STEREOCHEMISTRY OF FREE RADICAL ADDITIONS TO OLEFINS

BRUCE A. BOHM[1] AND PAUL I. ABELL

Department of Chemistry, University of Saskatchewan, Saskatoon, Canada[1] and Department of Chemistry, University of Rhode Island, Kingston, Rhode Island

Received September 11, 1961

CONTENTS

I. Introduction 599
II. Addition of Reagents Containing Bromine 599
A. Hydrogen Bromide 599
B. Bromine 603
C. Ethyl Bromoacetate 604
D. Bromotrichloromethane 604
III. Addition of Reagents Containing Sulfur 605
IV. Addition of Dinitrogen Tetroxide 607
V. Addition of Miscellaneous Reagents 607
A. Sulfur Dioxide 607
B. Oxygen to Indene 607
C. Silicochloroform 607
VI. Conclusions and Some Considerations of a General Mechanism 607
VII. References 609

I. INTRODUCTION

The study of the stereochemistry of free radical additions to olefins is a relatively recent addition to the chemistry of free radical reactions. In its short but productive life information of considerable interest has come forth. It is the purpose of this review to present the results of research on stereochemical aspects of radical addition reactions. The data to be presented will be discussed in terms of possible mechanisms which might account for the observed phenomena.

The subject matter of the present review will not contain any of the original work on free radical additions to olefins. For complete reviews of this earlier work the reader is referred to the papers of Hey and Waters (30) and Mayo and Walling (38).

II. ADDITION OF REAGENTS CONTAINING BROMINE

A. HYDROGEN BROMIDE

The stereochemistry of the free radical addition of hydrogen bromide to olefins has been studied in greater detail than that of other reagents. The results from studies using hydrogen bromide have greatly illuminated the general radical addition reaction and will be presented first in the discussion.

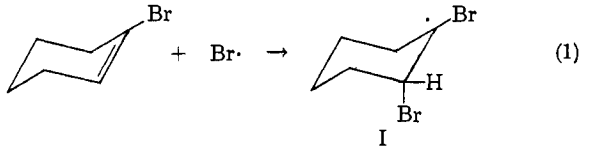
The addition of hydrogen bromide to cyclic olefins with an interest in the stereochemistry of the reaction was first studied by Goering, Abell, and Aycock (22). These workers chose 1-bromocyclohexene and 1-methylcyclohexene as their olefinic compounds. The use of the cyclic olefins avoided the complicating factor of *cis–trans* isomerization about the double bond by the adding reagent. The fact that hydrogen bromide caused isomerization of double bonds, presumably through a reversible addition process, was well established (29, 33, 37, 57).

The addition of hydrogen bromide to 1-bromocyclohexene in pentane proceeded rapidly when catalyzed by ultraviolet light or benzoyl peroxide. That this was a radical addition was indicated by the absence of the reaction in the presence of hydroquinone, diphenylamine, or ferric chloride. The sole product of the addition was shown to be *cis*-1,2-dibromocyclohexane. When 1-methylcyclohexene was treated with hydrogen bromide under free radical conditions the products of both radical and ionic addition processes were formed, *cis*-1-methyl-2-bromocyclohexane and 1-methyl-1-bromocyclohexane, respectively. Hydrogen bromide adds rapidly to 1-methylcyclohexene in the absence of catalysts to form, exclusively, 1-methyl-1-bromocyclohexane. In view of the facile transformation of secondary to tertiary halides (60) the authors examined the stability of the 1-methyl-2-bromocyclohexane under the conditions of the radical reaction. The secondary halide was recovered unchanged, indicating that it was the initial product in the reaction.

With the establishment of the structure of the radical addition product, the question of mechanism of addition may be approached. Insofar as the *cis*-bromides were the initial products of the reaction and that *cis*-isomers are thermodynamically less stable (5)

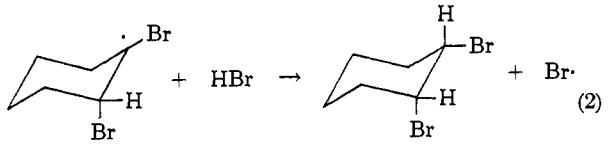
[1] To whom correspondence concerning this paper should be sent. This author wishes to express his thanks to the National Research Council of Canada for a Postdoctoral Fellowship, 1960–1961, at McGill University, where the initial work on this review was done.

than the *trans*-isomers, it is apparent that a *trans* addition process was in operation. The stepwise reaction may be represented as



(1)

I

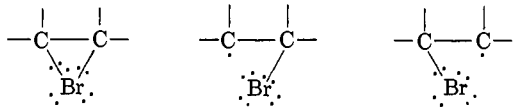


(2)

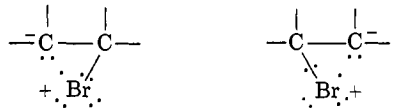
I II

In equation (1) a bromine atom (from homolytic cleavage of hydrogen bromide catalyzed by peroxide or ultraviolet light) attacks an olefin molecule to give rise to the intermediate free radical I. Reaction (2) is the chain transfer step wherein the intermediate free radical abstracts a hydrogen atom from a molecule of hydrogen bromide to give the saturated bromide II and a bromine atom which continues the chain process.

The classical, or open, intermediate radical could not account for the observed stereochemistry of the reaction according to the authors. They proposed instead a three-membered cyclic intermediate radical analogous to the bromonium ion involved in ionic additions of bromine. These forms can be written for this intermediate.



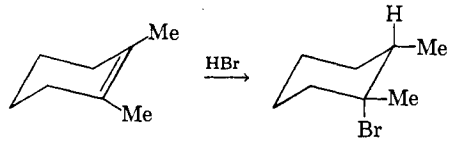
III IV V



VI VII

An immediate objection can be made to structure III wherein bromine has nine electrons in its outermost shell. Structures IV, V, VI, and VII contain three electron bonds. There is some justification for this type of structure, however. Pauling (44) states that for a three-electron bond to exist the atoms involved must be identical or very similar. To be stable this type of bond might be formed between atoms whose electronegativities differed by 0.5 unit or less. The difference between the electronegativities of carbon and bromine is 0.3 unit or within the limit of stability. The exact degree of stability, of course, is difficult to assess. If such a structure did exist the chain transfer step would involve approach of a molecule of hydrogen bromide from the side opposite to the bromine bridge. It would be unlikely that chain transfer could occur on the bridged side of the radical. Thus, operation of a bridged intermediate would result in a stereospecific addition process.

The stereochemistry of radical hydrogen bromide addition to 1,2-dimethylcyclohexene has been studied by Vittimberga (58).



The product reported was *trans*-1,2-dimethyl-1-bromocyclohexane which would be the expected product from a *trans* addition. The mechanism postulated for this addition included the bridged intermediate. Although a radical addition would lead to the observed *trans*-1,2-dimethyl-1-bromocyclohexane, exclusion of an ionic process, to account for at least a part of the final product, cannot be made with the present results.

Goering and Sims (26) continued the investigation of radical hydrogen bromide reaction with olefins. They reinvestigated the addition to 1-bromocyclohexene and also studied the addition to 1-chlorocyclohexene. The radical addition products, isolated in a way which avoided fractionation, showed that the reaction was virtually stereospecific. From 1-bromocyclohexene the investigators obtained 99.7% *cis*-1,2-dibromocyclohexane and 0.3% of the *trans* isomer while from 1-chlorocyclohexene they obtained 99.5% *cis*-1-chloro-2-bromocyclohexane and 0.5% of the *trans* isomer.

In order to determine more closely the mechanism of the addition these authors examined the possibility of pi-complex formation in the reaction. Such a complexation might be expected in view of the large excess of hydrogen bromide used in the addition reactions. Two possibilities exist for the over–all reaction: (1) the reaction could be a two step process, or (2) it could be a concerted process, with attack of the bromine atom on the olefin–hydrogen bromide complex and transfer of a hydrogen atom occurring simultaneously. Neither pathway would offer any particular advantage for a stereospecific addition for in both cases the same over–all stereochemical conditions exist, that is, if a pi-complex is present, it would be expected to collapse stereospecifically.

The authors showed, however, that a pi-complex was not a likely intermediate in the reaction. Two experiments demonstrated this. In the first, the addition of hydrogen bromide to 1-chlorocyclohexene was conducted in the presence of a large molar excess of anhydrous diethyl ether. Insofar as ethers complex to a greater extent than olefins, any complexation in the reaction presumably would involve the ether instead

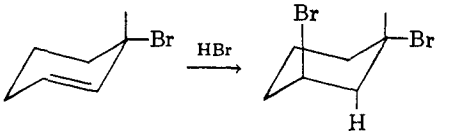
of the 1-chlorocyclohexene. Isolation of the addition products (avoiding fractionation) showed no loss of stereospecificity. In the second experiment the addition was run in the presence of a tenfold excess of anhydrous hydrogen chloride. Although hydrogen bromide has the greater tendency to complex, the workers reasoned that complexation would most likely involve hydrogen chloride due to the very large excess present. Again, isolation and identification of the products showed no loss of stereospecificity.

The radical addition of hydrogen bromide to two other 1-methylcycloalkenes has been studied. Howe (31) investigated the addition to 1-methylcyclopentene and reported the formation of at least 94.3% *cis*-1-methyl-2-bromocyclopentane. The addition to 1-methylcycloheptene has been reported by Abell and Bohm (1) to yield at least 95% of the *cis*-1-methyl-2-bromocycloheptane. Addition to these olefins corresponds, as in the six-membered ring, to a *trans* addition of the elements of hydrogen bromide.

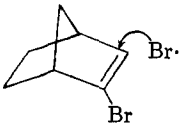
A possible explanation of these results is given in the work of Abell and Chiao (2) on additions of hydrogen bromide to 1-bromocyclobutene, 1-bromocyclopentene, and 1-bromocycloheptene. Ratios of *cis* to *trans* isomers of the 1,2-dibromides obtained were 79:21, 94:6, and 91:9, respectively. These workers interpreted the results in terms of a classical free radical intermediate and attributed the variation in specificity to a balance between mechanistic preference for a *trans* addition and steric inhibition to the formation of *cis* isomers. The formation of *cis*-1,2-dibromocyclobutane involves forcing the two bulky bromine atoms into a thermodynamically unfavorable configuration. Only in the case of the six-membered ring in the series (22) is the *cis*-1,2-dibromo compound unhindered and thus free to be formed by the preferred *trans* addition process. With the five-membered ring strain associated with the *cis* bromines can be alleviated somewhat by puckering of the ring. The seven-membered ring is more flexible than the six-membered ring although roughly equivalent axial–equatorial assignments can be made. Models show a possible configuration for the intermediate radical where *cis* bromines could be present in a thermodynamically favorable arrangement. On the other hand, it is possible, due to the flexibility of the ring, for considerable interaction between the bromines to occur in some conformations of the ring. Thus, some *trans*-dibromide is formed, although the *cis* compound predominates.

The results with the 1-methylcycloalkenes parallel closely the results of the vinyl halides. It would be of interest to learn whether 1-methylcyclobutene would give results similar to those of its bromine analog.

Kharasch, Sallo, and Nudenberg (34) obtained pure *trans*-1,3-dibromocyclohexane from the radical addition of hydrogen bromide to 3-bromocyclohexene-1. The formation of this compound may be explained by a stereospecific *trans* addition process.



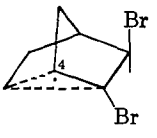
The foregoing information is in good agreement with the operation of a mechanism which includes a classical free radical intermediate. Also consistent with this are the results of LeBel (36) on the addition of hydrogen bromide to 2-bromo-2-norbornene. Reactions of norbornene derivatives differ from those of the monocyclic analogs as a result of considerable steric interaction due to the bicyclic structure. Approach of a bromine atom would be expected from the least hindered, or *exo*, direction of the molecule VIII.

VIII 

(*exo*)

The chain transfer step also involves a choice between an *exo* or an *endo* approach of hydrogen bromide. Approach from the *exo* side would be less hindered and would give rise to *trans*-2,3-dibromonorbornane (*cis* addition). Approach from the more hindered *endo* side would give rise to *exo-cis*-2,3-dibromonorbornane (*trans* addition). The product of the addition consisted of approximately 5/7 *trans*-2,3-dibromonorbornane and 2/7 *exo-cis*-2,3-dibromonorbornane. The lack of stereospecificity of the addition evidently arises from the steric repulsions present in the molecule. These repulsions make the chain transfer step much slower than in the case of the monocyclic olefins. The decrease in rate of the chain-carrying step allows sufficient time for some interconversion to occur, thus, a mixture of products is obtained.

Other mechanistic information may be gleaned from these results. The results obtained cannot be explained in terms of a pi-complex which, as was mentioned earlier, would be expected to collapse stereospecifically. It is also possible to eliminate the possibility of formation of a non-classical free radical in the addition process. Non-classical carbonium ions are encountered often in the chemistry of norbornyl derivatives. The equivalent free radical structure for the present case would be structure IX.



IX

Such an intermediate radical would give rise to 1,7-

dibromonorbornane by chain transfer at carbon atom number 4. No such compound, however, was detected.

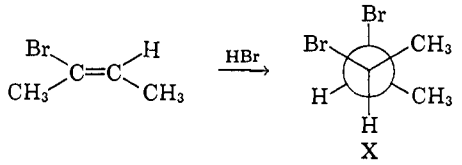
The work of Kooyman and Vegter (35) on the free radical halogenation of norbornane may be cited as further evidence for the importance of steric effects in radical reactions of bicyclo-compounds. These workers found in the ultraviolet light catalyzed reaction of norbornane and chlorine that approximately 70% of the product was the *exo*-2-chloronorbornane, approximately 25% was the *endo*-2-chloronorbornane, and the remainder was the 7-chloro compound. With bromine 75% *exo*-2-bromonorbornane was formed. With sulfuryl chloride, carbon tetrachloride, phosphorus pentachloride, and bromotrichloromethane approximately 95% *exo*-2-halide was formed. The accessibility of the radical from the *endo* side is less than that of the *exo* side as a result of the shielding effect of the methylene group in the 6-position. The difference in accessibilities increases with increase in the over-all bulk of the halogen donor molecule.

A radical addition of hydrogen bromide to *cis*- and *trans*-2-bromo-2-butene has been reported by Epstein (20) to be essentially stereospecific. Addition to the *cis* olefin gave 62% *meso*-2,3-dibromobutane, 15% 2,2-dibromide, and none of the *dl*-dibromide. Addition to the *trans* olefin gave mostly *dl*-dibromide with some *meso*-dibromide. The results were interpreted in terms of a stereospecific *trans* addition process. This conclusion was rationalized by citing Lepingle's (37) work on the isomerization of *cis*- and *trans*-2-bromo-2-butene wherein an equilibrium mixture of 83% *trans* and 17% *cis* was reported. Epstein's interpretation must be viewed with considerable caution, however, as the degree of isomerization in the additions was not determined, nor was the purity of the starting olefins accurately known.

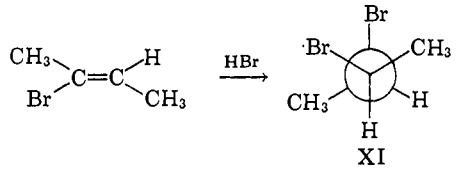
High degrees of stereospecificity recently have been reported by two groups of workers on the addition of hydrogen bromide to acyclic olefins under free radical conditions. In 1957 Goering and Larsen (23) reported the results of their preliminary investigation of the addition to *cis*- and *trans*-2-bromo-2-butenes. The reactions were run at −80° in liquid hydrogen bromide. Addition to the *cis* olefin gave 92% *meso*-2,3-dibromobutane, 5% *dl*-2,3-dibromobutane, and 3% 2,2-dibromobutane, the latter compound presumably formed by ionic addition. Addition to the *trans* olefin gave 5% unreacted olefin, 83% *dl*-dibromide, 8.5% *meso*-dibromide, and 3.5% 1,2-dibromide.

In an isomerization experiment, where *cis*-2-bromo-2-butene and liquid hydrogen bromide were allowed to stand together in the dark, 91.5% 2,2-dibromobutane and 8.5% bromobutene were obtained. The recovered olefin was mostly the *trans* isomer, which shows that some isomerization occurred under the conditions of the addition. In view of these data the authors concluded that a stereospecific *trans* addition process was functioning in the reaction. However, the possibility of some interconversion of radical intermediates cannot be ruled out strictly. It is clear, though, that individual intermediate radicals do exist and that the chain transfer step is indeed very rapid.

Further proof that the addition reaction is stereospecific was presented in a later paper by Goering and Larsen (24). At −80° the addition of hydrogen bromide and deuterium bromide to *cis*- and *trans*-2-bromo-2-butene each gave 100% of the product resulting from *trans* addition. Thus the *cis* olefin gave pure *meso*-2,3-dibromobutane X and the *trans* olefin gave pure *dl*-dibromide XI.



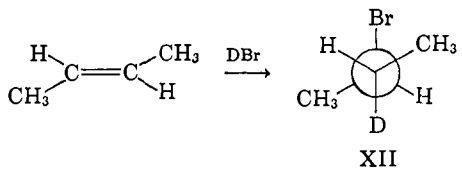
X



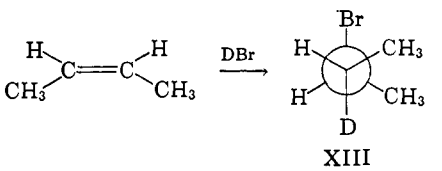
XI

As the temperature was raised the stereospecificity decreased so that at room temperature roughly the same mixture of products was obtained from each olefin. This was true for both hydrogen and deuterium bromide. At the low temperature the reaction was run in liquid hydrogen bromide so that a considerable excess of this reactant was present. With such an excess of adding reagent an intermediate free radical would have no difficulty in finding a molecule with which it could undergo chain transfer before interconversion occurred. As the temperature was raised the concentration of adding reagent was reduced to a point where some of the intermediate radicals had time to interconvert before encountering a molecule of hydrogen bromide with which they could undergo transfer.

Skell and Allen (51) have reported another stereospecific radical addition of deuterium bromide. Pure



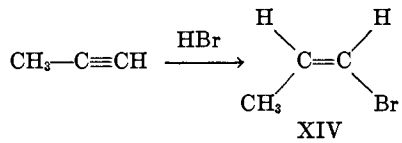
XII



XIII

erythro-3-deuterio-2-bromobutane XII was obtained from *trans*-2-butene while *cis*-2-butene yielded pure *threo*-3-deuterio-2-bromobutane XIII.

In the previous year Skell and Allen (50) found that radical addition of hydrogen bromide to propyne in the liquid phase gave exclusively *cis*-1-bromopropene XIV. The stereochemistry of the gas phase reaction



XIV

was attempted but any results from addition of hydrogen bromide were obscured by the rapid equilibrium of *cis* and *trans* isomers.

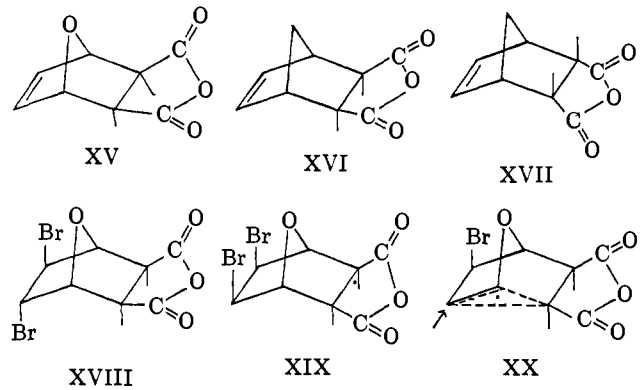
An earlier addition of hydrogen bromide to an acetylene was reported by Walling, Kharasch, and Mayo (59). Addition of two moles of hydrogen bromide to 2-butyne resulted in the formation of *dl*-2,3-dibromobutane as the sole product. The product could have been formed from either two consecutive *cis* or two consecutive *trans* additions. The authors, however, dismissed the possibility of consecutive, stereospecific steps. There seems very little doubt, however, in view of more recent work, that the product was formed by a stereospecific process.

Bergel'son (8) has studied the stereochemistry of hydrogen bromide additions to acetylene derivatives and has suggested a *cis* addition mechanism to account for the occurrence of *trans*-dibromoethylenes. 1-Bromopropyne at −78° in pentane gave a 92% yield of 1,2-dibromopropene of which about 75% was the *trans* isomer. 1-Bromo-3,3-dimethylbutyne gave an 89% yield of 1,2-dibromo-3,3-dimethylbutene-1 which contained 95% of the *trans* isomer under the same conditions. When the reactions were run without solvents similar results were obtained.

B. BROMINE

Free radical addition of halogens to olefins has been conducted for the most part in studies where stereochemistry was not being investigated. A relatively limited amount of work directed toward determination of the stereochemistry of these additions has been done. Only recently has a systematic approach been taken to the problem.

A radical addition of bromine to *exo-cis*-3,6-endoxo-Δ^4-tetrahydrophthalic anhydride XV has been reported by Berson and Swidler (10, 12). When the reaction was run with acetic acid or ethyl acetate as the solvent and in the absence of light, the sole product formed was the *trans*-5,6-dibromo compound XVIII. In the light, and using oxygen-free methylene chloride as solvent, the addition gave 56% XVIII and 36% of the *exo-cis*-5,6-dibromo compound XIX. Completely analogous results were obtained by Berson (11) in the addition



XV XVI XVII

XVIII XIX XX

of bromine to *exo-cis*-3,6-endomethylene-Δ^4-tetrahydrophthalic anhydride XVI. The *cis*-5,6-dibromide XIX formation was explained in terms of a radical process which possibly involved the intermediate radical XX. Attack of bromine at carbon number five (arrow) would give the *cis* product as a result of steric blocking of the *endo* direction by the anhydride function. That the anhydride contributes strongly in product determination is shown in the results of the addition of bromine to *endo-cis*-3,6-endomethylene-Δ^4-tetrahydrophthalic anhydride XVII (12). Addition to the *endo*-anhydride results in the formation of the *exo-cis*-5,6-dibromo isomer almost exclusively.

The bromination of 3,4,5,6-tetrachlorocyclohexene-1 under the influence of ultraviolet light has been reported by Riemschneider (45) to give two products. The major product had the higher melting point and was assigned the structure le2e(Br)3e4e5a6a(Cl). The structure of the lesser product was le2a(Br)3a4a5e6e-(Cl). With the formation of both isomers it is evident that the intermediate radical underwent some degree of interconversion during its lifetime.

Recently a series of papers appeared by a group of Russian workers dealing with the stereochemistry of bromine additions to some mono- and disubstituted acetylenes. The work was concerned to a certain extent with both ionic and free radical additions. The information pertinent to the present discussion is presented in Tables I and II.

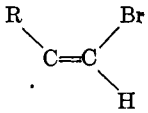
TABLE I

BROMINE ADDITIONS TO MONOSUBSTITUTED ACETYLENES

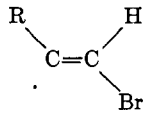
Compound	Conditions		% *cis*	% *trans*	Ref.
2-Propyn-1-ol	CCl_4	$h\nu$		74	40
2-Methyl-3-butyn-2-ol	Hexane	$h\nu$	91	9	40, 39
2-Methyl-3-butyn-2-ol acetate	Hexane	$h\nu$	92	8	40
1-Ethynylcyclohexanol	Hexane	$h\nu$	100	—	40
Acetylene	Hexane	Bz_2O_2	55	45	41
Propyne	Hexane	$h\nu$		77	41
3,3-Dimethyl-1-butyne	Hexane	$h\nu$	91		41

The course of the addition to the monosubstituted acetylenes is strongly influenced by the steric nature of

the alkyl substituent. The tendency for *cis* addition increases in the series H, CH_3, CH_2OH, $(CH_3)_2COH$, 1-hydroxycyclohexyl, $(CH_3)_3C$.



XXI



XXII

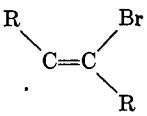
As the size of the alkyl group (R) increases, interaction between this substituent and the bromine atom also increases, thus making intermediate XXI less stable than XXII. The major proportion of the product in the case of a large R function is thus formed by attack of a bromine molecule on XXII.

TABLE II

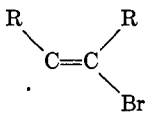
BROMINE ADDITIONS TO DISUBSTITUTED ACETYLENES

Compound	Conditions		% *cis*	% *trans*	Ref.
2-Butyn-1,4-diol	CCl_4	$h\nu$	84		7
2-Butyn-1,4-diol diacetate	Hexane	$h\nu$	78		7
Acetylenedicarboxylic acid	Ether	$h\nu$	82		7
2,5-Dimethyl-3-hexyne-2,5-diol	CCl_4	$h\nu$	78	16	7
Diphenylacetylene	Hexane	$h\nu$		69	7

The tendency for a *trans* addition process increases in the series CH_2OH, COOH, $(CH_3)_2COH$, phenyl. These results may be explained in terms of the thermodynamic stability of the intermediate radicals XXIII and XXIV. The product is governed by the steric

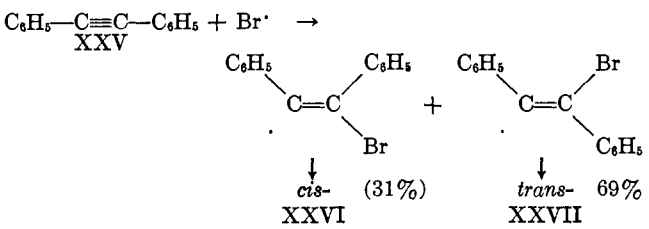


XXIII



XXIV

interactions present in the intermediates. If R–R interactions exceed R–Br interactions, structure XXIII would be more stable and product from a *trans* addition would predominate. If R–Br interactions are larger, intermediate XXIV would be more stable and *cis* addition would predominate. The order of increasing influence for the first four substituents represented in Table II is not clear-cut, but the effect is seen clearly in the case of diphenylacetylene XXV.

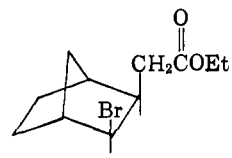


XXV → XXVI (*cis*-, 31%) + XXVII (*trans*-, 69%)

Bergel'son and Badenkova (9) have also investigated the addition of bromine to several olefinic compounds under free radical conditions. Ultraviolet light catalyzed addition to cyclohexene gave *trans*-1,2-dibromocyclohexane in 90% yield. Stereospecific addition of bromine was reported with the *cis*- and *trans*-2-butene-1,4-diols, the corresponding diacetates, and the *cis*- and *trans*-2,5-dimethyl-3-hexene-2,5-diols. It was demonstrated that isomerization had not occurred in the addition reactions.

C. ETHYL BROMOACETATE

The free radical addition of ethyl bromoacetate to norbornene has been reported by Weinstock (61) to yield *exo-cis*-2-carbethoxymethyl-3-bromonorbornane XXVI. Presumably, the steric blocking of the ethano



XXVI

bridge is greater than that of the carbethoxymethyl function with the result that both steps of the reaction occur from the less hindered or *exo* side of the molecule.

D. BROMOTRICHLOROMETHANE

In 1949 Kharasch and Friedlander (32) reported the results of their investigation of the ultraviolet light catalyzed radical addition of bromotrichloromethane to a series of olefins. The compounds used in the study were cyclopentene, cyclohexene, cyclopentadiene, cyclohexadiene, bicyclo[2.2.1]heptene-2, bicyclo[2.2.2]octene-2, dicyclopentadiene, and indene. All of the addition products, with the exception of those from bicycloheptene, bicycloöctene, and dicyclopentadiene, lost halogen easily when treated with base. The stability of the bicyclic adducts was explained in terms of the resistance to the formation of bridgehead double bonds (Bredt's rule) in the elimination of the hydrogen halide.

It was Fawcett (21), however, who interpreted the results of Kharasch and Friedlander's work in terms of the currently accepted mechanism. He suggested that the addition was a *trans* process with the bromotrichloromethane molecule approaching the intermediate from the side opposite to the trichloromethyl group in the chain transfer step.

A more comprehensive treatment of the stereochemistry of bromotrichloromethane addition to olefins is the work of Skell and Woodworth (55) on additions to *cis*- and *trans*-2-butene. Light initiated addition to the isomers at 0–25° gave mixtures of products which were identical. Under the conditions of the reaction there was no detectable interconversion of *cis*- and *trans*-2-butene. It is evident from the results that the addition of a trichloromethyl radical to either isomer forms an identical mixture of diastereomeric radicals. The chain transfer step, which is faster than the reverse of the

trichloromethyl radical addition step, occurs with the mixture of diastereomeric radicals to form the observed mixture of products.

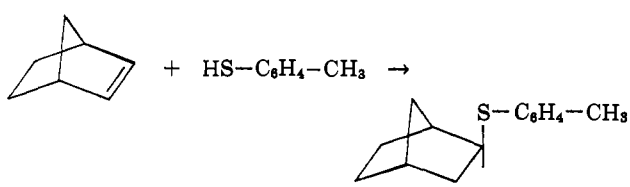
The participation of a three-membered ring intermediate in the addition can be ruled out. If such a stable bridged structure did exist *cis*-2-butene would give an intermediate radical having the *meso*-configuration, while an intermediate radical with the *dl*-configuration would be obtained from the *trans* olefin. The mixture of isomers derived from these olefins thus indicates the operation of an open chain radical.

This open chain structure can be planar or pyramidal. In order to account for the observed mixtures of diastereomers Skell and Woodworth suggested equilibrium of pyramidal intermediate radicals. The choice of a pyramidal intermediate was made after considerations of van der Waals force law between the nonbonded atoms and an extrapolation to the carbon atom of the bonding forces which make the pyramidal ammonia molecule more stable than the planar ammonia molecule. That the planar ammonia molecule is the structure of lesser stability is made more clear when it is pointed out that this is the transition state for the inversion of the pyramidal molecule.

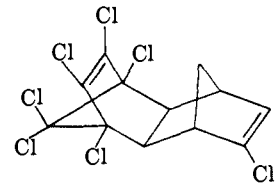
III. Addition of Reagents Containing Sulfur

In order to facilitate discussion of free radical additions of reagents containing sulfur, the various reagents concerned will be included in a single topic of discussion rather than separately. This is beneficial as it often allows comparisons to be drawn as the subject matter develops.

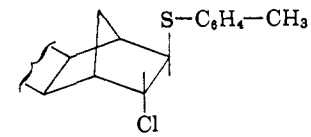
In 1954 Cristol and Brindell (17) reported the exclusive formation of the *exo* isomer in the addition of *p*-thiocresol to norbornene. These results show once again the striking steric blocking of the ethano bridge.



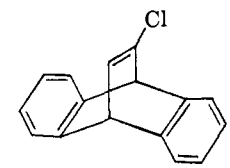
It is not possible to tell from these results, however, whether the over-all addition is *cis* or *trans*. It is most probable, though, that the addition is *cis* as addition of the same reagent to bicyclo[2.2.1]heptene derivative XXVII gave exclusively the product of *cis* addition XXVIII. Addition of *p*-thiocresol to 11-chloro-9,10-dihydro-9,10-ethanoanthracene XXIX (16) gave a mixture of products of which one-third resulted from *trans* addition and two-thirds from *cis* addition. The results of these investigations suggest the operation of a classical radical intermediate rather than a bridged structure.



XXVII



XXVIII



XXIX

A classical intermediate radical also has been postulated recently by Cristol and Reeder (19) in the addition of *p*-toluenesulfonyl chloride to two norbornenes. Norbornene itself and aldrin XXVII gave exclusively *trans* products in the addition reactions. Neither skeletal rearrangement nor *cis-exo*-compounds were detected in the reaction products. Presumably, the approach of a molecule of *p*-toluenesulfonyl chloride to the number three carbon atom of the intermediate is hindered in the *exo* direction by the large *p*-toluenesulfonyl group. Transfer is thus favored from the *endo*-side of the intermediate.

That the *p*-toluenesulfonyl group should present such steric crowding is borne out in other investigations involving molecules possessing this function. For instance, Bordwell and Cooper (13) reported the relative inertness of chloromethyl *p*-tolyl sulfone toward reaction with potassium iodide in acetone and demonstrated that the effect was purely steric in nature. These authors discussed a number of other instances where this effect also was observed.

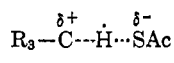
Stereospecific thiol additions would seem to be expected only in the case of olefins that were highly sterically hindered. Generally, however, additions of radicals involving sulfur have been shown not to be stereospecific, although relatively high degrees of stereoselectivity have been observed in most cases. Howe (31) studied the addition of a number of thiols to 1-methylcyclopentene. Addition of thiophenol produced 19.2% *trans* product (*cis* addition) when the mercaptan to olefin ratio was 1:1 and 21.2% *trans* product when the ratio was 20:1. *p*-Chlorothiophenol gave 17.05% *trans* product (ratio 1:1) and *p*-methylthiophenol gave 13.97% *trans* product (ratio 1:1). Hydrogen sulfide added to form 19.66% *trans* adduct when the ratio of reactants was 1:1 and 16.7% of the *trans* isomer when the ratio was 18:1. Benzyl mercaptan gave 10–20% *trans* product which was unstable under the reaction conditions. With thiol additions one encounters a series of compounds which are less reactive as chain-transfer reagents than is hydrogen bromide. As a result of the

slower second step in the reaction the intermediate radical has sufficient time for some isomerization to occur.

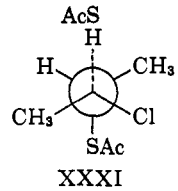
It would be interesting to speculate on the influence of electronic factors on the reaction. It is unfortunate that the data on the addition of *p*-substituted thiophenols are limited. Generalizations on the values obtained with the *p*-chloro- and *p*-methylthiophenols would be open to considerable criticism. Further study on a larger number of substituted thiophenols, however, might allow a decision to be made regarding the sensitivity of the reaction to changes in the electronic nature of the adding reagent.

Results similar to those just described have been obtained by other groups of workers. Goering, Relyea, and Larsen (25) reported predominantly *trans* addition of thiolacetic acid (66–73%), hydrogen sulfide (74.8%), and thiophenol (94.2%) to 1-chlorocyclohexene. Bordwell and Hewett (14) observed 85% *trans* addition of thiolacetic acid to 1-methylcyclohexene, 70% *trans* addition of thiolacetic acid to 1-methylcyclopentene, and predominantly *trans* addition of thiophenol to 1-methylcyclohexene.

Addition of thiolacetic acid at −78° to *cis*- or *trans*-2-chloro-2-butene has been shown to afford identical mixtures of products consisting of 90% *threo*- and 10% *erythro*-2-acetylmercapto-3-chlorobutane (42). At room temperature the olefins were isomerized rapidly by the adding reagent. The results were rationalized in terms of (1) development of some ionic character in the chain transfer step, and (2) minimization of steric interactions. Development of ionic character in the transfer step corresponds to the explanation offered by Greene, Remers, and Wilson (27) in their study of the free radical bromination of bibenzyl with N-bromosuccinimide. Applied to the present case a dipole such as XXX might be expected. If this were the case the dipole would be oriented away from the largest existing perma-



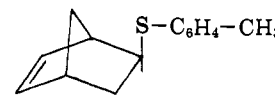
XXX



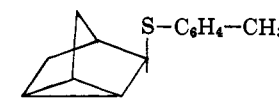
XXXI

nent dipole on the saturated carbon. This would lead to *trans* addition as shown in XXXI. Consideration of steric effects leads to the same conclusions. In the conformation shown, non-bonded interactions are at a minimum: the smaller of the two groups on the radical carbon (chlorine) lies in the "hole" between the methyl and acetylmercapto groups while the acetylmercapto radical lies between hydrogen and methyl and on the opposite side of the molecule. Both of these factors lead to the formation of the product from *trans* addition, *threo*-2-acetylmercapto-3-chlorobutane.

The question of classical *vs.* non-classical intermediate free radicals arose in the work of Cristol, Brindell, and Reeder (18) on the radical addition of thiocresol to norbornadiene. Two products were formed in the addition, 40% *exo*-5-norbornen-2-yl aryl ether XXXII and 60% 3-nortricyclyl aryl ether XXXIII.

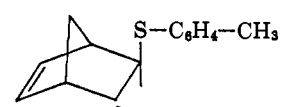


XXXII

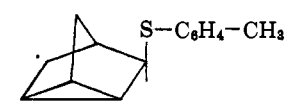


XXXIII

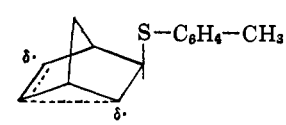
Two routes are possible for the formation of these products, one with a classical intermediate radical corresponding to each product and one having a non-classical radical capable of giving rise to either product. The classical radicals are shown below as XXXIV and XXXV which give rise to XXXII and XXXIII, respectively. The non-classical radical is represented as structure XXXVI. Attack of a thiocresol molecule at carbon two results in the formation of XXXII, while attack at carbon five gives XXXV.



XXXIV



XXXV



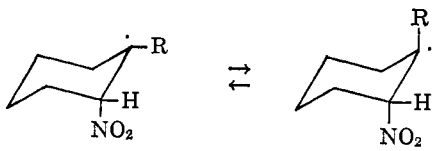
The authors reasoned, on the basis of work of Seubold (49) on mesomeric radicals in neophyl radical rearrangement, that the products of the reaction involving a non-classical radical intermediate would be independent of reactant concentration, whereas the ratio of products from a reaction involving separate classical radicals would be a function of mercaptan concentration. Experiments with varying mercaptan concentrations showed a definite relationship between product ratios and the mercaptan concentrations. The results are in line with LeBel's (36) conclusion on hydrogen bromide addition to norbornene that the over-all stereochemical picture of the reaction is quite clearly affected by the highly strained nature of the olefinic system.

Of considerable interest is the work of Skell and Allen (52) on the conditions necessary for stereospecific addition of mercaptans to olefins. *cis*- and *trans*-2-butene gave identical mixtures of *erythro*- and *threo*-3-deuterio-2-methylthiobutane when allowed to react with methylmercaptan (CH_3SD). When these olefins were treated with a mixture of methylmercaptan (CH_3SD) and deuterium bromide products from stereospecific reactions were formed. Thus, *cis*-2-butene gave *threo*-3-deuterio-2-bromobutane and *threo*-3-deuterio-2-methylthiobutane, while from the *trans* olefin *erythro*

isomers were obtained. These results require that the sole molecule participating in chain transfer be deuterium bromide. Stereospecific addition is achieved by rapid reaction of deuterium bromide with the 3-methylthio-2-butyl radicals before isomerization can occur.

IV. Addition of Dinitrogen Tetroxide

The stereochemistry and mechanism of the radical addition of dinitrogen tetroxide to olefins has been investigated by Brand and Stevens (15). The products of the additions were nitro nitrite esters which were hydrolyzed to the nitro alcohols and reduced under controlled conditions to the known amino alcohols. Addition to cyclohexene yielded 58% *trans*-2-nitrocyclohexyl nitrite, addition to cyclopentene yielded 84% *trans*-2-nitrocyclopentyl nitrite. These percentages refer to the amount of *trans* isomer present in the yield of addition product. Addition to 1-methylcyclohexene yielded, stereospecifically, 1-methyl-*trans*-2-nitrocyclohexyl nitrite. When R = H there is rapid



XXXVII XXXVIII

interchange between radicals XXXVII and XXXVIII. Chain transfer, therefore, occurs with an equilibrium mixture of the two radicals. When R = CH_3 a considerable increase in energy would be associated with displacement from an equatorial conformation XXXVII to an axial conformation XXXVIII. Thus, the equilibrium lies completely to the left where the chain transferring molecule approaches axially and stereospecific *trans* addition results.

V. Miscellaneous Addenda

A. SULFUR DIOXIDE

The copolymerization of *cis*- and *trans*-2-butene with sulfur dioxide has been studied by Skell, Woodworth, and McNamara (56). The isomeric olefins gave products with identical infrared spectra, indicating a non-stereospecific addition process. To eliminate the slight chance that the diastereomeric copolymers possessed identical infrared spectra another approach was taken. Mixtures of olefin, benzenesulfonyl iodide, and sulfur dioxide were allowed to react. There was no evidence for sulfur dioxide participation in the reaction, the sole products being identical mixtures of the 2-benzenesulfonyl-3-iodobutanes. Addition of benzenesulfonyl iodide to *cis*- and *trans*-2-butene has been shown to be non-stereospecific (54). Therefore, addition of sulfur dioxide, a slower reaction, is also not stereospecific.

B. OXYGEN TO INDENE

The reaction between indene and oxygen to form indene peroxide has been investigated by Russell (46). Reduction of the peroxide formed with lithium aluminum hydride produced *cis*- and *trans*-indene glycols in very nearly equal amounts. Thus, the addition of a peroxy radical and an oxygen molecule to indene has a very low degree of specificity.

C. SILICOCHLOROFORM

The stereospecific *trans* addition of silicochloroform to several acetylenic compounds has been reported by Benkeser and Hickner (6). Moderate yields of adduct were obtained by the benzoyl peroxide catalyzed addition to 1-pentyne, 1-hexyne, and 1-heptyne. Addition to phenylacetylene was unsuccessful, presumably due to steric crowding. When the addition is carried out using platinized charcoal stereospecific *cis* addition is observed. Undoubtedly, some polarization of the hydrogen–silicon bond occurs on the surface of the catalyst, which would be in line with the accepted mechanism of catalytic hydrogenation.

VI. Conclusions and Some Considerations of a General Mechanism

The addition of free radicals to olefins cannot be assigned a definite, unequivocal mechanism. Although the general, over-all pathway of these reactions is well established, the more intimate details of the various steps still are open to debate. We can, however, draw a fairly representative picture of what appears to be happening.

Let us take the evidence accumulated by the workers listed above and make an attempt to visualize the process involved when a molecule adds to a double bond *via* a radical pathway. The radical addition can, as we have seen repeatedly, be written as two separate steps: (1) formation of the intermediate free radical by the attack of some radical species on a double bond, and (2) chain transfer to yield a saturated molecule and a new free radical which carries on the chain process. Consideration of the various possible factors influencing these steps affords considerable insight into the general nature of the addition process.

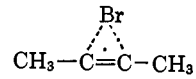
Approach of the attacking radical to a double bond (similar statements are true with triple bonded compounds) is generally considered to occur from a direction perpendicular to the sigma-bond of the bond in question (43, 48). Such a view is also in line with the molecular orbital treatment of Greenwood (28). Presumably, the radical "sees" the pi-electrons of the double bond as an ideal opportunity to satisfy its deficiency of electrons. In opposition to this view are Szwarc and co-workers

(4)* who concluded, from their work on methyl radical additions to olefins, that the most likely direction of approach of an attacking radical would be along the carbon–carbon double bond axis. Approach along the double bond axis cannot be ruled out on the basis of the evidence at hand, but it does not seem to contribute to an explanation of the observed stereochemistry.

The question of participation of a pi-complex in the addition process has been a point of interest. Interaction of an olefin's pi-electrons with a molecule of the addendum would yield a complex which would be expected to collapse stereospecifically upon attack by an incoming radical. A concerted process involving a complexed molecule also has been postulated. Stereospecific additions have been reported to occur in a limited number of cases wherein the participation of a complex was doubtful. The evidence, however, does not rigidly exclude complexation. Pi-complexation in the free radical chlorination of 2,3-dimethylbutane has been shown by Russell (47) to be quite significant. It should be borne in mind, however, that in Russell's studies the complexing agent was the solvent and not one of the reactants. It is clear that further investigation is necessary before a more definite answer can be given in connection with the problem of complexation in radical addition reactions.

In order to explain early stereospecific additions of hydrogen bromide a bridged intermediate radical, similar in nature to the bromonium ion, was proposed. Chain transfer then occurred at the side of the molecule opposite to the bridged structure to yield the stereospecific product. However, the substantial number of non-specific reactions throws doubt on the validity of this intermediate. One possible explanation is that an equilibrium exists between bridged and non-bridged intermediates such that one isomer would be formed from the bridged structure and the other isomer from the open intermediate radical. This explanation offers no particular advantage and opinion rests strongly in favor of an open or "classical" intermediate free radical.

Some very interesting results recently have been observed by Abell and Piette (3) which throw new light on the question of the bridged structure of intermediate radicals. The addition of hydrogen bromide to a number of olefins at 77°K. was studied by electron paramagnetic resonance spectroscopy. It was found that symmetrical olefins gave rise to spectra which could be interpreted as arising from symmetrical radicals. In a molecule such as butyne-2 this could mean that the bromine was located directly between carbons two and three in the intermediate which suggests a structure such as XXXIX.



XXXIX

Unsymmetrical olefins did not give rise to the same form of spectra so that it would appear that the intermediates from symmetrical and unsymmetrical olefins were different. It is not at all clear from these results what type of intermediate radical is formed from unsymmetrical olefins.

Evidence of the mobility of bromine atoms recently has been reported by Skell, Allen, and Gilmour (53). These investigators showed that abstraction of a primary hydrogen from either isopropyl bromide or *t*-butyl bromide produced migration of the bromine atom to the terminal carbon. In view of earlier work of Skell and Allen (52), this bromine migration must be an extremely rapid process. This rapid migration lends support to the participation of a bromine atom in bridge formation.

It is very important to realize that the e.p.r. results should be treated very cautiously. The reactions were run in the solid state where radical lifetimes were of substantial length. In the liquid phase the lifetimes of the radicals were too short to allow detection. It is quite obvious that much work is needed along these lines before any more definite assignments of intermediate structure can be made.

The intermediate radical structure which is more or less generally accepted is the classical structure. Stereochemical results of addition reactions can be accounted for satisfactorily in terms of an open radical, with both the cyclic and the acyclic olefins. If the adding reagent participates in chain transfer rapidly, as in the case of hydrogen bromide, and the concentration of this reagent is high, transfer occurs before the carbon bearing the free electron has time to invert its configuration. When the ability for chain transfer is lessened, as with the various thiols, sufficient time exists between intermediate formation and transfer for some inversion of configuration to occur, and hence a mixture of products to result.

The influence of steric effects in the addition of radicals to cyclic olefins has been demonstrated. In most cases addition proceeds by a *trans* mechanism giving rise, in the case of substituted olefins, to the thermodynamically less stable *cis* isomers as products. In cases where severe steric limitations are present in the molecule the addition proceeds, for the most part, to give rise to the structure having the smallest possible degree of steric interaction.

* NOTE ADDED IN PROOF.—A more recent article by Szwarc and co-workers (*J. Am. Chem. Soc.*, **83**, 1260 (1961)) has retracted the earlier (4) opinion that radical attack on an unsaturated bond occurred along that bond's axis.

VII. REFERENCES

(1) Abell, P. I., and Bohm, B. A., *J. Org. Chem.*, **26**, 252 (1961).
(2) Abell, P. I., and Chiao, C., *J. Am. Chem. Soc.*, **82**, 3610 (1960).
(3) Abell, P. I., and Piette, L. H., *J. Am. Chem. Soc.*, **84**, 916 (1962).
(4) Bader, A. R., Buckley, R. P., Leavitt, F., and Szwarc, M., *J. Am. Chem. Soc.*, **79**, 5621 (1957).
(5) Beckett, C. W., Pitzer, K. S., and Spitzer, R., *J. Am. Chem. Soc.*, **69**, 2488 (1947).
(6) Benkeser, R. A., and Hickner, R. A., *J. Am. Chem. Soc.*, **80**, 5298 (1958).
(7) Bergel'son, L. D., *Izvest. Akad. Nauk S.S.S.R., Otdel. Khim. Nauk*, 1066 (1960).
(8) Bergel'son, L. D., *Izvest. Akad. Nauk S.S.S.R., Otdel. Khim. Nauk*, 1235 (1960).
(9) Bergel'son, L. D., and Badenkova, L. P., *Izvest. Akad. Nauk S.S.S.R., Otdel. Khim. Nauk*, 1073 (1960).
(10) Berson, J. A., *J. Am. Chem. Soc.*, **76**, 4060 (1954).
(11) Berson, J. A., *J. Am. Chem. Soc.*, **76**, 5748 (1954).
(12) Berson, J. A., and Swidler, R., *J. Am. Chem. Soc.*, **75**, 4366 (1953).
(13) Bordwell, F. G., and Cooper, G. D., *J. Am. Chem. Soc.*, **73**, 5184 (1951).
(14) Bordwell, F. G., and Hewett, W. A., *J. Am. Chem. Soc.*, **79**, 3493 (1957).
(15) Brand, J. C. D. and Stevens, I. D. R., *J. Chem. Soc.*, 629 (1958).
(16) Cristol, S. J., and Arganbright, R. P., *J. Am. Chem. Soc.*, **79**, 6039 (1957).
(17) Cristol, S. J., and Brindell, G. D., *J. Am. Chem. Soc.*, **76**, 5699 (1954).
(18) Cristol, S. J., Brindell, G. D., and Reeder, J. A., *J. Am. Chem. Soc.* **80**, 635 (1958).
(19) Cristol, S. J., and Reeder, J. A., *J. Org. Chem.*, **26**, 2182 (1961).
(20) Epstein, M. E., Ph.D. Thesis, Syracuse University, 1951.
(21) Fawcett, F. S., *Chem. Revs.*, **47**, 219 (1950).
(22) Goering, H. L., Abell, P. I., and Aycock, B. F., *J. Am. Chem. Soc.*, **74**, 3588 (1952).
(23) Goering, H. L., and Larsen, D. W., *J. Am. Chem. Soc.*, **79**, 2653 (1957).
(24) Goering, H. L., and Larsen, D. W., *J. Am. Chem. Soc.* **81**, 5937 (1959).
(25) Goering, H. L., Relyea, D. I., and Larsen, D. W., *J. Am. Chem. Soc.*, **78**, 348 (1956).
(26) Goering, H. L., and Sims, L. L., *J. Am. Chem. Soc.*, **77**, 3465 (1955).
(27) Greene, F. D., Remers, W. A., and Wilson, J. W., *J. Am. Chem. Soc.*, **79**, 1416 (1957).
(28) Greenwood, H. H., *J. Am. Chem. Soc.*, **79**, 5365 (1957).
(29) Hammett, L. P., "Physical Organic Chemistry," McGraw-Hill Book Co., New York, N. Y., 1941, p. 376.
(30) Hey, D. H., and Waters, W. A., *Chem. Revs.*, **21**, 169 (1937).
(31) Howe, K., Ph.D. Thesis, University of Wisconsin, 1954.
(32) Kharasch, M. S., and Friedlander, H. N., *J. Org. Chem.*, 14, 239 (1949).
(33) Kharasch, M. S., Mansfield, J. V., and Mayo, F. R., *J. Am. Chem. Soc.*, **59**, 1155 (1937).
(34) Kharasch, M. S., Sallo, J. S., and Nudenberg, W., *J. Org. Chem.*, **21**, 129 (1956).
(35) Kooyman, E. C., and Vegter, G. C., *Tetrahedron*, 4, 382 (1958).
(36) LeBel, N. A., *J. Am. Chem. Soc.*, **82**, 623 (1960).
(37) Lepingle, M., *Bull. soc. chim. France*, [4] **39**, 741 (1926).
(38) Mayo, F. R., and Walling, C., *Chem. Revs.*, **27**, 351 (1940).
(39) Nazarov, I. N., and Bergel'son, L. D., *Zhur. Obshchei. Khim.*, **27**, 1540 (1957); *C.A.*, **52**, 3660g (1958).
(40) Nazarov, I. N., and Bergel'son, L. D., *Izvest. Akad. Nauk S.S.S.R., Otdel. Khim. Nauk*, 887 (1960).
(41) Nazarov, I. N., and Bergel'son, L. D., *Izvest. Akad. Nauk S.S.S.R., Otdel. Khim. Nauk*, 896 (1960).
(42) Neureiter, N. P., and Bordwell, F. G., *J. Am. Chem. Soc.*, **82**, 5354 (1960).
(43) Noyes, R. M., Dickinson, R. G., and Schomaker, V., *J. Am. Chem. Soc.*, **67**, 1319 (1945).
(44) Pauling, L., "The Nature of the Chemical Bond," 3rd Ed., Cornell University Press, Ithaca, N. Y., 1960, p. 343.
(45) Riemschneider, R., *Monatsh. Chem.*, **85**, 1133 (1954).
(46) Russell, G. A., *J. Am. Chem. Soc.*, **78**, 1035 (1956).
(47) Russell, G. A., *J. Am. Chem. Soc.*, **80**, 4987 (1958).
(48) Semenov, N. N., "Some Problems in Chemical Kinetics and Reactivity," Vol. I, Princeton University Press, Princeton, N. J., 1958, p. 68.
(49) Seubold, F. H., *J. Am. Chem. Soc.*, **75**, 2532 (1953).
(50) Skell, P. S., and Allen R. G., *J. Am. Chem. Soc.*, **80**, 5997 (1958).
(51) Skell, P. S., and Allen, R. G., *J. Am. Chem. Soc.*, **81**, 5583 (1959).
(52) Skell, P. S., and Allen, R. G., *J. Am. Chem. Soc.*, **82**, 1511 (1960).
(53) Skell, P. S., Allen, R. G., and Gilmour, N. D., *J. Am. Chem. Soc.*, **83**, 504 (1961).
(54) Skell, P. S. and McNamara, J. H., *J. Am. Chem. Soc.*, **79**, 85 (1957).
(55) Skell, P. S., and Woodworth, R. C., *J. Am. Chem. Soc.*, **77**, 4638 (1955).
(56) Skell, P. S., Woodworth, R. C., and McNamara, J. H., *J. Am. Chem. Soc.*, **79**, 1253 (1957).
(57) Taylor, T. W. J., and Murray, A. R., *J. Chem. Soc.*, 2078 (1938).
(58) Vittimberga, B. M., M.S. Thesis, University of Rhode Island, 1954.
(59) Walling, C., Kharasch, M. S., and Mayo, F. R., *J. Am. Chem. Soc.*, **61**, 1711 (1939).
(60) Walling, C., Kharasch, M. S., and Mayo, F. R., *J. Am. Chem. Soc.*, **61**, 2693 (1939).
(61) Weinstock, J., Abstracts of Papers, 128th ACS Meeting, Minneapolis, Minn., Sept. 11–16, 1955, p. 19–O.