

The Annulenes

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The "annulenes" is the name we gave a number of years ago to the completely conjugated monocarbocyclic polyenes, the ring size being indicated by a number in brackets.¹ It has been predicted that these substances will be aromatic, provided they contain $(4n + 2)$ π electrons ("Hückel's rule") and a reasonably planar carbon skeleton, and the ring size is below a certain limit.²

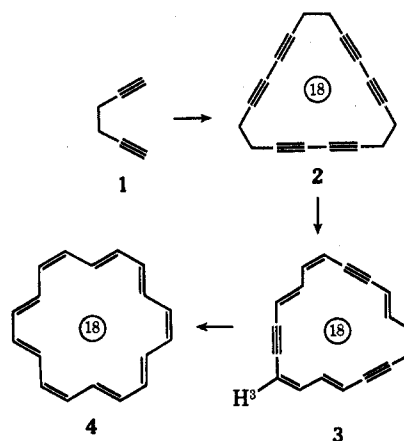
Benzene ([6]annulene), the classical aromatic substance, and the nonaromatic cyclooctatetraene ([8]-annulene) have, of course, been known for a long time. A number of larger ring annulenes³ have been synthesized in recent years, and a study of their behavior has contributed considerably to our understanding of the concept of aromaticity. Moreover, the annulenes have been found to exhibit several unusual properties, some of which will be discussed in this Account.

Syntheses of Annulenes and Dehydroannulenes.

Two general methods have been used for the synthesis of the annulenes. The first of these, developed by us,^{2a,b} involves the oxidative coupling of a suitable terminal diacetylene to a macrocyclic polyacetylene as the key step. The cyclic compound is then transformed to a dehydroannulene (completely conjugated monocarbocyclic polyenyne), usually by prototropic rearrangement. Finally, partial catalytic hydrogenation of the triple to double bonds leads to the annulene.

The synthesis of [18]annulene (4), the first higher annulene prepared, illustrates the method. Oxidative coupling of 1,5-hexadiyne (1) with cupric acetate in pyridine leads to the 18-membered ring cyclic "trimer" 2 in ~6% yield, beside other products.¹ Rearrangement of 2 with potassium *tert*-butoxide gives mainly the symmetrical 1,7,13-tridehydro[18]annulene (3),^{1,4,5} which is finally converted to [18]annulene (4) by partial catalytic hydrogenation over a palladium catalyst.⁶

The pure crystalline annulenes synthesized by this



method are [14]-, [16]-, [18]-, [22]-, and [24]annulene.^{2,7} In addition, [20]annulene⁸ and [30]annulene^{6,8} have been prepared, but these substances were not well defined and were probably not homogeneous. The dehydroannulenes are also of theoretical interest, since the criteria for aromaticity discussed for the annulenes apply also to the dehydro compounds as far as the out-of-plane π electrons are concerned. Dehydroannulenes of all ring sizes from the 12- to the 30-membered, inclusive, have now been synthesized by our method.^{2,9}

The second route to annulenes, developed by the groups of Schröder and Oth, Masamune, and van Tamelen, involves the photolytic ring opening of a polycyclic valence isomer. The only relatively stable annulene

(1) F. Sondheimer and R. Wolovsky, *J. Amer. Chem. Soc.*, **84**, 260 (1962).

(2) For references, see: (a) F. Sondheimer, *Pure Appl. Chem.*, **7**, 363 (1963); (b) F. Sondheimer, *Proc. Roy. Soc., Ser. A*, **297**, 173 (1967); (c) F. Sondheimer, *et al.*, *Chem. Soc., Spec. Publ.*, **No. 21**, 75 (1967); (d) F. Sondheimer, *Proc. Robert A. Welch Found. Conf. Chem. Res.*, **12**, 125 (1968).

(3) Many bridged annulenes have also been prepared, mainly by the groups of Badger, Boekelheide, and Vogel, but this work will not be discussed, except for some isolated examples.

(4) R. Wolovsky, *J. Amer. Chem. Soc.*, **87**, 3638 (1965).

(5) In the trivial nomenclature originally proposed by us,¹ 3 is named tridehydro[18]annulene, since it contains three acetylenic bonds. In another trivial nomenclature system, occasionally used subsequently by other workers, 3 is named hexadehydro[18]annulene, since it contains six fewer protons than [18]annulene. We suggest that our original nomenclature be used, in order to avoid confusion in the literature.

(6) F. Sondheimer, R. Wolovsky, and Y. Amiel, *J. Amer. Chem. Soc.*, **84**, 274 (1962).

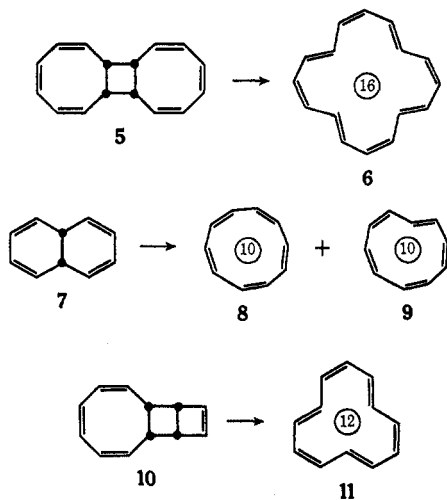
(7) R. M. McQuilkin, B. W. Metcalf, and F. Sondheimer, *Chem. Commun.*, 338 (1971).

(8) F. Sondheimer and Y. Gaoni, *J. Amer. Chem. Soc.*, **84**, 3520 (1962).

(9) R. M. McQuilkin and F. Sondheimer, *ibid.*, **92**, 6341 (1970).

In 1936, Franz Sondheimer emigrated from Germany to England, where he received his higher education at Imperial College, London. From 1949 to 1952, he worked on the total synthesis of steroids with R. B. Woodward. After working several years with Syntex, he became Head of the Organic Chemistry Department at Weizmann Institute. He returned to England in 1964, where he has been a Royal Society Research Professor, first at Cambridge, now at University College London. His main scientific interest is in the synthesis and study of new "unnatural" organic systems of theoretical interest.

prepared by this method so far is [16]annulene (**6**), which was obtained in 60% yield by photolysis of the cyclooctatetraene dimer **5** in ether at 0°. ^{10,11} This synthesis has made [16]annulene the most readily available of all the macrocyclic annulenes.



Similarly, [10]annulene (**8** and **9**)^{12,13} and [12]annulene (**11**)¹⁴ have been obtained by photolysis of the valence isomers **7** (at -60°) and **10** (at -100°), respectively, in tetrahydrofuran-*d*₈. The [10]- and [12]-annulenes could not be obtained completely pure, and had to be investigated in solution at low temperatures, since they rapidly undergo thermal rearrangements to bicyclic valence isomers at room temperature (see below).

Most of the higher annulenes and dehydroannulenes are highly colored (red or brown) crystalline substances, relatively stable at room temperature in solution, but less stable in the solid state. A number of properties of the various annulenes and dehydroannulenes have been investigated, but it will be possible to deal only with certain selected aspects.

Nmr Spectra of Annulenes and Dehydroannulenes.

As mentioned above, reasonably planar annulenes and dehydroannulenes should be aromatic, provided they contain $(4n + 2)$ out-of-plane π electrons and the ring size is below a certain limit. The latest calculations have indicated that the limit lies between the 22- and the 26-membered ring compounds.¹⁵

The synthesis of the $(4n + 2)$ -membered annulenes and dehydroannulenes has made it possible to test the theoretical predictions regarding the aromaticity of these substances. We equate aromaticity with π -

electron delocalization. There are, of course, a number of ways in which such delocalization can be detected. One consequence of π -electron delocalization is the ability to sustain a diamagnetic ring current in an applied magnetic field. Such a diamagnetic ring current is most easily detected by the nmr spectrum, in which the inner protons will be shielded and the outer protons deshielded.¹⁶ For convenience, molecules showing this effect in the nmr spectrum are named *diatropic*.¹⁷

Conversely, annulenes and dehydroannulenes containing $4n$ out-of-plane π electrons should sustain a paramagnetic ring current,¹⁸ a consequence of which will be to deshield the inner protons and shield the outer protons in the nmr spectrum. Substances showing this effect are nonaromatic, or perhaps antiaromatic (destabilized through cyclic conjugation),¹⁹ and are conveniently named *paratropic*.¹⁷ One advantage of this nomenclature is that it distinguishes between molecules showing a paramagnetic ring current and those showing no ring current, both of which were previously called "nonaromatic."

In practice, a difficulty in determining whether a given annulene is diatropic or paratropic is the fact that the nmr spectra are temperature dependent. Each proton can take the place of every other proton, and at higher temperatures the spectra of all the relatively stable annulenes examined so far consist of a singlet. This difficulty can be overcome by lowering the temperature. At low temperature, the nmr spectra of the $(4n + 2)$ systems [14]annulene,^{2b,c,20a} [18]annulene,^{2b,c} and [22]annulene⁷ are typical of diatropic systems, consisting of inner proton bands at high field (τ 10.61, 12.99, and 10.4–11.2, respectively) and outer proton bands at low field (τ 2.12, 0.72, and 0.35–1.5, respectively). Conversely, the low-temperature spectra of the $4n$ systems [16]annulene²¹ and [24]annulene²² are typical of paratropic systems, consisting of inner proton bands at low field (τ -0.56 and -2.9 to -1.2 , respectively), and outer proton bands at high field (τ 4.67 and 5.27, respectively). A similar, but smaller, paratropic effect is found for [12]annulene, although even at -170° some exchange still occurs.^{14b} The nmr spectra of the [10]annulenes **8** and **9** consist of signals in the τ 4.16–4.34 region,¹³ and these substances show no ring-current effects, presumably due to their nonplanarity.

The nmr spectra of most dehydroannulenes are essentially temperature independent. In this respect they are preferable to the annulenes for the study of

(10) G. Schröder and J. F. M. Oth, *Tetrahedron Lett.*, 4083 (1966).
 (11) G. Schröder, W. Martin, and J. F. M. Oth, *Angew. Chem.*, **79**, 861 (1967).
 (12) S. Masamune and R. T. Seidner, *Chem. Commun.*, 542 (1969).
 (13) E. E. van Tamelen and T. L. Burkoth, *J. Amer. Chem. Soc.*, **89**, 151 (1967); T. L. Burkoth and E. E. van Tamelen in "Non-benzenoid Aromatics," Vol. 1, J. P. Snyder, Ed., Academic Press, New York, N. Y., 1969, p 63; E. E. van Tamelen, T. L. Burkoth, and R. H. Greeley, *J. Amer. Chem. Soc.*, **93**, 6120 (1971).
 (14) (a) J. F. M. Oth, H. Röttele, and G. Schröder, *Tetrahedron Lett.*, 61 (1970); (b) J. F. M. Oth, J. M. Gilles, and G. Schröder, *ibid.*, 67 (1970).
 (15) M. J. S. Dewar and G. J. Gleicher, *J. Amer. Chem. Soc.*, **87**, 685 (1965).

(16) See L. M. Jackman, F. Sondheimer, Y. Amiel, D. A. Ben-Efraim, Y. Gaoni, R. Wolovsky, and A. A. Bothner-By, *ibid.*, **84**, 4307 (1962).

(17) I thank Dr. P. J. Garratt for this suggestion.

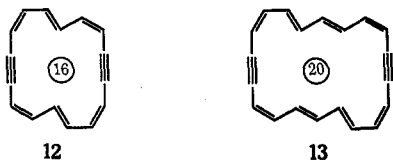
(18) J. A. Pople and K. G. Untch, *J. Amer. Chem. Soc.*, **88**, 4811 (1966); F. Baer, H. Kuhn, and W. Regel, *Z. Naturforsch. A*, **22**, 103 (1967); H. C. Longuet-Higgins, *Chem. Soc., Spec. Publ.*, No. 21, 109 (1967).

(19) See R. Breslow, J. Brown, and J. J. Gajewski, *J. Amer. Chem. Soc.*, **89**, 4383 (1967).

(20) (a) J. F. M. Oth, *Pure Appl. Chem.*, **25**, 573 (1971); (b) J. F. M. Oth, J. M. Gilles, E. P. Woo, and F. Sondheimer, *J. Chem. Soc. Perkin II*, in press.

(21) J. F. M. Oth and J. M. Gilles, *Tetrahedron Lett.*, 6259 (1968).
 (22) I. C. Calder and F. Sondheimer, *Chem. Commun.*, 904 (1966).

aromaticity in conjugated macrocyclic systems and parallel the behavior of most of the bridged annulenes.³ Thus, the spectrum of the diatropic 1,7,13-tridehydro[18]annulene (**3**) at room temperature consists of an inner proton band at high field (τ 8.26) and outer proton bands at low field (τ 1.90–2.98), and this is essentially unchanged on heating to 150°. The main reason for the temperature independence presumably is that moving the inner protons to "outer" positions by rotation of the trans double bonds leads to a nonequivalent conformer which is energetically less favored than conformer **3**. This is confirmed by the fact that the nmr spectra of certain dehydroannulenes such as 1,9-bisdehydro[16]annulene (**12**) and 1,11-bisdehydro[20]annulene (**13**), in which rotation of the trans double



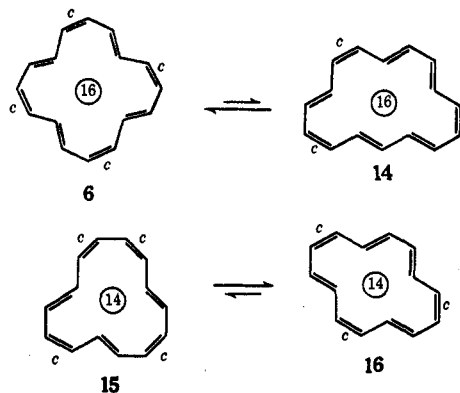
bonds does lead to equivalent structures, are indeed temperature dependent²⁰ (in the spectra of **12** and **13**, the trans olefinic protons appear as averages at room temperature, but as discrete inner and outer protons at -80°). However, even in the case of **12** and **13**, the nmr spectra at room temperature can be interpreted, since the outer protons attached to the cis double bonds are essentially unaffected.

The nmr spectra of more than 20 dehydroannulenes, from the 12- to the 30-membered, have now been determined, and the anticipated effect was observed in practically every case. Thus, in the $(4n + 2)$ series, all the 14-, 18- and 22-membered ring dehydroannulenes examined proved to be diatropic,^{20,9} while the 26- and 30-membered-ring compounds no longer revealed a ring current.^{20,23} These results, and those obtained with [14]-, [18]-, and [22]annulene, fully confirm the theoretical predictions regarding the aromaticity of $(4n + 2)$ - π -electron systems.

In the dehydro[$4n$]annulene series, all of the 12-, 16-, 20-, and 24-membered-ring compounds examined (except for the octadehydro[24]annulene **50** discussed below) are paratropic.^{20,24} A bisdehydro[28]annulene, belonging to the next higher $4n$ -ring series, has also been synthesized,^{2d} but the nmr spectrum could not be measured due to the very low solubility of this substance in most solvents. The question of the limiting ring size for a paramagnetic ring current in a $4n$ system has therefore not yet been answered.

Configurational Isomerism of Annulenes and Dehydroannulenes. It was recognized some years ago that crystalline [14]annulene was converted to an equilibrium mixture of two stereoisomers on dissolution at room temperature.^{2b} It seemed likely that these were conformational isomers, since cis-trans isomerism was

not expected to occur under such mild conditions (by analogy with linear conjugated polyenes²⁵). However, it has been shown recently by the group of Oth^{21,26} that crystalline [16]annulene (**6**) is converted in solution to an equilibrium mixture of the configurational isomers **6** and **14** in a ratio of 83:17 at -140° . It was suspected that [14]annulene underwent the same type of configurational, rather than conformational, isomerism. This has now been confirmed by determination of the nmr spectrum at very low temperatures (-155°), which showed that the major isomer possesses structure **16**, and the minor one structure **15**.^{20a} The equilibrium at -10° consists of **16** and **15** in a ratio of 92:8. It is of interest that our original assignment of the "tri-cis" structure **16** to crystalline [14]annulene,^{2a,b} but the



"tetra-cis" structure **6** to crystalline [16]annulene,^{2a,b} has proved to be correct. These structural assignments were based mainly on symmetry considerations, which evidently have some merit in the absence of more unequivocal evidence!

The ready interconversion of different configurational isomers of annulenes explains the observation that different syntheses of [16]annulene^{10,27} and [18]annulene,⁴ which formally were expected to give different configurational isomers, in fact yielded identical compounds.

In the dehydroannulene series, there is one example of the interconversion of two isomers. Two monodehydro[14]annulenes have been isolated, one of which is transformed to the other on standing in ether solution.^{2b} The nmr spectra^{2b,c} reveal both isomers to be made up of two trans and four cis double bonds, beside the acetylene. Both substances were therefore considered to have the symmetrical structure **17**, the isomerism being conformational in nature. However, this now seems unlikely, in view of the above-described findings with [14]- and [16]annulene, and we do not believe there to be any example of conformational isomers of an annulene or dehydroannulene being isolated as discrete compounds. The two monodehydro[14]annulenes probably differ in the arrangement of the cis and trans double bonds; *e.g.*, they might be represented by structures **17** and **18**. Unfortunately, it is not yet pos-

(25) See L. Zechmeister, *Fortschr. Chem. Org. Naturst.*, **18**, 223 (1960).

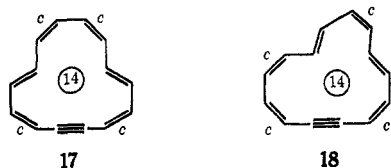
(26) J. F. M. Oth, G. Anthoine, and J. M. Gilles, *Tetrahedron Lett.*, 6265 (1968).

(27) I. C. Calder, Y. Gaoni, and F. Sondheimer, *J. Amer. Chem. Soc.*, **90**, 4946 (1968).

(23) C. C. Leznoff and F. Sondheimer, *J. Amer. Chem. Soc.*, **89**, 4247 (1967).

(24) I. C. Calder, Y. Gaoni, P. J. Garratt, and F. Sondheimer, *ibid.*, **90**, 4954 (1968).

sible to assign definite structures to these substances,

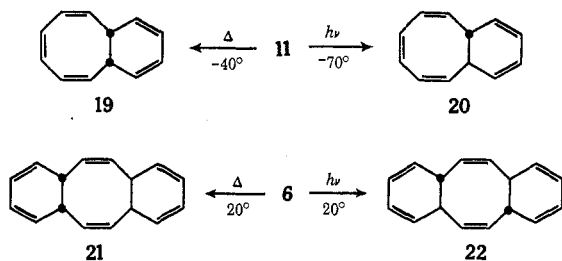


in view of the complexity of the nmr spectra and the lack of success in an X-ray crystallographic analysis of the stable isomer.²⁸ However, it may be of significance that the stable isomer gives [14]annulene in ~30% yield on partial catalytic hydrogenation, but the unstable one gives no [14]annulene under the same conditions.^{2b}

Valence Isomerism of Annulenes and Dehydroannulenes. Several annulenes undergo thermal or photochemical valence isomerization. The extreme ease of these reactions in the case of [10]- and [12]-annulenes is responsible for the instability of these substances.

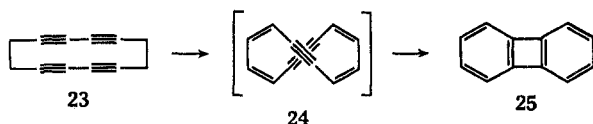
Thus, *all-cis*-[10]annulene (**8**) appears to give *cis*-9,10-dihydronaphthalene (**7**) on heating at -10° .¹² On the other hand, irradiation of **8** at -60° leads to *trans*-9,10-dihydronaphthalene, which is also obtained by heating mono-*trans*-[10]annulene (**9**) at -25° .¹²

In the case of [12]annulene (**11**), heating at -40° gives rise to the *cis* bicyclic isomer **19**, while irradiation at -70° leads to the corresponding *trans* isomer **20** (as well as **19**, formed thermally from **11**).^{14a} Similarly,



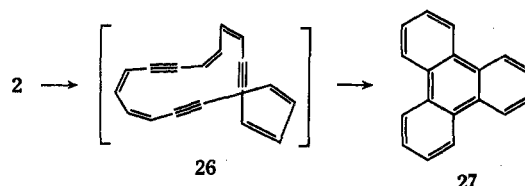
[16]annulene (**6**) on heating at 20° or above gives the di-*cis* tricyclic isomer **21**, while irradiation at 20° yields the di-*trans* isomer **22**.¹¹ All these valence isomerizations are in accord with orbital symmetry considerations,²⁹ except that in the case of [12]annulene it must be assumed that **11** is in dynamic equilibrium with another configuration containing three consecutive *cis* double bonds.^{14a}

None of the dehydroannulenes have been found to undergo analogous valence isomerizations. However, rearrangement of **23** with potassium *tert*-butoxide gives rise to biphenylene (**25**) as the major product, besides smaller amounts of 1,5-bisdehydro[12]annulene and



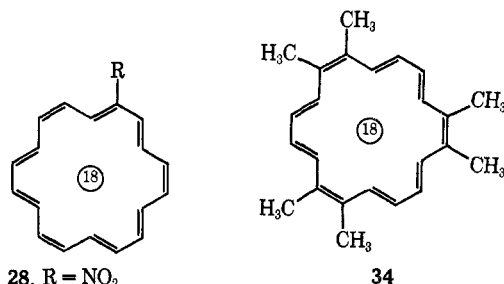
1,5,9-tridehydro[12]annulene.^{2b} The anticipated product, 1,7-bisdehydro[12]annulene (**24**), was not isolated, and it seems most probable that **24** was in fact formed but underwent valence isomerization to biphenylene.

Similarly, rearrangement of **2** with potassium *tert*-butoxide leads to triphenylene (**27**) in addition to 1,7,13-tridehydro[18]annulene (**3**).³⁰ The formation of triphenylene probably involves *all-cis*-1,7,13-tridehydro[18]annulene (**26**) as an intermediate, which undergoes valence isomerization.



Substituted Annulenes and Dehydroannulenes. A number of substituted annulenes and dehydroannulenes have been prepared, both by substitution of the basic system, as well as by independent syntheses.

Although it appeared originally that [18]annulene failed to undergo electrophilic substitution reactions (and was therefore not a classical aromatic substance),⁶ later work showed that under suitable conditions the substance could be converted to the nitro derivative **28**,³¹ acetyl derivative **29**,³¹ bromide **30**,³² and carboxaldehyde **31**.³² Further, methyl[18]annulene (**32**)³² has been prepared from the bromide **30**, and methyl [18]-



- 28**, R = NO₂
29, R = COCH₃
30, R = Br
31, R = CHO
32, R = CH₃
33, R = COOCH₃

annulene-carboxylate (**33**)³² from the aldehyde **31**. 1,2,7,8,13,14-Hexamethyl[18]annulene (**34**) has been obtained by partial catalytic hydrogenation of the corresponding tridehydro compound.³³ The nitration of nitro[18]annulene (**28**) has been studied in order to determine the direction of electrophilic substitution of monosubstituted [18]annulenes, but a complex mixture of isomeric dinitro[18]annulenes was obtained.³²

The nmr spectra of the various monosubstituted [18]annulenes^{31,32} at low temperatures were as ex-

(30) Y. Amiel and F. Sondheimer, *Chem. Ind. (London)*, 1162 (1960).

(31) I. C. Calder, P. J. Garratt, H. C. Longuet-Higgins, F. Sondheimer, and R. Wolovsky, *J. Chem. Soc. C*, 1041 (1967).

(32) E. P. Woo and F. Sondheimer, *Tetrahedron*, **26**, 3939 (1970).

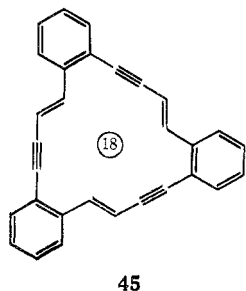
(33) F. Sondheimer and D. A. Ben-Efraim, *J. Amer. Chem. Soc.*, **85**, 52 (1963).

(28) R. Mason, private communication.

(29) See R. B. Woodward and R. Hoffmann, "The Conservation of Orbital Symmetry," Verlag Chemie, Weinheim/Bergstr., 1970.

9-bromo-1,5-bisdehydro[12]annulene (**44**) is of interest, since the presence of the substituent prevents exchange of the trans double bond protons.³⁶ The inner proton in the room temperature spectrum therefore resonates at $\tau -6.4$, the very low-field position providing dramatic confirmation of the paratropic nature of the 12- π -electron system. By comparison, the trans double bond protons in the unsubstituted compound **43** appear as an average at $\tau -1.18$ in the room temperature spectrum,^{2c} and this is essentially unchanged even at -130° .³⁷

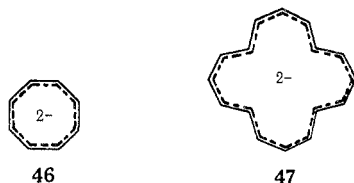
A number of benz-fused annulenes and dehydroannulenes have also been prepared. For instance, the tribenz-1,7,13-tridehydro[18]annulene (**45**) has been



synthesized.³⁸ The 18-membered ring in this substance is no longer diatropic, and the presence of the fused benzene rings may therefore completely change the properties of the macrocyclic ring. These fused derivatives will not be discussed further.

Dianions of Annulenes and Dehydroannulenes. In principle, it should be possible to convert a nonaromatic [4*n*]annulene or dehydro[4*n*]annulene to an aromatic (4*n* + 2)- π -electron system by preparation of the dianion.

This type of transformation was first realized in the eight-membered-ring series by Katz,³⁹ who showed that reaction of cyclooctatetraene with potassium in tetrahydrofuran leads to the diatropic dianion **46** via the radical anion. The nmr spectrum of the dianion was almost identical with that of cyclooctatetraene, the deshielding effect of the diamagnetic ring current balancing the shielding due to the excess electron density.



Similarly, [16]annulene on reaction with potassium in tetrahydrofuran-*d*₈ gave first the radical anion and then the dianion.²⁶ This dianion possesses structure **47**, formally derived from the [16]annulene isomer **6**;

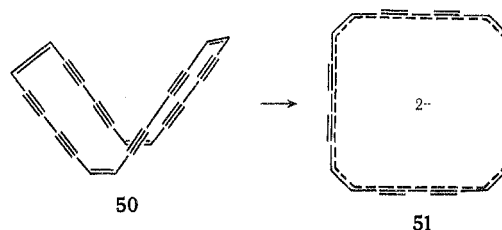
no dianion derived from isomer **14** was detected. As expected for an 18- π -electron system, the dianion **47** proved to be diatropic, the nmr spectrum consisting of an inner proton band at very high field (τ 18.17) and outer proton bands at low field (τ 1.17, 2.55).²⁶ Unlike the neutral compound, the dianion **47** was quite stable, the nmr spectrum being essentially unchanged at 140° or after heating at 100° for 2 days.

Similar dianions can be prepared from dehydro[4*n*]annulenes. Thus, reaction of 1,5-bisdehydro[12]annulene (**43**) with potassium in tetrahydrofuran-*d*₈ gives the radical anion and then the dianion **48**, which is



diatropic (nmr spectrum: inner proton, τ 16.88; outer protons, τ 2.03–2.47, 3.31–4.01).⁴⁰ As expected, the exchange between the trans double bond protons which occurs in the neutral molecule **43** even at -130° does not take place in the dianion **48**, the high-field inner proton band being observable at 30° . In the case of 1,5,9-tridehydro[12]annulene, it is advantageous to use sodium-potassium alloy at 0° , since in general dehydroannulenes appear to be polymerized with potassium much more rapidly than annulenes. Under these conditions, 1,5,9-tridehydro[12]annulene gave the radical anion and then the diatropic dianion **49** (nmr spectrum: all protons, τ 3.26, *vs.* τ 5.58 in the neutral compound).⁴⁰

An interesting dianion in the 24-membered ring series was prepared from 1,3,7,9,13,15,19,21-octadecahydro[24]annulene (**50**). This dehydroannulene is the cyclic "tetramer" of *cis*-3-hexene-1,5-diyne, from which it was synthesized *via* the corresponding linear "dimer."⁴¹ The dehydro[24]annulene **50** is formally derived from cyclooctatetraene by insertion of four 1,3-diyne groupings, and, like this substance, appears



to be nonplanar. This nonplanarity is unusual for a dehydroannulene, and is presumably due to the presence of four *cis* double bonds as well as the comparative rigidity imposed by the four 1,3-diyne units. Reaction of **50** in tetrahydrofuran-*d*₈ with potassium led first to the radical anion and then to the dianion **51**, containing 26 out-of-plane π electrons.⁴¹ The dianion **51** seems to be a planar diatropic system, the fact

(36) K. G. Untch and D. C. Wysocki, *J. Amer. Chem. Soc.*, **89**, 6386 (1967).

(37) J. E. Anderson, private communication.

(38) K. Endo, Y. Sakata, and S. Misumi, *Tetrahedron Lett.*, 2557 (1970).

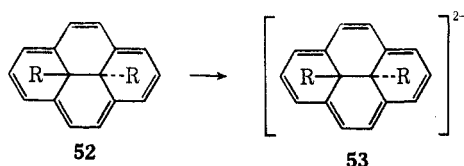
(39) T. J. Katz, *J. Amer. Chem. Soc.*, **82**, 3784, 3785 (1960).

(40) P. J. Garratt, N. E. Rowland, and F. Sondheimer, *Tetrahedron*, **27**, 3157 (1971).

(41) R. M. McQuilkin, P. J. Garratt, and F. Sondheimer, *J. Amer. Chem. Soc.*, **92**, 6682 (1970).

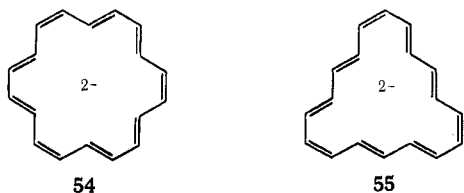
that the nmr spectrum is very similar to that of **50** presumably being due to the same reason as discussed above for **46**. It therefore appears that a dianion containing as many as 26 out-of-plane π electrons can be aromatic, unlike corresponding neutral molecules.

In principle, it should also be possible to convert an aromatic $[4n + 2]$ annulene to a nonaromatic $4n-\pi$ -electron system by preparation of the dianion. This type of reaction was first achieved by Boekelheide, *et al.*,⁴² who showed that bridged [14]annulenes of type **52** (R = alkyl) on treatment with potassium in tetrahydrofuran-*d*₈ gave first the radical anions and then the dianions (**53**). As expected, the conversion of **52** to **53** involves the transformation of a strongly



diatropic to a strongly paratropic system (*e.g.*, when R = CH₃, the methyl protons in the nmr spectrum move from τ 14.25 to -11.00 , and the outer protons from τ 1.33–2.05 to 13.19–13.96).

Recently, it has been possible to effect this type of transformation with an unbridged annulene, by careful attention to reaction conditions. Treatment of [18]annulene (**4**) with potassium in tetrahydrofuran-*d*₈ at -80° led to the radical anion and then (after several days) to the dianion.^{20b} The dianion was very strongly paratropic, in accord with a $20-\pi$ -electron system, the inner protons in the nmr spectrum giving rise to bands at τ -19.5 and -18.1 (!), and the outer protons to a band at τ 11.13. The very low-field positions of the inner proton bands are remarkable, the value of τ -19 being the lowest yet recorded for a proton bound to carbon. The fact that the inner protons in the nmr spectrum of the dianion give rise to two separate bands in a ratio of $\sim 7:3$ indicates that the dianion is a $\sim 7:3$ mixture of two species, probably **54** and **55**.

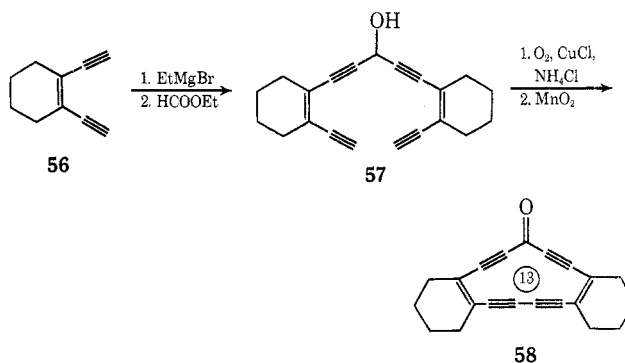


Annulenones and Dehydroannulenones. All of the annulene derivatives discussed so far contain an *even* number of carbon atoms in the ring. In addition, it is, of course, possible to consider annulenes containing an *odd* number of carbon atoms, and some success has been achieved recently in the synthesis of such compounds.

The main type of "odd" annulene to be discussed is completely conjugated monocyclic ketones, which

have been named "annulenones." Such compounds might be aromatic if they contain a $(4n + 3)$ -membered ring, and nonaromatic if they contain a $(4n + 1)$ -membered ring, due to the electron-withdrawing properties of the oxygen of the carbonyl group. In agreement with this are the properties of the aromatic $[4n + 3]$ annulenone cyclopropenone and the nonaromatic $[4n + 1]$ annulenone cyclopentadienone.^{2d} However, the properties of cycloheptatrienone (tropone), the largest $[4n + 3]$ annulenone known until very recently, are suggestive of nonaromaticity.^{43,44} It was obviously of interest to synthesize macrocyclic annulenone derivatives, both in the $[4n + 3]$ and the $[4n + 1]$ series, in order to study their properties.

The first large-ring $[4n + 1]$ annulenone derivative to be obtained is the bis(tetramethylene)-2,6,8,12-tetradecahydro[13]annulenone **58**, which was synthesized by the route **56** \rightarrow **57** \rightarrow **58**.⁴⁵ The ketone **58** was expected to be paratropic, but no clear-cut evidence



regarding this point could be obtained, since **58** contains no protons bound directly to the macrocyclic ring. A number of reactions have been carried out with **58**, *e.g.*, condensation with cyclopentadiene led to the corresponding fulvalene derivative.⁴⁵

Attempts were made to obtain the unsubstituted 2,6,8,12-tetradecahydro[13]annulenone by carrying out an analogous synthesis starting from *cis*-3-hexene-1,5-diyne. However, the closure corresponding to that of **57** led only to polymeric material,⁴⁶ presumably due to instability of the unsubstituted 13-membered-ring compound.

Unsubstituted dehydroannulenones could, however, be obtained in the 17-membered-ring series. *trans*-4-Octene-1,7-diyne was subjected to a reaction sequence corresponding to **56** \rightarrow **58**, and the resulting 17-membered-ring ketone **59** was treated with potassium *tert*-butoxide. This reaction resulted in dehydrogenation as well as rearrangement, giving rise to the tetradecahydro[17]annulenone **60**⁴⁷ or to the tri-*trans* tridehydro[17]annulenone **61**⁴⁸ and di-*trans* tridehydro-

(43) D. J. Bertelli and T. G. Andrews, *ibid.*, **91**, 5280 (1969).

(44) D. J. Bertelli, T. G. Andrews, and P. O. Crews, *ibid.*, **91**, 5286 (1969).

(45) G. M. Pilling and F. Sondheimer, *ibid.*, **90**, 5610, 5611 (1968); **93**, 1970, 1977 (1971).

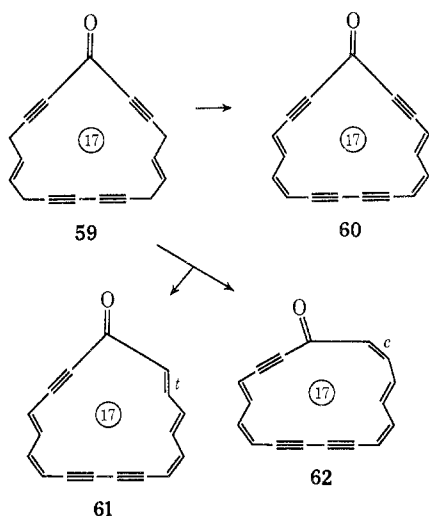
(46) R. M. McQuilkin, unpublished experiments.

(47) G. W. Brown and F. Sondheimer, *J. Amer. Chem. Soc.*, **91**, 760 (1969).

(48) J. Griffiths and F. Sondheimer, *ibid.*, **91**, 7518 (1969).

(42) R. H. Mitchell, C. E. Klopfenstein, and V. Boekelheide, *J. Amer. Chem. Soc.*, **91**, 4931 (1969).

[17]annulenone **62**,⁴⁹ depending on the exact reaction

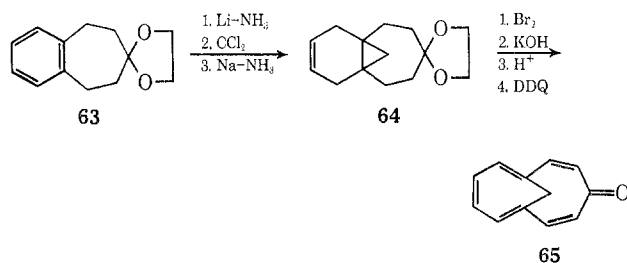


conditions. Of these, **61** was obtained most readily (25–30% yield).

The dehydro[17]annulenones **60**, **61**, and **62** are again $[4n + 1]$ annulenone derivatives and should be paratropic. This proved to be the case, since in the nmr spectra the inner proton resonances occurred at unusually low field ($\tau \sim -0.5$ to 0.4) and the outer proton resonances at considerably higher field ($\tau \sim 3.5$ – 5.0).^{47–49} This effect could be increased by protonation, as shown by the nmr spectrum of **61** measured in deuteriotrifluoroacetic acid (inner protons, $\tau \sim -2.0$; outer protons, $\tau \sim 3.6$ – 5.0).⁵⁰

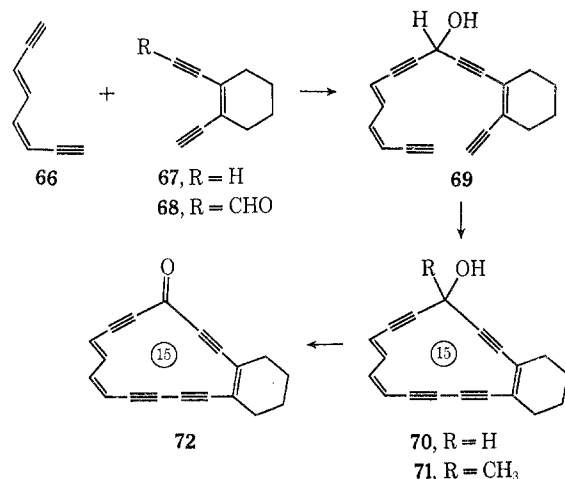
The catalytic partial hydrogenation of the tridehydro[17]annulenones **61** and **62** was investigated.⁴⁹ Although evidence was obtained that **62** gives rise to bisdehydro- and monodehydro[17]annulenones, there was no indication that [17]annulenone itself was formed. It is possible that [17]annulenone is a very unstable substance, undergoing self-condensation in the same way as the lower homolog cyclopentadienone. The presence of the acetylenic bonds in the dehydro[17]annulenones would be expected to stabilize these substances. They may well owe their existence to the presence of these acetylenic bonds.

In the potentially aromatic $[4n + 3]$ annulenone series, the first derivative of a large-ring member to be synthesized was 4,9-methano[11]annulenone (**65**), prepared by Vogel, *et al.*,⁵¹ by the route **63** \rightarrow **64** \rightarrow



65.⁵² The bridged [11]annulenone **65** appeared to be nonaromatic, as judged by an analysis of the vicinal coupling constants of the olefinic protons in the nmr spectrum. On the other hand, protonation converted **65** to an aromatic system, as shown by the nmr spectrum determined in deuteriotrifluoroacetic acid.⁵¹

In the 15-membered-ring series, early efforts to obtain unbridged macrocyclic $[4n + 3]$ annulenone derivatives involving base treatment or a bromination-dehydrobromination sequence as the last step were unsuccessful.⁴⁶ It was therefore decided to build up a dehydro[15]annulenone from completely conjugated terminal diacetylenes. The C_8 compound required was *cis,trans*-3,5-octadiene-1,7-diyne (**66**), for which a satisfactory synthesis was developed.⁵³ The " C_8 " component was the disubstituted *cis*-3-hexene-1,5-diyne **67**,⁴⁵ which was converted to the aldehyde **68**⁵⁴ by reaction of the mono-Grignard derivative with dimethylformamide and then with acetic acid. Treatment of the mono-Grignard derivative of **66** with **68** led to a $\sim 1:1$ mixture of **69** and its stereoisomer.⁵⁴ Oxidative coupling with oxygen, cuprous chloride, and ammonium chloride gave the extremely unstable cyclic "monomer" **70**, which was oxidized directly with MnO_2 to the tetramethylene-2,6,8,14-tetrahydro[15]annulenone **72**.⁵⁴ As expected, this $[4n + 3]$ annulenone derivative was found to be diatropic, the inner olefinic proton resonance (τ 4.99) now occurring at higher field than the outer proton signals (τ 2.35–3.72) in the nmr spectrum. The effect could be increased by protonation, as shown by the nmr spectrum of **72** determined in deuterio-



trifluoroacetic acid (inner proton, τ 6.51; outer olefinic protons, τ 1.93–3.26).⁵⁴

A suitable model lacking a ring current is the tertiary carbinol **71**, obtained from **72** by reaction with methyl-lithium.⁵⁴ Compared with the nmr spectrum of this model, the inner olefinic proton resonance in the spectrum of **72** has shifted *upfield* by $\tau \sim 2.0$ and the outer

(52) The isomeric 2,7- and 3,8-methano[11]annulenones have also been synthesized by this group,⁵¹ but no details have been published yet.

(53) G. H. Mitchell and F. Sondheimer, *J. Amer. Chem. Soc.*, **91**, 7520 (1969).

(54) G. P. Cotterrell, G. H. Mitchell, F. Sondheimer, and G. M. Pilling, *ibid.*, **93**, 259 (1971).

(49) J. Griffiths and G. V. Meehan, unpublished experiments.

(50) G. V. Meehan, unpublished experiments.

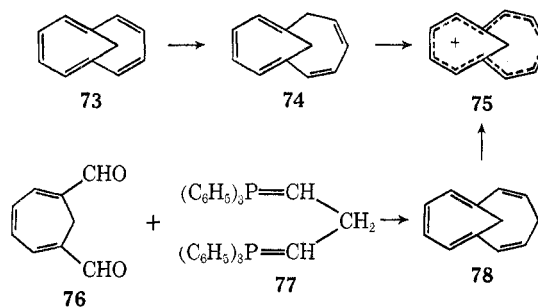
(51) W. Grimme, J. Reisdorf, W. Jünemann, and E. Vogel, *J. Amer. Chem. Soc.*, **92**, 6335 (1970).

ones have each shifted *downfield* by $\tau \sim 0.7$. Conversely, in the tetrahydro[17]annulenone **60**, the inner olefinic proton resonance has shifted *downfield* by $\tau \sim 3.3$ compared with that of **71**, while the outer ones have each shifted *upfield* by $\tau \sim 0.6$. Similar shifts are observed for the allylic proton bands in the nmr spectra of the cyclohexene-fused compounds. This band in **72** is shifted *downfield* by τ 0.35 compared with that of **71**, while in **58** it is shifted *upfield* by τ 0.35. The dehydro[$4n + 1$]annulenones **58** and **60** (as well as **61** and **62**) are therefore paratropic, and the dehydro[$4n + 3$]annulenone **72** is diatropic, the effects paralleling those found for the dehydro[$4n$]annulenes and dehydro[$4n + 2$]annulenes, respectively.

The conclusion that the dehydro[15]annulenone **72** is diatropic and therefore presumably aromatic is in contrast to the apparent lack of aromaticity of the lower [$4n + 3$]annulenones tropone^{43,44} and 4,9-methano[11]annulenone (**65**).⁵¹ However, it must be borne in mind that the argument involving nmr data which indicates nonaromaticity in tropone and **65** is based on coupling constants, while that which indicates aromaticity in **72** is based on chemical shifts. There may be no contradiction in these findings. Further discussion regarding this point must wait until more information is obtained about the effect of delocalization on both nmr coupling constants and chemical shifts in annulene and dehydroannulene derivatives. In this connection it is of interest that in the dehydroannulene and the dehydroannulenone series, both paratropic and diatropic compounds shown apparently identical first-order coupling constants of the olefinic proton resonances.

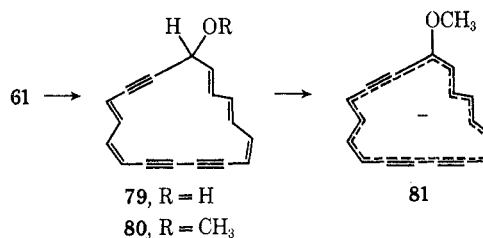
Monoionic "Odd" Annulenes and Dehydroannulenes. Another type of "odd" annulene is monoionic species. If we consider a $(4n + 3)$ -membered ring, then the cation will be a $(4n + 2)$ - π -electron system and should be aromatic. Well-known examples are the aromatic cyclopropenium and tropylium cations.^{2d} Conversely, in a $(4n + 1)$ -membered ring, the anion will be a $(4n + 2)$ - π -electron system and should be aromatic. Examples are the aromatic cyclopentadienyl and cyclononatetraenyl anions.^{2d} It was of interest to synthesize and study larger ring monoanions and cations. Derivatives of two such ions have been obtained recently.

The first of these is the bridged [11]annulenium cation **75**, which was prepared as the fluoroborate by Vogel, *et al.*, by two routes. The first^{55a} involved ring expansion of 1,6-methano[10]annulene (**73**) with diazomethane and cuprous chloride, followed by hydride abstraction from the resulting **74** with triphenylmethyl fluoroborate. Alternatively,^{55b} Wittig reaction between the dialdehyde **76** and the diylide **77** led to **78**, which on hydride abstraction as previously gave the fluoroborate of **75**. As expected for a ten- π -electron system, the nmr spectrum of **75** clearly showed it to be diatropic



(olefinic protons, τ 0.4–1.7; methylene protons, τ 10.3 and 11.8).

The only nonbridged large-ring monoion obtained so far is the methoxytridehydro[17]annulenyl anion **81**.⁴⁸ Reduction of the tri-trans tridehydro[17]annulenone **61** with NaBH_4 gave the alcohol **79**, which was converted to the methyl ether **80**, by means of



methyl iodide and silver oxide. Finally, reaction of **80** in tetrahydrofuran- d_8 with methyllithium at -80° led to the lithium salt of **81**.⁴⁸ The anion **81** contains 18 out-of-plane π electrons and should therefore be diatropic. This was confirmed by the nmr spectrum, in which the inner proton resonances appear at very high field (τ 18.54–19.09) and the outer protons at low field (τ -0.47 to 2.16).⁴⁸ As expected, this is a reversal of the effect shown by the paratropic 16- π -electron precursor **61**. The very high-field position of the inner proton bands in the nmr spectrum of **81** is particularly noteworthy, the value of $\tau \sim 19$ being the highest yet recorded for a proton bound to carbon. Records are therefore held by the inner proton resonances in the nmr spectrum of the 18-membered-ring 20- π dianion **54** (τ -19), as well as of the 17-membered-ring 18- π monoanion **81** (τ $+19$), at each extreme of the spectral range!

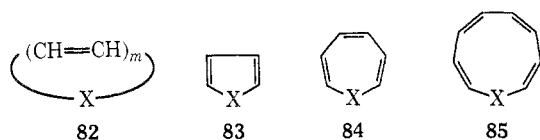
As yet, it has not been possible to prepare a non-bridged large-ring aromatic monocation. It should be possible to convert the tetrahydro[15]annulenone **72** to a tetrahydro[15]annulenium cation, a member of this series, and work toward this end is in progress.

Heteroannulenes. All of the annulene derivatives discussed so far, both in the "even" and the "odd" series, contain carbocyclic rings. We can, of course, also consider annulenes containing heteroatoms, the so-called heteroannulenes.

Various types of heteroannulenes may exist, but only odd-membered-ring monoheterocycles of type **82** ($X = \text{O}, \text{NR}, \text{or S}$) will be discussed. When m is an even number, these are $(4n + 2)$ - π -electron systems, and might be aromatic. Conversely, when m is an odd number, these are $4n$ - π -electron systems and

(55) (a) W. Grimme, H. Hoffmann, and E. Vogel, *Angew. Chem.*, **77**, 348 (1965); (b) E. Vogel, R. Feldmann, and H. Düwel, *Tetrahedron Lett.*, 1941 (1970).

should not be aromatic. In agreement with this are the aromatic properties of the well-known five-membered-ring members furan, pyrrole, and thiophene (type **83**)

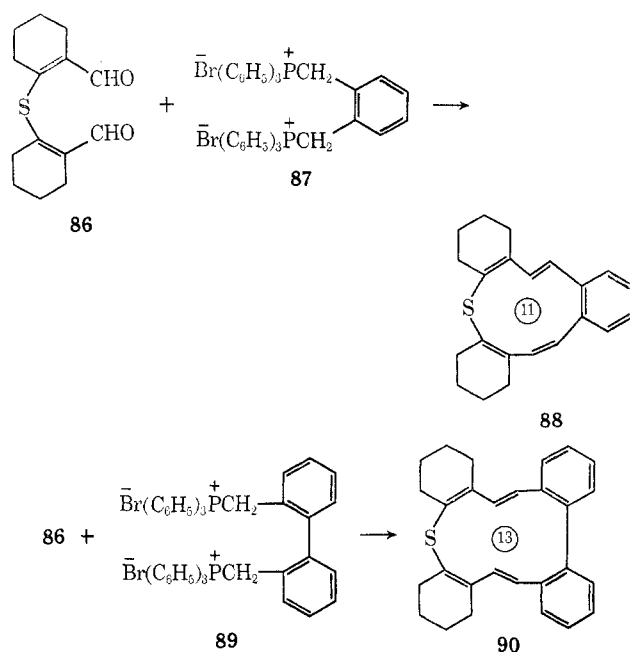


($m = 2$) and the nonaromatic properties of the corresponding seven-membered-ring members oxepin,^{56,57} azepine,⁵⁷ and thiepin^{57,58} (type **84**) ($m = 3$). Recently, certain nine-membered ring members [oxonin,^{59,60} azonines,^{59,61} and fused thionins⁶² (type **85**) ($m = 4$)] have been synthesized, but only the azonines **85** ($X = \text{NH}$, NCH_3 , NC_2H_5 , or $\text{NCH}_2\text{C}_6\text{H}_5$) appear to show some aromatic properties⁵⁹ despite the fact that all these are ten- π -electron systems.

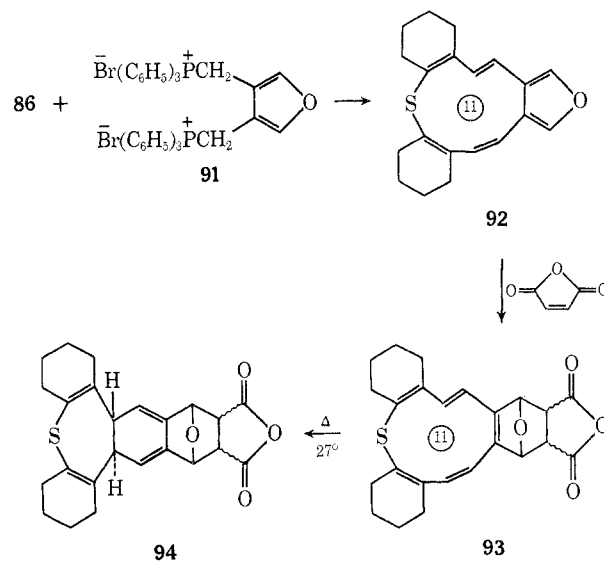
We have been interested in the synthesis of macrocyclic heteroannulenes of type **82**. Preliminary attempts by us and by others⁶³ to prepare certain members by the acetylene coupling route were unsuccessful, since the final introduction of full conjugation could not be effected. However, fused 11- and 13-membered-ring sulfur heterocycles of type **82** could be obtained, using a double Wittig reaction between a dialdehyde and a diylide in order to form the macrocyclic ring. Thus, reaction of the readily available dialdehyde **86**⁶⁴ with the bisphosphonium salt **87** in the presence of lithium ethoxide led to the fused thia[11]annulene **88** in 2% yield, while the similar reaction of **86** with **89** gave the fused thia[13]annulene **90** in 12% yield.⁶⁵

The nmr spectra of both **88** and **90** indicated that they are nonplanar molecules, devoid of appreciable ring-current effects due to the macrocyclic rings, despite the fact that **88** might have been expected to be paratropic and **90** diatropic. The lack of ring current in **88** and **90** may, of course, be due to the presence of the fused benzene rings (see discussion of substance **45**). It was therefore of interest to synthesize thia[11]annulenes and thia[13]annulenes not fused to benzene rings, and some success in this objective has been achieved in the thia[11]annulene series.

Wittig reaction of **86** with the bisphosphonium salt **91** in the presence of lithium ethoxide gave the furan-



fused thia[11]annulene (**92**) in 5% yield.⁶⁶ The furan ring in this substance was then modified through Diels-Alder reaction, a number of dienophiles being investigated. The most interesting results were obtained with maleic anhydride at room temperature, when nmr spectrometry showed that a mixture of the exo and endo



isomers ($\sim 2:1$) of the hexaalkyl mono-trans thia[11]annulene **93** was formed.⁶⁶ The nmr spectra of these substances showed no ring-current effects (olefinic protons, τ 3.23–4.34), despite the fact that they might have been paratropic. They are presumably nonplanar, due to bond angle strain in the planar molecules, like the related mono-trans [10]annulene **9**.

The thia[11]annulenes **93** readily cyclized to the trans-fused dihydrobenzothiepin derivatives **94** (exo and endo isomers), the reaction in benzene at room temperature being complete in ~ 3 hr.⁶⁶ This cyclization, of course, is analogous to the cyclization of the mono-

(56) See E. Vogel and H. Gunther, *Angew. Chem.*, 429 (1967).

(57) See L. A. Paquette in "Nonbenzenoid Aromatics," Vol. 1, J. P. Snyder, Ed., Academic Press, New York, N. Y., 1969, p 249.

(58) See J. M. Hoffmann and R. H. Schlessinger, *J. Amer. Chem. Soc.*, 92, 5263 (1970).

(59) A. G. Anastassiou, S. W. Eachus, R. P. Cellura, and J. H. Gebrian, *Chem. Commun.*, 1133 (1970), and references to work by this group cited there.

(60) S. Masamune, S. Takada, and R. T. Seidner, *J. Amer. Chem. Soc.*, 91, 7769 (1969).

(61) S. Masamune, K. Hojo, and S. Takada, *Chem. Commun.*, 1204 (1969).

(62) A. P. Bindra, J. A. Elix, P. J. Garratt, and R. H. Mitchell, *J. Amer. Chem. Soc.*, 90, 7372 (1968); P. J. Garratt, A. B. Holmes, F. Sondheimer, and K. P. C. Vollhardt, *ibid.*, 92, 4492 (1970).

(63) See W. Carruthers and M. G. Pellat, *J. Chem. Soc. C*, 1485 (1971).

(64) M. Weissenfels and M. Pulst, *Tetrahedron Lett.*, 3045 (1968).

(65) A. B. Holmes and F. Sondheimer, *J. Amer. Chem. Soc.*, 92, 5284 (1970).

trans [10]annulene **9** to *trans*-9,10-dihydronaphthalene.¹²

Conclusion. There are several aspects of annulene chemistry in which only little progress has been made so far. Among these are the synthesis of heteroannulenes and of metalloorganic annulene complexes. Doubtlessly this gap will be filled during the next few years.

However, the most urgent need in the annulene field is to discover methods whereby these substances can be synthesized simply and in quantity. At present, all the higher unbridged annulenes, except [16]annulene, have been obtained in only quite small amounts, and after tedious separation procedures. This has severely limited the study of the chemical and physical properties of the annulenes. It is instructive to remember that although cyclooctatetraene was first prepared by Will-

stätter in 1911, it was only after Reppe made this substance readily available during World War II that the explosive growth of cyclooctatetraene chemistry took place. Doubtlessly, the chemistry of the higher annulenes would enjoy a similar growth were they to become equally readily available.⁶⁷

I wish to thank all my coworkers, mentioned in the references, for their important contributions. In particular I thank Dr. P. J. Garratt for valuable discussions and criticisms. Generous financial support by the Royal Society and the Science Research Council is also gratefully acknowledged.

(67) NOTE ADDED IN PROOF. Syntheses of the paratropic [20]annulene⁶⁸ and the diatropic monodehydro[26]annulene⁶⁹ have now been described, as well as of the diatropic [12]annulene dianion.⁷⁰ Isomers **8** and **9** of [10]annulene have been isolated as pure crystalline substances.⁷¹

(68) B. W. Metcalf and F. Sondheimer, *J. Amer. Chem. Soc.*, **93**, 6675 (1971).

(69) B. W. Metcalf and F. Sondheimer, *ibid.*, **93**, 5721 (1971).

(70) J. F. M. Oth and G. Schröder, *J. Chem. Soc. B*, 904 (1971).

(71) S. Masamune, K. Hojo, K. Hojo, G. Bigam, and D. L. Rabenstein, *J. Amer. Chem. Soc.*, **93**, 4966 (1971).

(66) A. B. Holmes and F. Sondheimer, *Chem. Commun.*, 1434 (1971).