/15 mm, and sulfur di-t-octylimine, b.p. 88–90 °C/0.15 mm, were made in this way. The same sulfur diimines are also obtained in somewhat lower yields by pyrolysis of the product formed by reaction of sulfur monochloride and excess t-alkylamine. The diimines are hydrolysed slowly by water but rapidly by dilute hydrochloric acid. Oxidation of *(1)* with dilute H_2O_2 produces *N,N'*-di-t-alkylsulfamides. The sulfur diimines *(1)* probably have structures with large contributions from the resonance forms *(1a)* and *(1b)*. Its structure has an ylide character



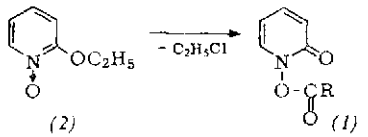
(1) *(1a)* *(1b)*

which opens a large range of possibilities for reactions, *e.g.* with carbonyl compounds, isocyanates, isothiocyanates, and thioureas. / Tetrahedron Letters *1965*, 1487, 1491 (1965) / –Ma. [Rd 348/557 IE]

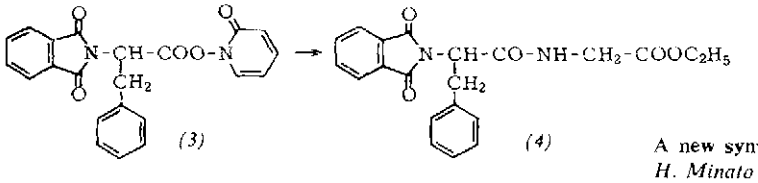
The redox potentials of alkyl-substituted quinone/hydroquinone systems were measured by *O. Ryba, J. Petranek,* and *J. Pospisil*. Since the quinones decompose readily, the redox potentials can be determined only by measurement of the polarographic half-wave potentials. The half-wave potentials of hydroquinones substituted by methyl, ethyl, isopropyl, t-butyl, 3,3-dimethylpropyl, and 2,2,4,4-tetramethylbutyl groups in the 2- or 2- and 5-positions can be represented as a linear function of the sum of the steric substitution constants E_S. The additivity of the effects of individual substituents is not valid for 2,6-dialkylated hydroquinones. / Coll. czechoslov. chem. Commun. *30*, 843 (1965) / –Hz. [Rd 360/569 IE]

Preparation of metal fluorides by the fluidized bed process was achieved by *H. W. Roesky, O. Glemser,* and *K. H. Hellberg*: 0.5–1.0 g of metal powder (Mn, Pb, Bi, or Re) reacted quantitatively with elemental fluorine within a few minutes in a vertical electrically heated tube 15 mm in diameter and 600 mm long made of pure nickel. Metal powder with a grain diameter of 0.062–0.075 mm is placed in a nickel sieve below the reaction zone and gas is then passed in from below at a rate fast enough to give a fluidized bed 10 cm long. The temperature above the fluidized bed is 700–800 °C. The fluorides formed are collected in cold traps made of silica or teflon and characterized by chemical analysis or infrared spectroscopy. MnF_4, PbF_4, BiF_5, and ReF_7 were made in this way. / Chem. Ber. *98*, 2046 (1965) / –Gn. [Rd 367/576 IE]

1-Acyloxy-2(1*H*)-pyridones *(1)*, a new class of activated esters, are described by *L. A. Paquette*. Electrophilic attack by acyl halides on 2-ethoxypyridine-1-oxide *(2)* at room temperature causes an exothermic reaction with release of ethyl halide and formation of *(1)*. For example, with acetyl chloride, the resultant pyridone *(1)* has R = CH_3 and m.p. 93–94 °C, and the yield is 86 %; with benzoyl chloride, R in *(1)* = C_6H_5, the m.p. is 140 °C, and the yield is 93 %. The



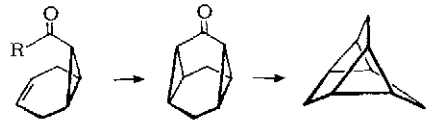
(2) *(1)*



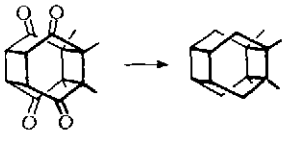
(3) *(4)*

acetyl derivative *(1)* is hydrolysed quantitatively by water to 1-hydroxy-2(1*H*)-pyridone; transacetylation occurs with butanol and butylamine. The high reactivity of *(1)* can be used for synthesizing peptides. The ester *(3)* is obtained in quantitative yield from phthaloyl-L-phenylalanyl chloride and *(2)* and condenses with glycine ethyl ester to give optically pure ethyl phthaloyl-L-phenylalanylglycinate *(4)*. / J. Amer. chem. Soc. *87*, 1407 (1965) / –Ma. [Rd 332/541 IE]

The synthesis of asteranes is reported by *U. Biethan, U. von Gizycki*, and *H. Musso*. In the asteranes, cyclohexane rings are fixed in the boat form. Triasterane, *i.e.* tetracyclo-[3.3.1.$0^{2,8}$.$0^{4,6}$]nonane *(4)*, m.p. 110 °C, was prepared from *endo*-Δ^3-norcarene-7-carbonyl chloride *(1)* *via* the diazo ketone *(2)*, which was decomposed in boiling hexane with copper powder to give the ketone *(3)*, which on Wolff-Kishner reduction affords *(4)*. Tetramethyltetraasterane *(6)*, *i.e.* 1,2,7,8-tetramethylpentacyclo[6.4.0.$0^{2,7}$.$0^{4,11}$.$0^{5,10}$] dodecane, m.p. 283–286 °C, was synthesized from the cage dimer *(5)* of



(1) R = Cl *(3)* *(4)*
(2) R = CHN_2

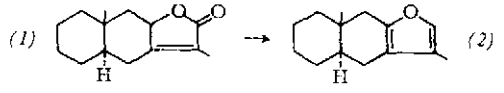


(5) *(6)*

2,3-dimethylbenzoquinone *via* its tetrahydrazone, which on heating with KOH in ethylene glycol gave a mixture of hydrocarbons that were separated by gas chromatography. Analogously, the hydrazone of the cage dimer of 2,5-dimethylbenzoquinone gives rise to a tetramethyltetraasterane, m.p. 106–108 °C; the positions of the methyl groups in this compound are not yet known with certainty. / Tetrahedron Letters *1965*, 1477 / –Ma. [Rd 350/559 IE]

The reaction of sodium and potassium with dimethyl sulfoxide (DMSO) has been examined by *D. E. O'Connor* and *W. L. Lyness*. Na and K react with excess DMSO to form a mixture of the salts of methanesulfenic acid and methylsulfinylmethide $CH_3SOCH_2^{\ominus}$ plus some methane and dimethyl sulfide. Two primary reactions occur with almost equal rate with Na: reductive cleavage of the C–S bond to yield sodium methanesulfenate and methylsodium, and cleavage of the S–O bond to give dimethyl sulfide and Na_2O. The strong bases $NaCH_3$ and Na_2O react with more DMSO to produce sodium methylsulfinylmethide, methane, and NaOH. The C–S fission predominates in the reaction with K. Both sodium and potassium methanesulfenates are stable for several days at room temperature in the reaction mixture. Alkylation of the methanesulfenates with alkyl bromides or iodides gives the corresponding methyl alkyl sulfoxides in good yields. No *O*-alkylated products can be detected. / Abstracts 149th Meeting Amer. Chem. Soc. *1965*, 45P / –Ma. [Rd 336/545 IE]

A new synthesis of furan compounds has been published by *H. Minato* and *T. Nagasaki*. A solution of dialkylaluminum hydride or tri-isobutylaluminum in tetrahydrofuran is added to a solution of an α,β-unsaturated γ-lactone derivative such as *(1)* and stirred for about an hour at room temperature

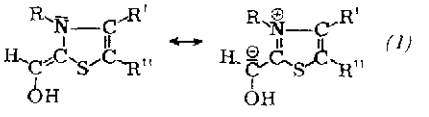


(1) *(2)*

under nitrogen. The solution is then acidified and the furan derivative is extracted: *e.g.*, *(2)* is obtained in 74 % yield. / Chem. and Ind. *1965*, 899 / –Ma.

[Rd 349/558 IE]

"Activated formaldehyde" is 2-hydroxymethylthiamine pyrophosphate *(1)*, according to *G. Kohlhaw, B. Deus*, and *H. Holzer*. This is an intermediate of the degradation of glyoxylic acid in *Escherichia coli* by glyoxylate carboligase. Glyoxylate is activated by condensation with thiamine pyrophosphate (TPP) and then decomposes into *(1)* and carbon dioxide. The *(1)* then reacts with another molecule of glyoxylate to give



(1)

TPP-activated tartronmonoaldehyde, which is reduced to glyceric acid by the corresponding reductase and DPNH. Compound *(1)* was isolated by chromatography on acetylated Dowex 2 of incubation mixtures containing pyruvate oxidase from pig heart, TPP, and glyoxylate and detected by cleavage of [2–^{14}C]-labelled *(1)* with hydroxylamine to give glycolhydroxamic acid or by oxidation with 2,6-dichlorophenylindophenol to [^{14}C]formate. / J. biol. Chemistry *240*, 2135 (1965) / –Hö. [Rd 370/579 IE]

The formation of streptococcal proteinase from cymogen was investigated by *W. H. Stein, S. Moore, et al.* This conversion is catalysed by trypsin, subtilisin, or the proteinase itself (autocatalysis). A polypeptide containing about 100 amino acids is split from the cymogen (molecular weight 44000). An intermediate with 17 amino acids fewer than cymogen can be isolated; after liberation of its sole mercapto group, this intermediate exhibits proteolytic activity. The removal of the 17 amino acids therefore exposes the active center. The peptide containing about 100 amino acids released during the activation is the carrier of the immunochemical specificity of cymogen. The free proteinase does not react with cymogen antiserum. / J. biol. Chemistry *240*, 1138 (1965) / –Hö. [Rd 376/585 IE]

Organikum. Organisch-Chemisches Grundpraktikum (Practical Organic Chemistry). Edited by a group of authors from the Technische Universität Dresden (Germany). VEB Deutscher Verlag der Wissenschaften, Berlin 1964. 3rd revised Edition, XII + 596 pp., Appendix, 106 illustrations, imitation leather, DM 36.–.

The reform in the study of chemistry that is currently the subject of so much discussion in Germany obviously cannot be achieved without a well-grounded change in our practical courses in chemistry. A new textbook of practical organic chemistry that leaves the beaten track to follow new paths is therefore particularly interesting at the present time. The "Organikum", first published in 1962 and now in its fourth edition, appeared at just the right time, and its authors – a group of young lecturers and assistants at the Technische Universität Dresden – are to be congratulated on their outstanding and well-deserved success.

The book begins with an introduction to laboratory practice (approx. 100 pp.), which is both good and complete as far as conventional laboratory methods are concerned. Better treatment could have been accorded to more recent developments, such as thin-layer chromatography. In the section on the determination of the physical properties of organic compounds, no mention is made of proton magnetic resonance and mass spectrometry, although the importance of these two methods in the routine work of the organic chemist is as great as that of electronic and infrared spectroscopy, which are discussed at some length.

The real interest in this book is to be found in the section dealing with preparations (approx. 400 pp.), in which it is attempted, more consistently than in any other practical textbook, to synchronize the teaching of preparative techniques with the learning of the mechanistic principles of the reactions treated. As a logical consequence of this program, the material is arranged not according to classes of compounds, but according to reaction types. The didactic advantage of this arrangement is obvious, although it must not be overlooked that not all reactions of practical importance can be forced with the same ease into the "Procrustes bed" of a system of reaction mechanisms. This may be the reason for the accentuation, in this book, of certain reactions whose inclusion cannot be explained solely on the basis of preparative importance.

The isolation and purification of natural products is completely neglected in the "Organikum"; this is regrettable, since it means that the important extraction and partition techniques are also omitted. The chemistry of natural products could also be allowed more space in the discussion of the preparative methods. For example, the remarks on peptide syntheses (p. 378) are rather insufficient. Other desirable improvements in the next edition would be a better account of organometallic reactions and the inclusion of the most important new types of reactions such as hydroboration, the Wittig reaction, and reductions with diimide, which are not mentioned in the present edition. Criticism could be made of some details of the treatment of reaction mechanisms, but this is unimportant in comparison with the success achieved by this book in the dovetailing of theoretical knowledge with practical laboratory arts.

Another new interesting and remarkable feature of the book is that it does not give detailed recipes for the preparation of individual compounds, but contains instead general procedures for certain reactions, together with brief notes on special points to be observed in the preparation of particular compounds. This is to prevent the student from carrying out a preparation mechanically, as frequently happens when very detailed instructions are given. Moreover, the number of preparations that can be covered by the "Organikum" is greatly increased (to about 1000). Since these general, standardized procedures can also be used for the corresponding reactions of new compounds or compounds that are not mentioned, the "Organikum" is also valuable as a small handbook on methods for graduate students and advanced chemists.

In the basic organic practical course, however, the almost exclusive use of general procedures also has certain disadvantages. In Heidelberg we have found that, especially at the beginning of the laboratory course, the student often experiences difficulties as a result of the generalized, and hence necessarily less precise, instructions; this is aggravated by the fact that, for some incomprehensible reason, the "Organikum" begins the section on preparations with free radical reactions, which are not altogether simple from the point of view of method. Furthermore, since special procedures are not given, no mention can be made of special phenomena (intermediate coloration, formation of precipitates, *etc.*) observed during the reaction in particular cases, the observation and interpretation of which can teach the student a great deal. The complete absence of small-scale experiments with the compounds prepared does not exactly help to improve the student's power of observation or to increase his interest in experimenting, and this, after all, is the principal purpose of the practical organic chemistry course. It may be possible in a later edition to find a compromise that takes these points more satisfactorily into account.

The last chapter, which deals with the identification of organic compounds, is without a doubt the weakest part of the book. It is disappointing to find that this book, which is so progressive in other respects, does not also follow new paths in organic analysis by the use of modern separation processes and physico-chemical methods of analysis to supplement the conventional methods.

The presentation of the book is good, and the quality of the paper is much better than in the earlier editions. With a few exceptions, the formulae are clear and contain no errors. Unfortunately, even in the new editions, the index is still bound separately.

Even those who, like the reviewer, find some fault with the conception and details of this book will recognize that the "Organikum" must be regarded as one of the most significant innovations in German literature on organic chemistry in the last few years. This book has set a standard against which other present and future laboratory books must and will be measured.

H. A. Staab [NB 420/281 IE]

Organische Chemie. Ein Lehrbuch für Naturwissenschaftler, Mediziner und Techniker (Organic Chemistry. A Textbook for Science, Medicine, and Technology Students). By *F. Nerdel*, in collaboration with *B. Schrader*. Verlag Walter de Gruyter & Co., Berlin 1964. 2nd completely revised and extended edit., XII + 209 pp., 48 figs., linen DM 18.– (about $4.50).

This revised and expanded second edition is intended, as the subtitle and the size of the book indicate, for students taking chemistry as a minor subject. The content is divided into six sections: I. Fundamentals of theoretical organic chemistry; II. Systematic organic chemistry; III. Macromolecular organic materials; IV. Solvents, plasticizers, and surfactants; V. Biochemistry; VI. Analytical methods in organic chemistry.

It is very welcome that the attempt is made to convey a complete survey of organic chemistry on only 200 pages, for a book of this length can in fact be mastered by the readers for whom it is intended. One can be of different opinions concerning the selection of material dealt with and one must ask whether the

structure of the atom should be examined here and whether terpenes are a suitable class of compounds with which to demonstrate the variability of organic compounds to medical or engineering students.

Parts III–VI of the book (by *Schrader*) do in fact serve its purpose; they record an abundance of interesting facts and relationships which are presented clearly but sometimes very tersely and schematically (*e.g.* ion exchangers on p. 136). However, the presentation given to many fundamentals in Parts I and II (by *Nerdel*) is unsatisfactory (*e.g.* mesomerism on p. 16). On p. 81 it is stated that the anions derived from keto and enol forms of ethyl acetoacetate differ only in the distribution of their charge. Apart from the fact that the polar limiting structure of the carbonyl group is said to be very important for understanding its reactions (p. 50), reaction mechanisms frequently are discussed, apparently without a proper knowledge of the issues at stake, in the most primitive manner, *e.g.* the Wurtz synthesis (p. 41), the aldol condensation (p. 54), and the Hofmann elimination (p. 62). The print in the formulae is not always very good, *e.g.* the formula for acetylene on p. 56. Printing errors are few, *e.g.* at the center of p. 71 it should read "Seite 113" and not "Seite 13".

Before this book – the arrangement of which must be acknowledged to be most useful – can be recommended without reservations to students, the first two chapters must be thoroughly revised. *H. Musso* [NB 399/257 IE]

Chelating Agents and Metal Chelates. Edited by *F. P. Dwyer* and *D. P. Mellor*. Academic Press, New York-London 1964. 1st edit., XV + 530 pp., numerous figs. and tables, linen $ 17.–.

This volume contains ten chapters written by different authors on metal chelates. Nevertheless, the content and arrangement of the chapters give the book the character of a textbook, for first bonding relationships are discussed, followed by descriptions of the types of metal chelates, their stereochemistry, and some special facets of the subject such as redox potentials, complexes with ethylenediamine-tetraacetic acid and related substances, and some naturally occurring chelates. Overlapping has been largely avoided. However, a uniform symbol for the metal-ligand bonds would have been better. For example, different formulations are given for acetylacetonates on pp. 34 and 100.

D. P. Craig and *R. S. Nyholm* have contributed a very original presentation of the nature of the metal-ligand bond. The authors did not wish to deal with the ligand field theory in this connection, and this restriction must be accepted. However, their mention of this theory could at least have been coupled with a few references for those interested. The sections on bi- and polydentate ligands by *H. A. Goodwin*, *C. M. Harris*, and *S. E. Livingstone* and on optical phenomena with metal chelates by *A. M. Sargeson* are well written. In the specialized section, the selection of topics is typical for the research sphere of the editors. The reviews of "Metal Chelates in Biological Systems" (*F. P. Dwyer*) and of "Metal Activation by Enzymes and the Catalytic Effect of Metal Complexes" (*A. Shulman* and *F. P. Dwyer*) are undoubtedly profitable and up-to-date undertakings; however, both chapters are so fragmentary and apparently so much tailored to the interests of the authors that they cannot claim to be of general interest. The problems discussed are almost all very difficult to approach experimentally: for example, metal ion activation of proteolytic enzymes, the toxic effect of metal ions, and even the effect of metal ions on microorganisms. It would have been better to include a discourse on the chemistry of the known naturally occurring metal chelates and to use this as a basis to discuss the mechanisms of their biochemical action instead of introducing these somewhat vague concepts. Enzymes containing copper or molybdenum are not mentioned, for example, and iron complexes not containing porphyrins and the vitamin B_{12} coenzymes are omitted; this shows clearly how unfortunate the selection is. An attractive chapter on porphyrin complexes by *J. E. Falk* and *J. N. Phillips* is included.

Since the biochemical aspects of metal chelates receive too little attention here, the book cannot be recommended to biochemists, microbiologists, enzymologists, or medical researchers. *E. Bayer* [NB 368/226 IE]

Peroxidase. The Properties and Uses of a Versatile Enzyme and of Some Related Catalysts. By *B. C. Saunders*, *A. G. Holmes-Siedle*, and *P. B. Stark*. Butterworths, London 1964. 1st edit., X + 271 pp., numerous illustrs. and tables, linen £ 3.0.0 (about $ 8.30).

In his foreword, *Lord Todd* remarks that monographs of this type are very valuable and provide incentives to advanced students and scientists, and one can certainly second his statement. All the authors have once been members of *Todd*'s research group and they have succeeded here in reproducing the current status of our knowledge of peroxidase and the hemin enzymes generally in a concise and concentrated form. Fourteen sections are given dealing with diverse aspects of this group of enzymes such as their occurrence, purification, properties, detection and assay, and particularly their behavior in kinetic spectroscopy and EPR measurements. A valuable feature for the non-specialist is the section in which the modern concepts of the electronic configuration of hemin-iron enzymes and the structure of coordination compounds are used to interpret the optical and catalytic (or enzymatic) properties. This excellent presentation makes it obvious that modern enzymology has become an exact science.

The main stress in the book is laid on the chemistry of peroxidases, and it is therefore understandable that biological aspects are somewhat neglected. For this reason, some of the applications of peroxidase that have become so important (*e.g.* for the specific detection of glucose in combination with notatin) receive only brief reference. As a special case, catalase receives a separate section; however, the question of the biological function of this enzyme is only touched upon.

These remarks do in no way deprecate the value of this book as an extremely welcome source of information. This is due in no small extent to the lists of the oxidation products identified to date which arise on treatment of various substrates with peroxidase and to the spectra of all known hemin compounds, including data on their optical and magnetic properties. *H. Aebi* [NB 387/245 IE]

The Chemistry of Beryllium. By *D. A. Everest*. Topics in Inorganic and General Chemistry. Edited by *P. L. Robinson*, Vol. 1. Elsevier Publishing Co., Amsterdam-London-New York 1964. 1st edit., IX + 151 pp., several figs. and tables, linen DM 25.– (about $ 6.25).

Here the author attempts to give a summarical presentation of the chemistry of beryllium, deliberately omitting some aspects such as beryllium ceramics and intermetallic compounds; the material otherwise covered does indeed review the whole of beryllium chemistry.

Chapter 1 is an introduction to beryllium chemistry, and Chapter 2 reviews the solution chemistry of the element. Chapter 3 deals with simple oxygen salts of Be and Chapter 4 with its halides. Chapter 5 describes the complex compounds of Be and Chapter 6 its simple binary compounds. Chapter 7 then deals with organoberyllium compounds, and the production of beryllium from its ores is discussed in Chapter 8. The analytical chemistry of beryllium forms the topic of Chapter 9. The toxicity of beryllium and safety measures are dealt with in Chapter 10, and the nuclear properties of Be are discussed in the last chapter.

The material covered is very extensive; however; some striking faults are observed, especially with regard to the presentation of the material. The sequence of the chapters suffices to show that there is a lack of coherence in the treatment. The sequence 1-11-8-9-6-4-3-2-5-7-10 would have been more reasonable. Without exception, the text is a conglomeration of fragmentary data placed one after the other and conveys the general impression of a poor set of lecture notes. No signs of strict organization can be detected. It is noticeable that although many structural data are given, only few lattice constants are recorded in text. It would certainly have been easy to have included highly condensed tables of physical data. Similarly, there are no illustrations of lattice models, which would have been quite in place in such a book. Although intermetallic compounds have been disregarded, a detailed discussion of the element itself at least ought to have been given. In the chapter on the extraction of Be from its ores, although many individual processes are described, not a single flow sheet is given, even though such flow sheets serve well to convey a clear understanding of technical processes. Some important facts are completely overlooked, *e.g.* the preparation of $BeCl_2$ and $BeBr_2$ for atomic weight determinations (according to *Hönigschmid*) and the very instructive health precautions used at Oak Ridge (Report Y-868). In Chapter 11 it is not mentioned that ^{10}Be has been electromagnetically enriched (Report Y-577, Oak Ridge) or that $RaBeF_4$ and BePo have been used as homogeneous neutron sources.

These shortcomings, particularly the lack of clarity in the arrangement of the material, make the book difficult to work through. The reader is confronted with a vast number of facts, some of which are incompletely reported, without being able to recognize any clear principles. Purchase of the volume can be recommended only with restrictions.

F. Weigel [NB 385/243 IE]

Tetracyclic Triterpenes. By *G. Ourisson, P. Crabbé*, and *O. R. Rodig*. Editions Scientifiques Hermann, Paris; Hermann Publishing Ltd., Huddersfield, Yorkshire 1964. 2nd edit., 237 pp., linen £ 2.19.0 (about $ 8.25).

This monograph is a translation and extension of the older French edition of 1961 [1]. The authors deal first with the chemistry of the tetracyclic triterpenes (including methyl steroids and nor-compounds such as limonin); they do not discuss the individual compounds in sequence but describe general reactions which can occur in the various rings and in the side chain. These general reactions are then contrasted with the anomalous behavior of certain representatives of a given group, particular attention being directed to stereochemical effects in this connection. This system provides an excellent didactic approach to the subject. Rather unusual is the extension of *Ruzicka*'s convention of writing a large dot to designate the stereochemistry at ring junctions also to hydrogen atoms not in an angular position. This formulation is however not applied consistently throughout the book. Two chapters on the total synthesis and the biochemistry of the title compounds close the general section.

In the "catalogue", the formulae, melting points, and specific optical rotations of all the known tetracyclic triterpenes are given in summary. A particularly valuable appendix follows in which the infrared and ultraviolet absorption bands and the amplitudes of the Cotton effects of the most frequently occurring chromophores are tabulated.

Ourisson and his coauthors have succeeded in presenting the interesting chemistry of the tetracyclic triterpenes in a masterly, comprehensive form. Their book can be recommended highly to anyone seeking detailed information in this field.

G. Snatzke [NB 410/267 IE]

[1] For a review of the French edition see Angew. Chem. *76*, 355 (1964).

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