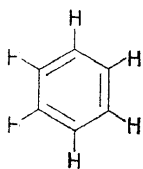


RECENT ADVANCES IN THE CHEMISTRY OF LARGE-RING CONJUGATED SYSTEMS

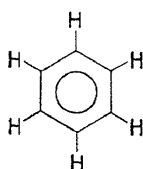
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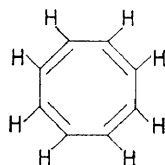
One of the classical problems of organic chemistry concerns the question whether monocyclic hydrocarbons formally made up of alternating single and double bonds will show so-called "aromatic" behaviour. The best-known example of this type of compound of course is benzene, which exhibits typical aromatic properties. Among these may be mentioned the fact that benzene does not consist of distinct single and double bonds (as in formula I), but all the bonds are equivalent (as in formula II).



(I)



(II)



(III)

Ever since the last century chemists have speculated whether benzene and related benzenoid compounds are unique in being aromatic, or whether higher vinylogues would show similar properties. It was in this connection that Willstätter as long ago as 1911¹ prepared cyclo-octatetraene (III), and showed that this substance is not at all aromatic; that is, it behaves chemically much more like a normal conjugated polyene than a benzenoid compound.

Since Willstätter's synthesis, considerable theoretical work has been done in this field. As a result, it has been predicted that compounds of the type under discussion will be aromatic provided their carbon skeleton can exist in a configuration which is reasonably planar, and they contain a closed shell of $(4n + 2)$ π -electrons². This is the so-called "Hückel's rule", based on quantum mechanical considerations, which in effect means that the presence of an *odd* number of double bonds is required for aromaticity. In addition, the ring-size should be below that for which Longuet-Higgins and Salem³ have predicted the occurrence of bond-alternation; unfortunately, the exact value of this limiting ring-size is uncertain.

At this point I would like to define the term "aromatic". A compound is considered to be aromatic if there is a measurable degree of cyclic delocalization of a π -electron system in the ground state of the molecule^{4, 5}. This will result in a lower energy content than would be predicted from classical considerations, in carbon-carbon bonds intermediate in length between those

usual for single and double bonds, as well as in the ability to sustain a magnetically induced ring current of π -electrons. This last-mentioned property is especially important from an experimental point of view, since it can be detected simply by determination of the nuclear magnetic resonance (n.m.r.) spectrum^{4, 5}.

This "modern" definition of aromaticity is in contrast to the "classical" definition, which equates aromaticity with unusual stability and the property to undergo substitution rather than addition reactions. This cannot really be considered a valid definition, since chemical reactivity is not a property of the molecule in the ground state, but is dependent on the difference in free energy between that of the ground state and that of the transition state for the chemical change involved⁶. Thus, if this difference were small, the compound would be reactive, irrespective of its energy content in the ground state.

Let us now examine which monocyclic conjugated polyenes should be aromatic, on the basis of our criteria for aromaticity. The fact that cyclo-octatetraene (III) is not aromatic is of course as expected, since Hückel's rule is not obeyed. In *Figure 1* scale diagrams† of the next higher members are presented⁷. These substances have been named "annulenes", the ring size being indicated by a number in brackets. It is clear that [10]annulene, the member following cyclo-octatetraene, obeys Hückel's rule. However, it can be seen from the diagram that very severe steric interaction of the internal hydrogen atoms would occur in a planar molecule. The

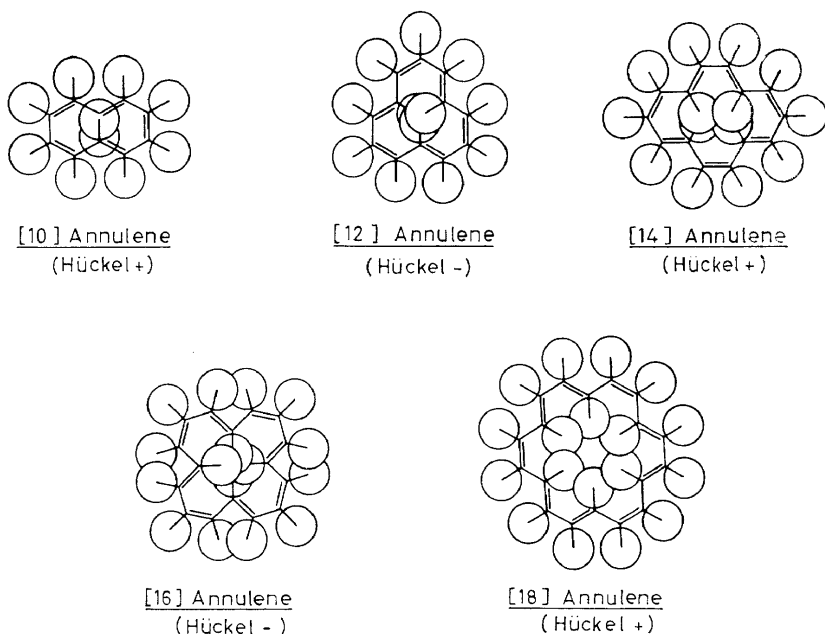


Figure 1

† The following dimensions have been used in drawing the diagrams: carbon-carbon bond lengths (all equal), 1.40Å; carbon-hydrogen bond lengths, 1.10Å; hydrogen radii, 1.00Å; all angles 120 or 240° (except in [16]annulene).

carbon skeleton in [10]annulene therefore cannot be planar, unless it possesses very unusual bond angles, and this compound would consequently not be expected to be aromatic. [12]Annulene does not comply with Hückel's rule and also could not be planar in view of the steric interaction of the internal hydrogen atoms, and therefore should not be an aromatic compound. [14]Annulene, while obeying Hückel's rule, is a compound in which the overcrowding of the internal hydrogen atoms is still so severe in the planar molecule as to make it very unlikely that a coplanar configuration could be attained. [16]Annulene should also still be non-aromatic, since Hückel's rule is not obeyed, in addition to the existence of overcrowding of the internal hydrogen atoms. However, when we come to [18]annulene, we arrive at a substance which not only complies with Hückel's rule, but (as can be seen from the scale drawing) the overcrowding of the internal hydrogen atoms is not so extreme as to exclude a reasonably coplanar carbon skeleton. In addition, [18]annulene is presumably below that ring-size for which Lenguet-Higgins and Salem³ have predicted the occurrence of bond-alternation. This substance is, therefore, the first annulene after benzene for which aromatic character would be predicted from theoretical considerations.

Until recently, it has not been possible to test these speculations experimentally since the only annulenes known were benzene and cyclo-octatetraene, despite many synthetic attempts to prepare other members. In this paper I should like to describe the work which we have done during the last few years at the Weizmann Institute of Science, which has made available a variety of annulenes. The availability of these substances, as well as of their acetylenic precursors, the so-called dehydro-annulenes, has made it possible to test the validity of our theoretical ideas regarding aromaticity. Lack of time does not allow a description of our work in detail; instead I would like to give a survey dealing mainly with the highlights, with special emphasis on the more recent developments.

Of prime importance in this work was the discovery of a simple method for the synthesis of large-ring hydrocarbons containing α,γ -diacetylene groupings. It was found that oxidative coupling of a straight-chain α,ω -diacetylene of type (IV) (Figure 2) in aqueous ethanol with oxygen in the presence of cuprous chloride and ammonium chloride (the so-called Glaser conditions⁸ for the coupling of ethynyl compounds) yielded the cyclic dimer (V) in addition to linear coupling products^{9, 10}. As shown, this reaction led to the cyclic dimer when $n = 3, 4$ or 5 . In the case of $n = 2$, a dark insoluble polymeric material was obtained instead of cyclic material¹⁰; I will return to this point later.

Another method of coupling of the diacetylenes (IV) involved oxidation by means of cupric acetate in pyridine solution, conditions developed by Eglinton at the University of Glasgow. This reaction was found to take an extraordinary course: a wide variety of cyclic products of type (VI) was produced, such as the cyclic monomers and dimers (when the value of n was high enough)¹¹, as well as the cyclic trimers, tetramers, pentamers, hexamers, etc.¹² These oxidative procedures made available highly unsaturated large-ring compounds, and appeared to have potentialities for the synthesis of annulenes.

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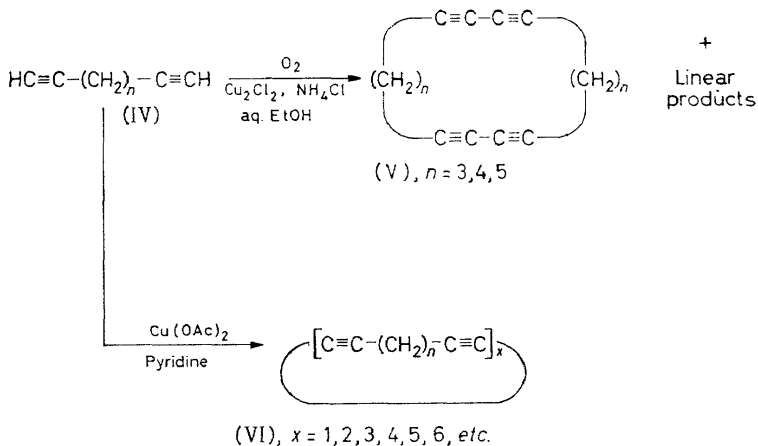


Figure 2

Another discovery of interest was the observation that aliphatic 1,5-diacetylenes of type (VII) (Figure 3) on treatment with potassium t-butoxide in t-butyl alcohol underwent a smooth prototropic rearrangement to give the corresponding 1,3-dien-5-yne (VIII) in high yield¹³. For instance, 1,5-hexadiyne (IX) under these conditions yielded 65 per cent of 1,3-hexadien-5-yne (X), consisting of 65 per cent of the *cis* isomer and 35 per cent of the *trans* isomer¹³. A possible approach to completely conjugated monocyclic systems, therefore, appeared to involve the synthesis of large-ring compounds made up of 1,5-diyne units through oxidative coupling of an appropriate α,ω -diacetylene, followed by prototropic rearrangement.

The simplest method for constructing large-ring compounds made up of 1,5-diyne units involved the coupling of 1,5-hexadiyne (IX) itself. This diacetylene on treatment with cupric acetate in pyridine solution at 55° for 3 hours yielded a complex mixture which was separated by careful chromatography on alumina. This procedure yielded 6 per cent of the cyclic

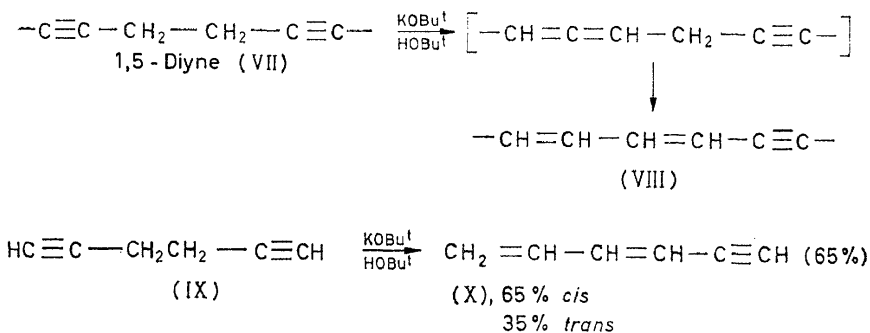


Figure 3

ADVANCES IN THE CHEMISTRY OF CONJUGATED SYSTEMS

trimer (XI), 6 per cent of the cyclic tetramer (XII), 6 per cent of the cyclic pentamer (XIII) and 3 per cent of the cyclic hexamer (XIV), in addition to other substances (*Figure 4*†)^{12, 14}. The carbon skeleton of each of these cyclic compounds was identified through full hydrogenation to the corresponding saturated cycloalkane, and such confirmation of structure by full hydrogenation was carried out routinely for all the other unsaturated compounds described in the sequel.

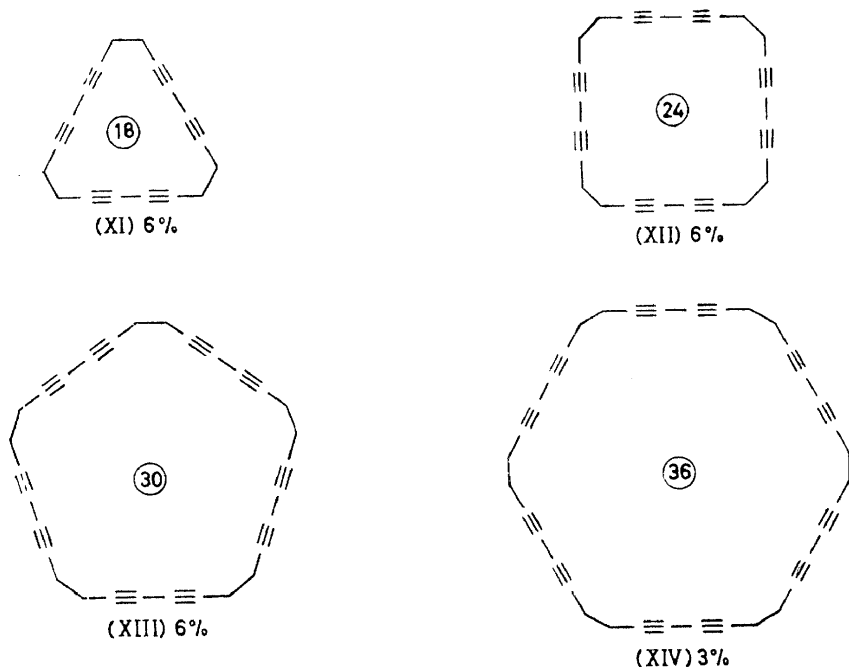


Figure 4

Each of the cyclic substances shown in *Figure 4* is made up of 1,5-diyne groupings, and should be convertible to a dehydro-annulene by prototropic rearrangement. In practice, treatment of the eighteen-membered cyclic trimer (XI) with potassium *t*-butoxide in *t*-butyl alcohol at 90° for 30 minutes gave in 50 per cent yield a light-brown crystalline substance, which must be the symmetrical tridehydro-[18]annulene shown in *Figure 5*^{14, 15}. This product was formed from (XI) by rearrangement of each 1,5-diyne unit to a 1-(*trans*)-ene-3-(*cis*)-ene-5-yne unit, exactly as had happened with 1,5-hexadiyne itself. This tridehydro-[18]annulene was the first completely conjugated macrocyclic compound prepared by us. Its ultraviolet spectrum is indicated in *Figure 5*, and the n.m.r. spectrum will be discussed later.

One of the most interesting questions regarding tridehydro-[18]annulene was whether the acetylenic bonds in this compound could be hydrogenated to double bonds. In fact, this reaction could be brought about quite simply,

† The numbers given inside the formulae in this and subsequent figures indicate the size of the ring.

partial hydrogenation at atmospheric pressure over a palladium catalyst in benzene solution giving rise to [18]annulene in about 30 per cent yield^{16, 17}. That the product, which crystallized as long brown-red needles, was an annulene followed from the elemental analysis, the fact that the infrared spectrum no longer showed the acetylene band at about 4.6μ present in the precursor, while full hydrogenation smoothly yielded cyclo-octadecane. It can be seen that in passing from tridehydro-[18]annulene to [18]annulene, the main ultraviolet maximum has been shifted from 334 to 369μ , and has almost doubled in intensity (from $\epsilon = 160,000$ to $\epsilon = 300,000!$). This behaviour suggested that the [18]annulene actually possessed the configuration shown which could be reasonably planar, rather than an alternative non-planar one. The correctness of this configuration has subsequently been confirmed by X-ray methods (see below).

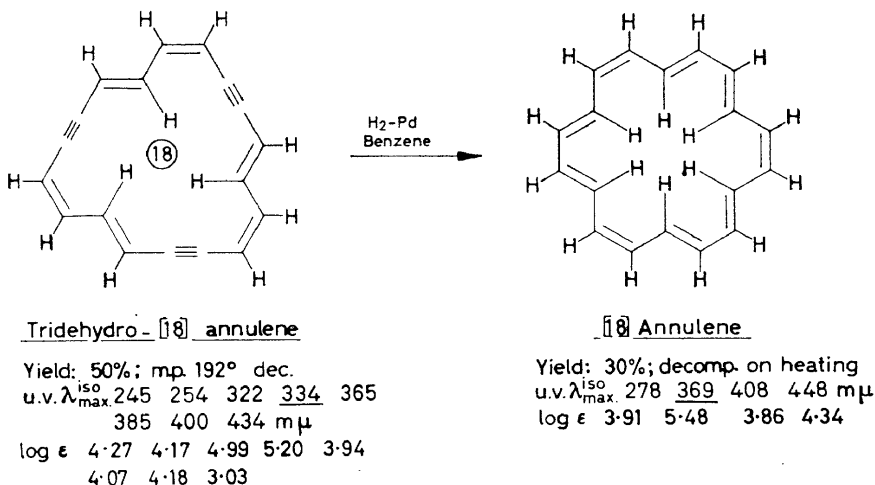


Figure 5

A model of [18]annulene (built from "Catalin" molecular models) is shown in Figure 6. Although the hydrogen van der Waals radii in these models may be too short, it is apparent that the interaction of the internal hydrogen atoms should not be so severe as to prevent the carbon skeleton from being reasonably planar.

It will be recalled that [18]annulene is the first annulene after benzene for which aromatic character was predicted, and the question arises: is this in fact an aromatic compound? One possible way to answer this question is by X-ray crystallographic methods. An X-ray analysis has in fact been carried out by Bregman *et al.*¹⁸ at the Weizmann Institute, and this analysis (see Figure 7) fully confirms the configuration which we had assigned to [18]annulene. The X-ray analysis also yielded the following information¹⁸. The compound possesses a centre of symmetry, a fact which by itself rules out bond-alternation. The deviation of the carbon skeleton from a mean plane is no more than 0.1 \AA , in agreement with our expectation that [18]-annulene is a reasonably planar compound. Most important, there are two

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different types of carbon-carbon bonds (see *Figure 8*), the "cisoid" bonds (indicated by thick lines) with a length of $1.419 (\pm 0.004) \text{ \AA}$, and the "transoid" bonds (indicated by thin lines) with a length of $1.382 (\pm 0.003) \text{ \AA}$. Although the reasons for this non-equivalence of the carbon-carbon bonds is not known with certainty, this result clearly rules out bond-alternation, which would have resulted in bond-lengths successively short and long.

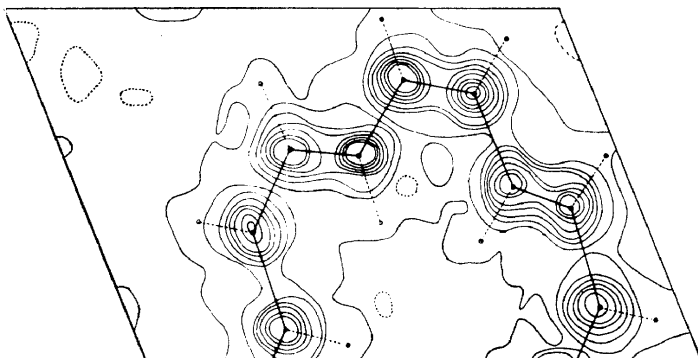


Figure 7. X-ray crystallographic analysis of [18]annulene¹⁸

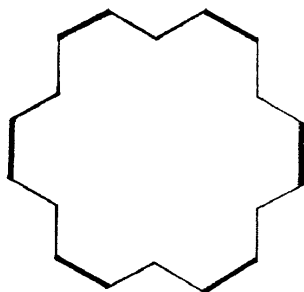


Figure 8

By contrast, the non-aromatic cyclo-octatetraene shows single bond-lengths of 1.46 \AA , alternating with double-bond lengths of 1.33 \AA . On this basis then, [18]annulene is definitely aromatic.

As mentioned previously, one of the consequences of π -electron delocalization in a cyclic system is the ability to sustain an induced ring current, which is associated with a secondary magnetic field. In the case of a compound such as [18]annulene, having protons both inside and outside the ring, the result of this magnetic field is to shield the inside protons and deshield the outside protons. It was therefore of interest to determine the n.m.r. spectrum of [18]annulene, since, if it were aromatic, the inner protons should absorb at unusually high field and the outer protons at unusually low field.

The n.m.r. spectrum of [18]annulene, carried out by Bothner-By at the Mellon Institute, is shown⁵ in *Figure 9*. It was difficult to obtain a satisfactory spectrum in view of the very low solubility of the substance in most

organic solvents, and this spectrum, measured in perdeuteriotetrahydrofuran, still leaves something to be desired. However, two broad bands are apparent, one at very low field (1.1τ) due to the outer protons, and one at very high field (11.8τ) due to the inner protons. The relative area of the two bands was almost exactly 2:1, in accord with 12 protons being outside and 6 inside the ring. This result clearly demonstrates the existence of a ring current, showing [18]annulene to be aromatic.

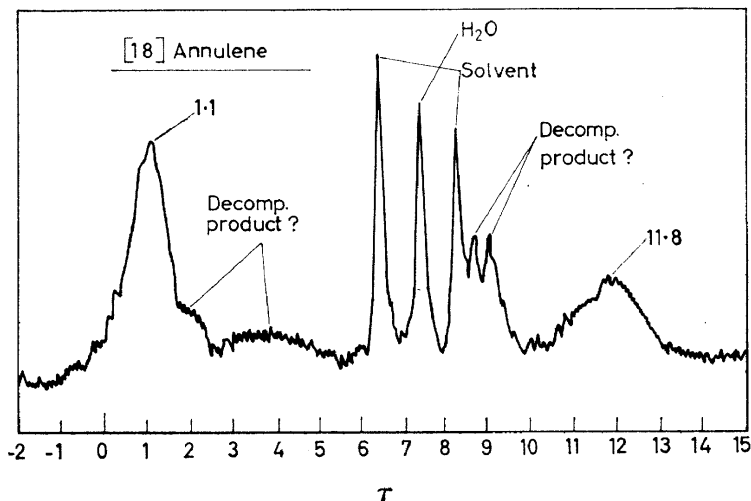


Figure 9

(Reproduced by courtesy of the American Chemical Society⁵)

Despite these results, [18]annulene showed hardly any of the chemical behaviour usually associated with a classical "aromatic" compound. Thus, [18]annulene showed no very unusual stability properties, and it reacted readily with bromine as well as with maleic anhydride to give addition products. Various aromatic substitution reactions such as Friedel-Crafts acylation, sulphonation, *etc.*, were attempted, but only destruction of the starting material was observed¹⁷. In summary, it is evident that in [18]-annulene a separation exists between aromaticity in the modern and classical sense.

We now come to the 24-membered ring series. It will be recalled that one of the products of the oxidative coupling of 1,5-hexadiyne was the cyclic tetramer (XII). Like the cyclic trimer, this tetramer is made up of 1,5-diyne units, and on treatment with potassium *t*-butoxide in *t*-butyl alcohol an analogous rearrangement took place. The resulting tetrahydro-[24]-annulene, formed in about 40 per cent yield, probably possesses the structure shown in Figure 10^{14, 19}. It crystallized as dark purple prisms, resembling potassium permanganate in appearance. Partial hydrogenation of this tetrahydro-[24]annulene in benzene solution over a palladium catalyst then gave about 15 per cent of an unstable, very dark blue, almost black, crystalline substance, which was clearly a [24]annulene in view of the elemental composition, the absence of any acetylenic bands in the infrared,

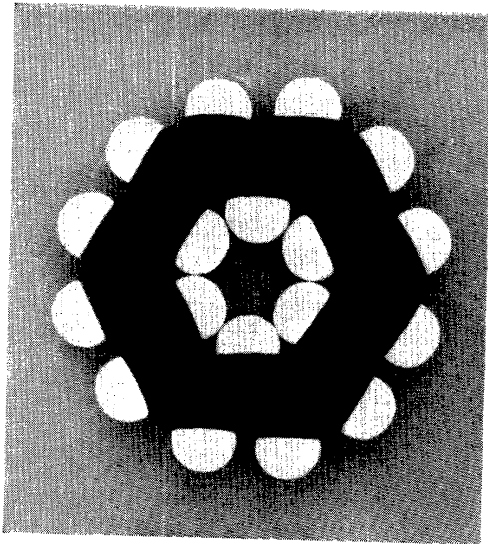


Figure 6

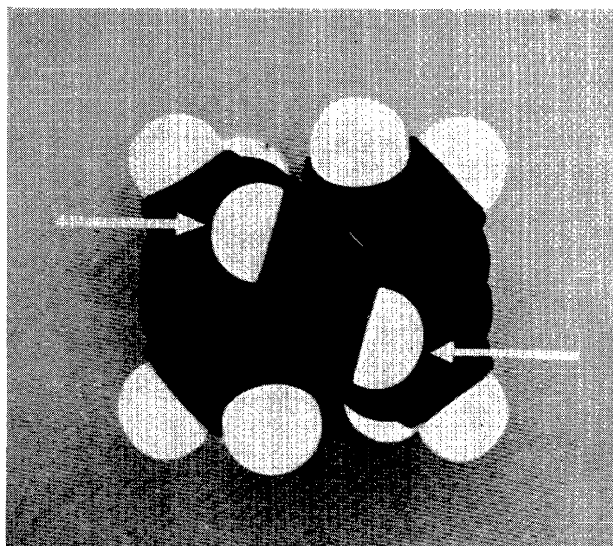


Figure 16

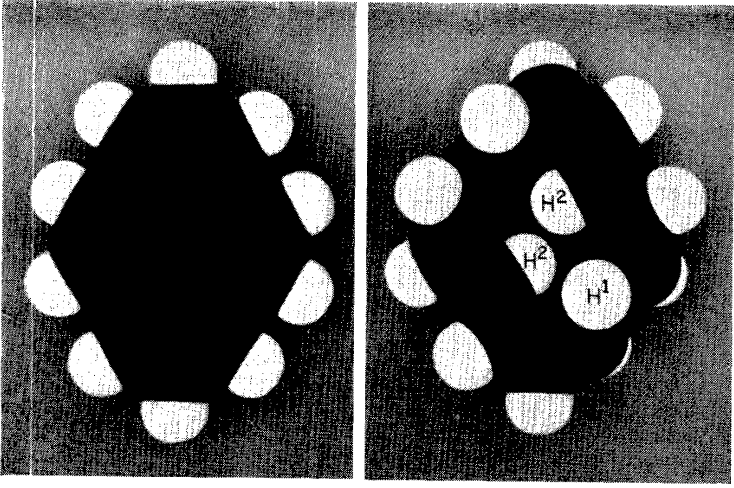


Figure 24

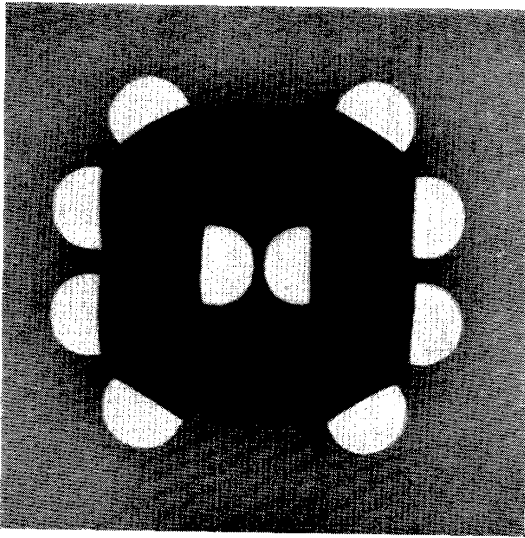


Figure 26

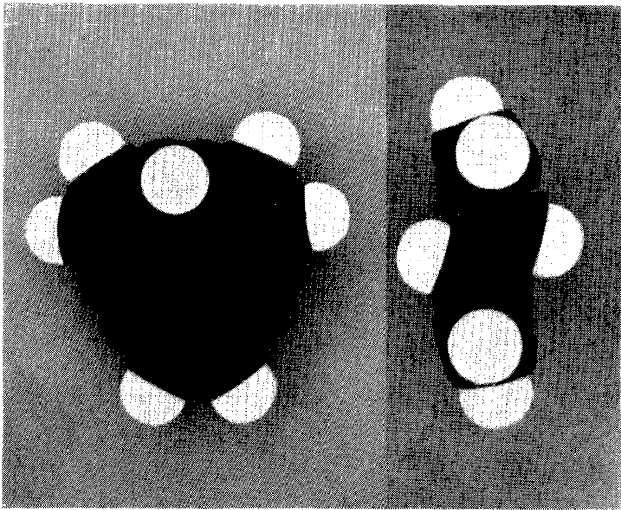


Figure 31

and the fact that full hydrogenation readily yielded cyclotetracosane^{17, 19}. The exact configuration of this [24]annulene is unknown, but the structure (XVa) (possessing 4 *cis* double bonds symmetrically placed) or (XVb) (possessing 3 *cis* double bonds symmetrically placed) appears to be the most likely.

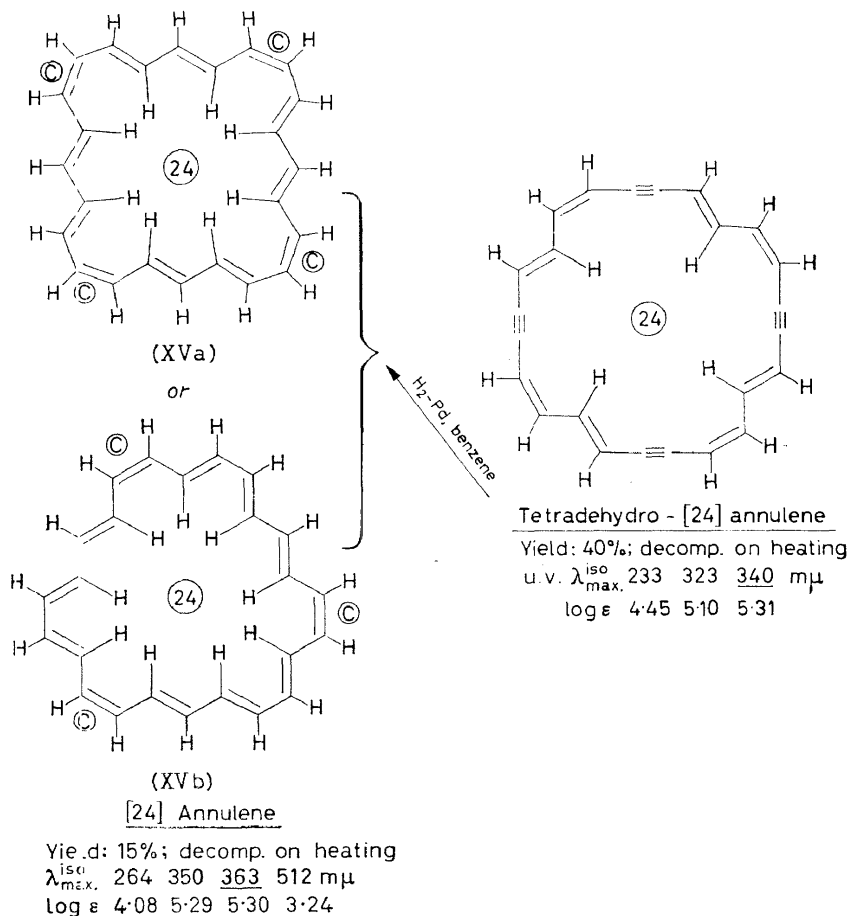


Figure 10

[24]Annulene does not obey Hückel's rule, and therefore should not be aromatic. In fact the substance was found not to be aromatic, since the n.m.r. spectrum, shown in Figure 11, consists of only one broad band at 3.16 τ , due to all the protons⁵. The position of this band is close to that observed for the olefinic protons of linear conjugated polyenes, and clearly no ring current exists.

Let us now consider the possible aromaticity of dehydro-annulenes. The same type of considerations discussed before for the annulenes should apply

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to the corresponding dehydro-compounds. Consequently, tetrahydro-[24]annulene, containing 24 out-of-plane π -electrons, should be non-aromatic, since Hückel's rule is not obeyed. In accord with theory, the n.m.r. spectrum of tetrahydro-[24]annulene (*Figure 12*) gives no indication of any ring current. There is no absorption at high field, a complex band in the region 3.6–4.7 τ due to the "outer" protons being apparent, as well as a double doublet at 1.80 τ due to the "inner" protons⁵. That this assignment is correct follows from the relative intensities of the two sets of bands, as well as from the multiplicity of the 1.80 τ band.

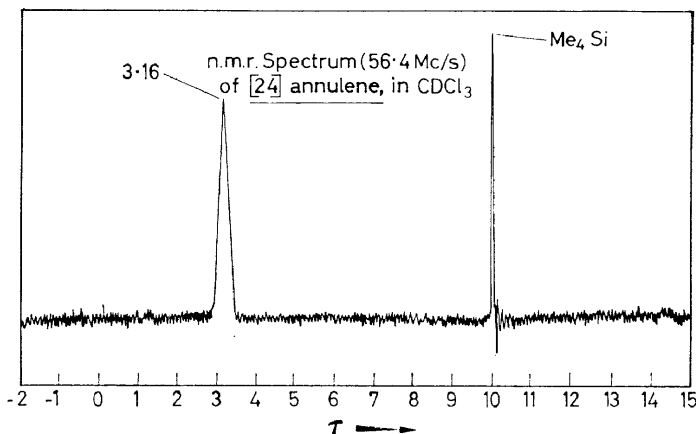


Figure 11

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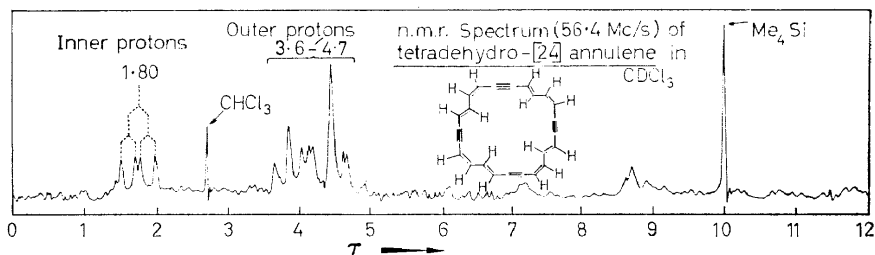


Figure 12

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In contrast to the "non-Hückel" tetrahydro-[24]annulene, the previously discussed tridehydro-[18]annulene obeys Hückel's rule, since it contains 18 out-of-plane π -electrons. In addition, tridehydro-[18]annulene is expected to be a planar molecule, and it should therefore be aromatic. The n.m.r. spectrum of tridehydro-[18]annulene is shown⁵ in *Figure 13*. It can be seen clearly that a ring current does in fact exist, a complex band assigned to the outer protons appearing at low field (in the 1.7–3.1 τ region), and a double doublet assigned to the inner protons at high field (at 8.26 τ).

By comparison, this "inner proton" double doublet in tetrahydro-[24]-annulene had appeared far down field, at 1.80 τ (Figure 12). Yet tridehydro-[18]annulene and tetrahydro-[24]annulene differ structurally only in the fact that the ene-ene-yne grouping is repeated three times in the former

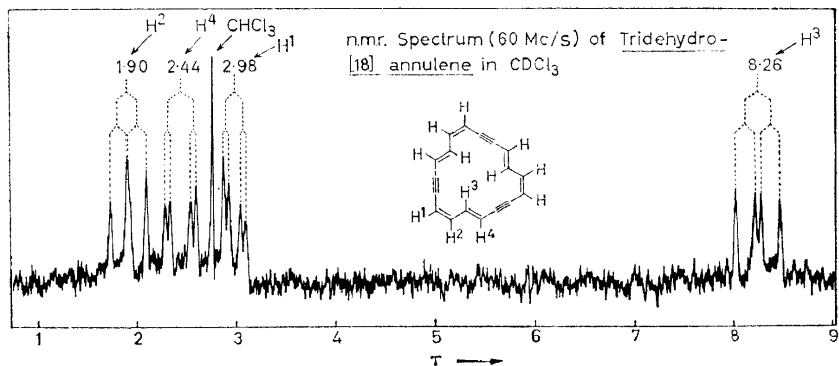


Figure 13

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and four times in the latter, and this striking difference in the positions of the inner proton bands in the two compounds is in accord with our theories regarding the importance of Hückel's rule for aromaticity.

In the case of tridehydro-[18]annulene it is possible to carry out a first-order analysis of all the bands in the n.m.r. spectrum (see Figure 13), and this analysis clearly shows the correctness of the structure which we had assigned to the substance.

If I were to follow the order of our work historically, I should now give an account of the synthesis of fully conjugated thirty-membered ring cyclic compounds, derived from the cyclic pentamer of 1,5-hexadiyne^{14, 17, 20, 21}. However, when we come to these very large-ring conjugated systems, we find that they are no longer highly crystalline, well-defined compounds, and they become too insoluble for the n.m.r. spectra to be determined. Our efforts more recently have consequently been directed towards some of the smaller ring annulenes and dehydro-annulenes, especially since in these smaller compounds the question of the relationship between planarity and aromaticity can be studied experimentally. The remainder of this lecture will therefore deal with our efforts to prepare various annulenes and dehydro-annulenes with ring-sizes intermediate between that of cyclo-octatetraene and of [18]annulene.

In order to prepare conjugated sixteen-membered ring compounds, the most suitable starting material was found to be the symmetrical *trans*-4-octene-1,7-diyne (XVI) (Figure 14)²². This diacetylene on coupling under the Glaser conditions yielded about 3 per cent of the cyclic dimer (XVII) as well as 25 per cent of the linear dimer (XVIII)²². The cyclic dimer proved to be quite an unstable compound, presumably because of ring strain, and exploded at about 215° on attempted melting point determination.

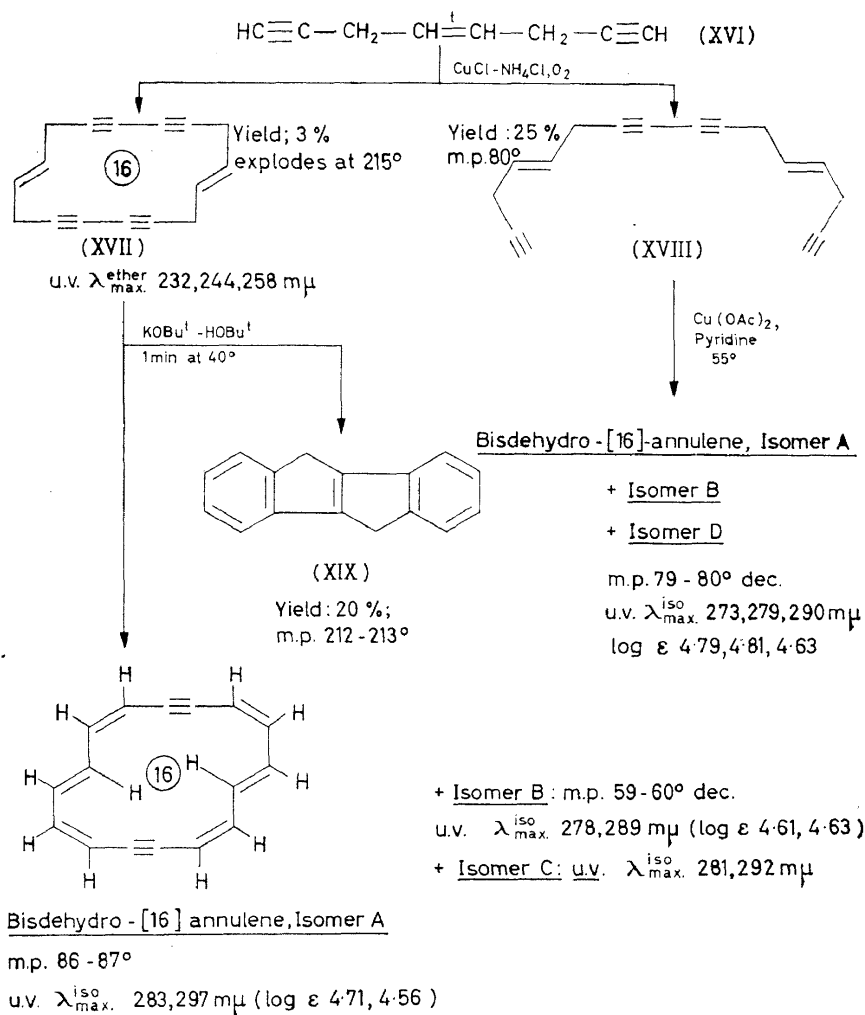


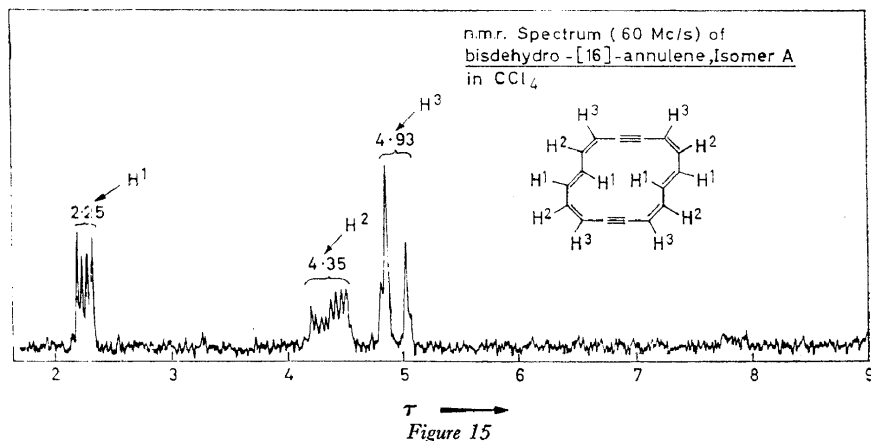
Figure 14

It can be seen that the cyclic dimer (XVII) is made up of 1,4-enyne groupings, which were expected to undergo ready isomerization. In fact, treatment with potassium *t*-butoxide in *t*-butyl alcohol under mild conditions, for 1 minute at 40°, resulted in conjugation²². The product consisted of about 10 per cent of an isomeric mixture of bisdehydro-[16]annulenes, as well as about 20 per cent of the dibenzdihydropentalene (XIX)²³, formed by a transannular reaction. The mixture of bisdehydro-[16]annulenes was found to be quite complex, consisting of three different isomers (isomer A, B and C), all showing similar ultraviolet spectra. Of these, only isomer A was reasonably stable. This isomer, which formed large brown plates and had the properties shown in Figure 14, was found to possess the symmetrical structure given on the basis of the n.m.r. spectrum which is discussed below.

The unstable isomer B could also be obtained in crystalline form, as dark-brown plates with the properties indicated, but the structure of this and of isomer C is unknown.

In order to obtain larger amounts of the bisdehydro-[16]annulenes, the linear dimer (XVIII) was coupled with cupric acetate in pyridine and ether at 55°. This reaction resulted in cyclization as well as in isomerization, yielding directly a mixture from which three different isomers of bisdehydro-[16]annulene could again be isolated. Two of these proved to be identical with isomers A and B, respectively, while the third (isomer D), was new. Some properties of this isomer D, which formed dark-brown needles, are shown in *Figure 14*. This isomer was also found to be very unstable (for instance in one case it detonated with a flash of fire on being touched with a spatula), and its exact structure is unknown.

We return now to bisdehydro[16]annulene, isomer A, the n.m.r. spectrum of which is shown in *Figure 15*. An analysis of the spectrum gives clear



indication that the compound possesses the structure shown. The quartet centred at 2.25 τ is assigned to the four protons (H^1 , see *Figure 15*) attached to the two *trans* double bonds. These protons are all equivalent because of the non-planarity of the molecule, as will be apparent from a model discussed below. The octet which appears at 4.35 τ is assigned to the four H^2 protons, and the doublet at 4.93 τ to the four H^3 protons. The positions of these bands show the substance to be non-aromatic, in agreement with the fact that it does not obey Hückel's rule.

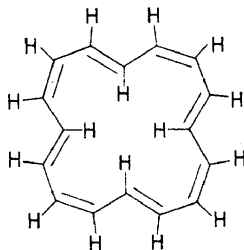
A molecular model of bisdehydro-[16]annulene, isomer A, is pictured in *Figure 16*. Only one of the two *trans* double bonds can be seen, and the two protons attached to this double bond (H^1 in *Figure 15*) are indicated by arrows. It is clear that each of these protons is equally situated in relation to the rest of the molecule, causing their equivalence in the n.m.r. spectrum; the same is of course true for the protons attached to the other *trans*-double bond. Similarly, the four protons marked H^2 in *Figure 15* are all equivalent to each other, as well as the four H^3 protons.

Bisdehydro-[16]annulene, isomer A (*Figure 14*), was partially hydrogenated in benzene solution over a palladium catalyst. This reaction yielded

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about 20 per cent of a substance, crystallizing as brown prisms, some properties of which are indicated in *Figure 17*. This is clearly a [16]annulene, the probable configuration of which is given, in view of the elemental analysis, the absence of acetylenic bands in the infrared, and the full hydrogenation results.

[16]Annulene, being a 16 π -electron system, does not comply with Hückel's rule and should therefore not be aromatic. In fact the n.m.r. spectrum, given in *Figure 18*, provides no evidence of any ring current. Only one band, assigned to all the protons, appears at 3.27 τ , this position being close to that observed for the olefinic protons of linear conjugated polyenes.



[16] - Annulene

Yield: 20%; m. p. 92-93° dec.

u.v. $\lambda_{\text{max}}^{150}$ 2.85 μ

$\log \epsilon$ 4.86

Figure 17

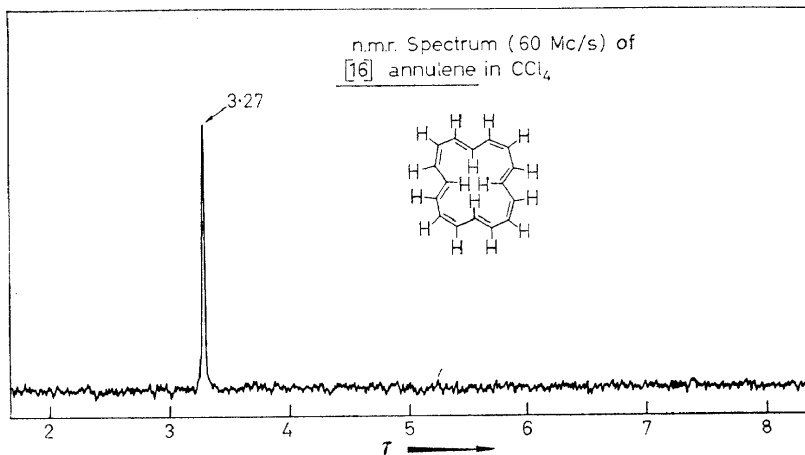


Figure 18

We now come to the cyclic C_{14} -series. This is a series of considerable interest since a 14 π -electron system complies with Hückel's rule, and conjugated members should therefore be aromatic provided they are reasonably planar.

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The starting material was the linear C_{14} -compound (XX), containing three acetylenic and two *trans*-ethylenic bonds²⁴, shown in *Figure 19*. Oxidative coupling with cupric acetate in pyridine at 50° gave a mixture of products, from which the cyclic monomer (XXI) could be isolated. This appears to be a highly strained compound, and it exploded at about 100° on attempted melting point determination.

The cyclic monomer (XXI) again is made up of 1,4-enyne groupings and should be isomerized with base under mild conditions. In practice, treatment of this substance with potassium *t*-butoxide in *t*-butyl alcohol for 1 minute at 60° gave rise to two different conjugated monocyclic compounds. These substances, both of which crystallized as bright red plates, were at first thought to be different isomers of the expected monodehydro-[14]-annulene²⁴.

The substance obtained in larger amount will be discussed first. This compound, obtained in about 2 per cent over-all yield, proved in fact to be a monodehydro-[14]annulene containing four *cis*- and two *trans*-double bonds, such as (XXIIa) (see *Figure 19*). The ratio of outer:inner protons in

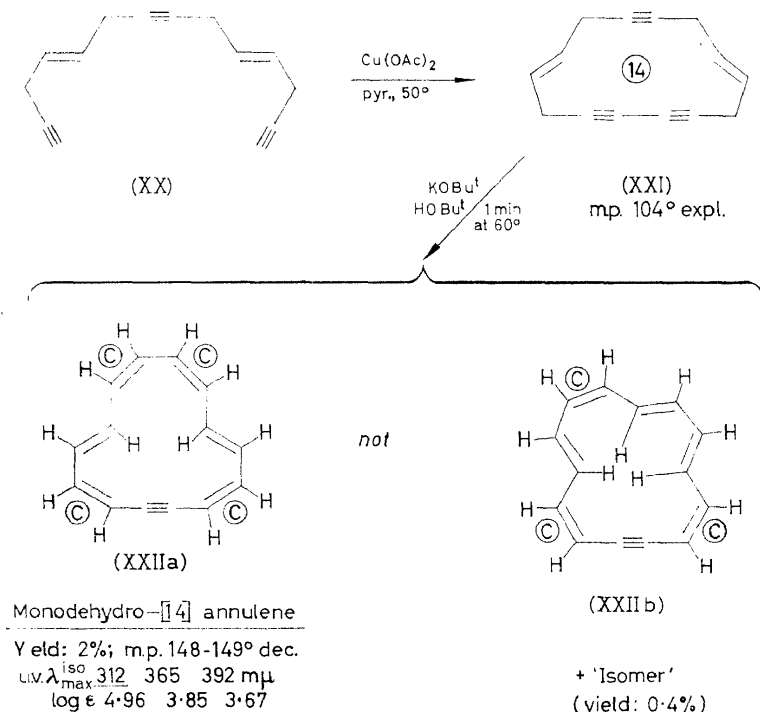


Figure 19

this structure is 5:1, whereas in an alternative structure such as (XXIIb), containing three *cis*- and three *trans*-double bonds, the ratio is 3:1. The n.m.r. spectrum of the monodehydro-[14]annulene is shown⁵ in *Figure 20*. The spectrum consists of a complex band at low field (in the 1.2-2.7 τ region) due to the outer protons, and a double doublet at high field (at

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10.70 τ) due to the inner protons. The ratio of the two bands is almost exactly 5:1, leading us to assign a structure such as (XXIIa) to the compound. The spectrum clearly shows the existence of a ring current, demonstrating the compound to be aromatic. This observation is in keeping with the presence of 14 out-of-plane π -electrons, and it indicates that the carbon

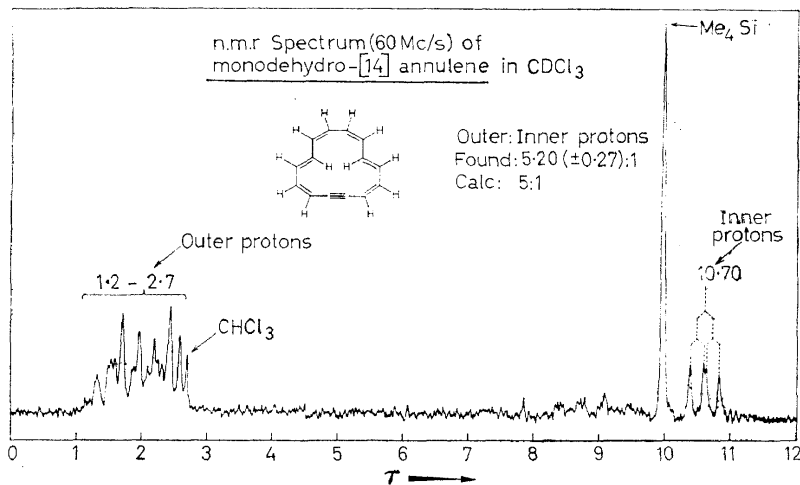
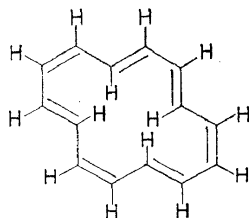


Figure 20

(Reproduced by courtesy of the American Chemical Society⁹)

skeleton is reasonably planar, in-plane deformations of the normal bond-angles presumably having occurred.

The above-described monodehydro-[14]annulene was partially hydrogenated in benzene solution over a palladium catalyst (Figure 21)²⁴. This experiment led in about 15 per cent yield to a substance, crystallizing as well-defined brown needles, which was clearly a [14]annulene in view of the analytical, infrared and full hydrogenation results. That the [14]annulene actually has the configuration shown in Figure 21 was demonstrated by X-ray crystallography (see below).



[14] Annulene

Yield: 15%, m.p. 134 -135° dec.
u.v. $\lambda_{\text{max}}^{\text{iso}}$ 317, 376 μ
 $\log \epsilon$ 4.84, 3.76

Figure 21

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As mentioned earlier, [14]annulene, while obeying Hückel's rule, could be planar only if extreme distortion of bond angles occurred, in view of the serious overcrowding of the inner hydrogen atoms in a planar structure. In order to gain information regarding the relationship between planarity and aromaticity, it was obviously of interest to investigate the degree of planarity of the carbon skeleton of [14]annulene, and to find out whether in fact this represents an aromatic system.

An X-ray crystallographic analysis of [14]annulene is being carried out by Bregman, and the results available at present are shown²⁵ in *Figure 22*. This analysis confirms the configuration shown in *Figure 21*. However the results do not yet provide any quantitative information regarding bond lengths and angles, or the planarity of the molecule.

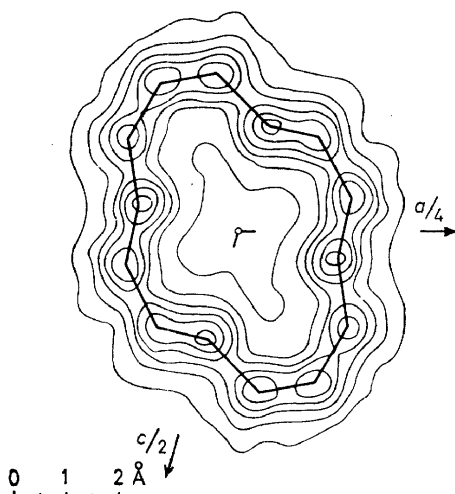


Figure 22. X-ray crystallographic analysis of [14]annulene
(Reproduced by courtesy of J. Bregman. *Nature* **194**, 679, 1962.)

The n.m.r. spectrum of [14]annulene (*Figure 23*) consists of two bands, a weak one at 3.93τ and a stronger one at 4.42τ . We had assumed at first that the weak band was due to a decomposition product, formed during the period between preparation of the solution (in Israel) and determination of the spectrum (in England). However, it has now been found from spectra of freshly prepared solutions that in fact both bands are due to the substance itself. Moreover, the ratio of the lower to higher field band is almost exactly 1:6, indicating the former to be due to two protons and the latter to twelve protons. We believe the explanation to be as follows: because of the overcrowding of the inner protons in a planar molecule, the substance exists in a non-planar conformation derived from the planar structure shown in *Figure 23* by moving one of the inner protons marked H^1 upwards and the other downwards, while the inner protons marked H^2 stay inside the ring system. The lower field band is then assigned to the two inner protons marked H^2 ,

while the higher field one is assigned to the other twelve protons of the molecule.

Figure 24 (left side) pictures a model of [14]annulene containing a planar carbon skeleton and normal bond angles. It is evident that the four inner protons cannot be accommodated, and in fact they have had to be omitted for this reason. On the right side of Figure 24 is a picture of a model of the molecule as we believe it actually exists. It can be seen that two of the inner

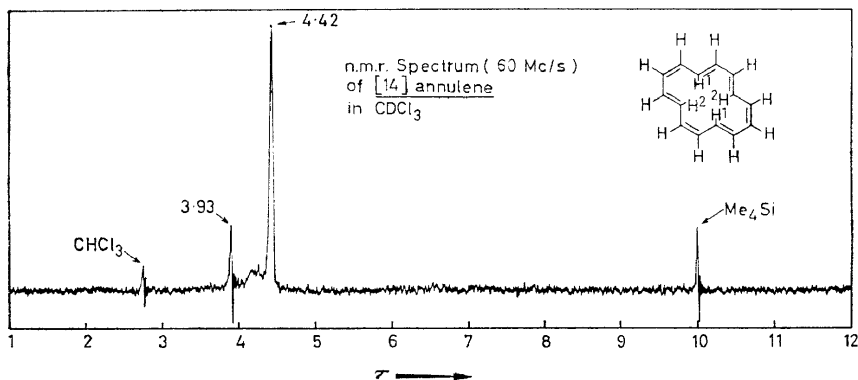


Figure 23

(Reproduced by courtesy of the American Chemical Society²)

protons (marked H²) remain inside the ring, while one (marked H¹) is now above the general plane of the ring, and the other (which cannot be seen in Figure 24) is below.

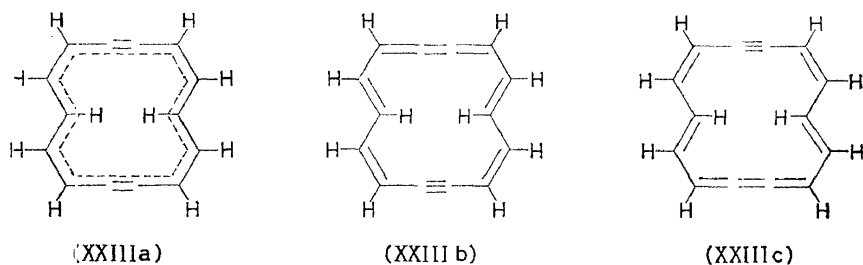
A very interesting feature of the n.m.r. spectrum of [14]annulene is that there is no evidence of any ring current, the position of the main band being very similar to that of cyclo-octatetraene. [14]Annulene is clearly not an aromatic compound, despite the fact that Hückel's rule is obeyed. By contrast, a ring current had been found in the closely related monodehydro-[14]annulene (Figure 20), which is presumably planar since it possesses only two instead of four inner protons in a planar conformation. The reason for the non-aromaticity of [14]annulene must therefore be due to its non-planarity, and this provides a striking demonstration of the importance of planarity for aromaticity.

It was mentioned above that isomerization of the C₁₄ cyclic monomer (XXI) had yielded not only the monodehydro-[14]annulene (XXIIa), but also in minor amount a substance considered to be an isomer (see Figure 19). This second substance, like the first, crystallized as red plates, but it showed a characteristic red-green tint in solution. It exhibited some noteworthy properties. For example, it was exceptionally stable, and its ultraviolet spectrum showed an unusual maximum at 586 mμ; in addition, the main band of the ultraviolet spectrum (at 309 mμ), though very close to that of the monodehydro-[14]annulene (at 312 mμ), was about twice as intense²⁴.

On further investigation it has been found that this second substance in fact is 1,8-bisdehydro-[14]annulene (Figure 25), containing two hydrogen atoms less than expected²⁶. This is an unusual structure in view of the fact

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that no conventional formula made up of conjugated double or triple bonds can be written, since there is an odd number of carbon atoms joining the two formal triple bonds on either side. The compound is most conveniently represented by formula (XXIIIa) (*Figure 25*). Classical Kekulé resonance forms can of course be written, as shown in formulae (XXIIIb) and (XXIIIc), but these contain a cumulene grouping.



1,8 - Bisdehydro - [14] annulene

Yield: 0.4%

u.v. $\lambda_{\text{max}}^{\text{iso}}$ 309 402 410 424 586 m μ
 log ϵ 5.24 3.84 3.88 4.37 3.46

Figure 25

A molecular model of 1,8-bisdehydro-[14]annulene is pictured in *Figure 26*. It is apparent that both inner hydrogen atoms can be accommodated in a planar structure and, consequently, the molecule should be able to exist in the planar conformation shown.

The n.m.r. spectrum of 1,8-bisdehydro-[14]annulene is shown in *Figure 27*.

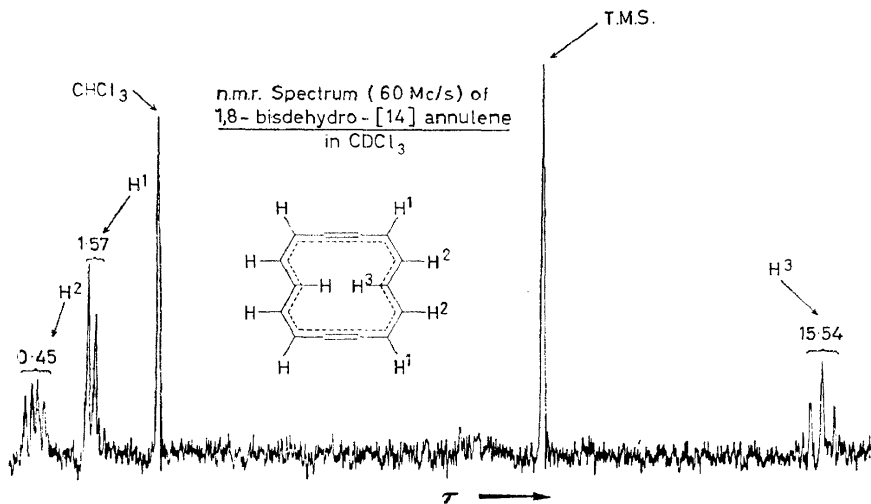


Figure 27

It was an analysis of this spectrum which had first excluded a monodehydro-[14]annulene formulation and pointed to the structure shown²⁶. The quartet at 0.45 τ is assigned to the four outer H² protons, the doublet at 1.57 τ to the four outer H¹ protons, and the symmetrical triplet at 15.54 τ to the two inner H³ protons. Most striking about the spectrum is the fact that the outer protons appear at low field and the inner protons at very high field. Clearly a strong ring current exists and the substance is aromatic. This is in keeping with expectation, since the carbon skeleton is coplanar and Hückel's rule is obeyed in view of the presence of 14 out-of-plane π -electrons.

A full three-dimensional X-ray crystallographic analysis of bisdehydro-[14]annulene has been carried out by Mason and Bailey at Imperial College, the result of which is indicated²⁷ in *Figure 28*. It is clear that the compound does in fact possess the structure deduced from the n.m.r. spectrum.

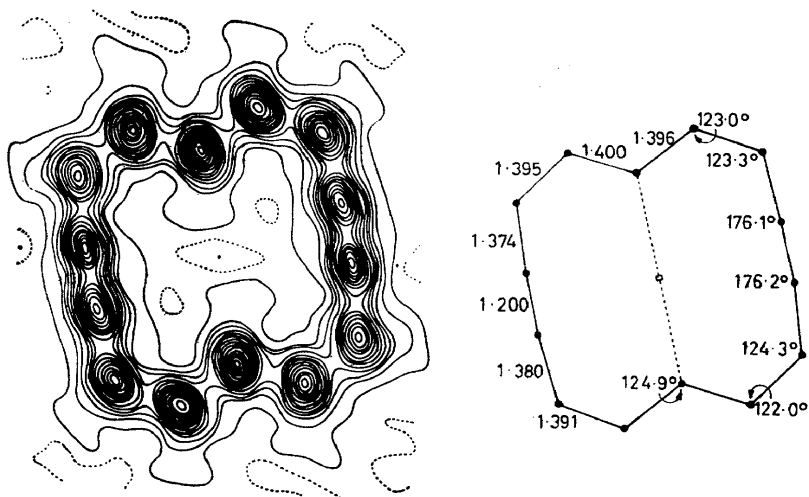


Figure 28. X-ray crystallographic analysis of 1,8-bisdehydro-[14]annulene
(Reproduced by courtesy of N. A. Bailey and R. Mason. *Proc. Chem. Soc.* 1963, 180.)

The molecule has a centre of symmetry, and is planar (r.m.s. deviation 0.004 Å). The various bond lengths and bond angles are summarized in *Figure 28* (right side). The observed bond lengths indicate essentially complete π -electron delocalization, showing the compound to be aromatic. Also of interest is the observation that each of the acetylenic bonds and the adjoining carbon atoms on either side do not fall exactly on a straight line, the acetylenic bonds being slightly "bent out".

Various properties and reactions of this interesting aromatic compound are now being studied, and it has already been found that it can be nitrated and acylated. Also under investigation is the mode of its formation. So far, a precursor has been isolated in pure crystalline form, which proved to be another bisdehydro-[14]annulene, the exact structure of which is not yet known.

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Finally, some experiments in the cyclic C_{12} -series are described; these are summarized²⁸ in *Figure 29*. The starting material once more was 1,5-hexadiyne (IX). It has been mentioned above that it had not been possible to prepare the twelve-membered cyclic dimer (XXIV) (*Figure 29*) from this compound, since coupling with cupric acetate in pyridine had given the

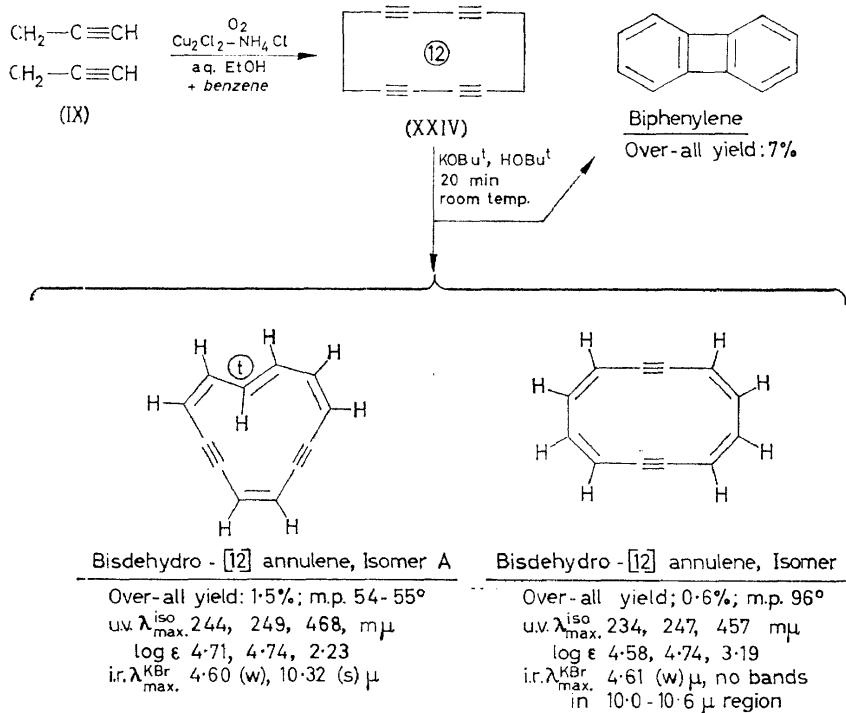


Figure 29

cyclic trimer and higher cyclic compounds^{12, 14}, while coupling under the Glaser conditions had given only a dark-brown insoluble polymer in addition to linear products¹⁰. We suspected that the brown polymer obtained under the Glaser conditions was due to the fact that the cyclic dimer (XXIV) had actually been formed, but was not soluble in the aqueous ethanol and had decomposed. It can be appreciated that this cyclic dimer would be a very highly strained compound, expected to be quite unstable. The oxidation of 1,5-hexadiyne was therefore re-investigated under the Glaser conditions (involving the passage of oxygen through a solution of the diacetylene in aqueous ethanol in the presence of cuprous chloride and ammonium chloride), but now a large amount of benzene was added in order to keep the products in solution. Chromatography on alumina then led to solutions which did indeed contain the cyclic dimer (XXIV), since full hydrogenation yielded cyclododecane²⁸. However, it was found to be quite impossible to isolate this dimer, in view of its extreme instability. For instance, the substance was converted into an insoluble brown-black polymer as soon

as its solution was taken to dryness at 0°. In fact, this ready decomposition could be used to determine which chromatography fractions contained the cyclic dimer, by observing whether a few drops allowed to evaporate on a watch-glass left a black residue or not.

In view of this extreme instability, the chromatography fractions containing the cyclic dimer (XXIV) were subjected directly to isomerization with potassium *t*-butoxide in *t*-butyl alcohol for 20 minutes at room temperature. It will be noted that this isomerization took place under much milder conditions than had to be employed for the higher cyclic polymers of 1,5-hexadiyne¹⁴. The main product obtained from this reaction, in about 7 per cent over-all yield, was found to be biphenylene, a transannular reaction having occurred²⁸. In addition, two coloured compounds could be isolated, which proved to be two different isomers of bisdehydro-[12]-annulene, isomer A being formed in about 1.5 per cent over-all yield and isomer B in about 0.6 per cent over-all yield.

Bisdehydro-[12]annulene, isomer A, possesses the structure shown in *Figure 29*, containing three *cis* and one *trans* double bonds, as evidenced by the n.m.r. spectrum which will be discussed below. This isomer, which proved to be very unstable in the solid state, crystallized as brown needles, which gave pink-violet solutions. The melting point and spectral properties are indicated in the figure.

Bisdehydro-[12]annulene, isomer B, exhibited an n.m.r. spectrum indicating it to possess the structure shown in *Figure 29*, containing all four double bonds in the *cis*-configuration. This isomer, which proved to be considerably more stable than isomer A, crystallized as brick-red needles, which gave pink solutions. Other properties of isomer B are also given in the figure. It can be seen that the ultraviolet spectral properties of the two isomers are quite similar. In the infrared both isomers show an acetylene band at about 4.60 μ ; isomer A in addition exhibits a strong *trans*-ethylenic band at 10.32 μ which is absent in isomer B, in agreement with the assigned structures.

The n.m.r. spectrum of bisdehydro-[12]annulene, isomer A, is shown in *Figure 30*. The spectrum is fully in accord with the structure shown, existing in a non-planar conformation, the *trans*-double bond being perpendicular to the plane of the rest of the ring. This non-planarity causes the protons marked H¹, H², H³ and H⁴ (see *Figure 30*) on one side of the molecule to be equivalent to the corresponding ones on the other side. This will be apparent

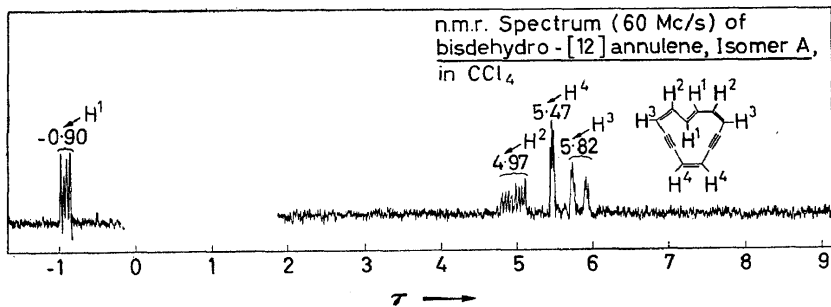


Figure 30

from a model discussed below. Of the various bands in the spectrum, the quartet centred at -0.90τ is assigned to the two H^1 protons, the octet at 4.97τ to the two H^2 protons, the band at 5.47τ to the two H^4 protons, and the doublet at 5.82τ to the two H^3 protons. The spectrum, except for the H^4 band, is very similar in type to that of the bisdehydro-[16]annulene, isomer A, discussed previously (see *Figure 15*). This is in agreement with the assigned structure, since the last mentioned compound has the same arrangement of protons as the bisdehydro-[12]annulene, isomer A, except that it lacks the H^4 protons. It is to be noted that the spectrum shown in *Figure 30* gives no indication of any ring current; this is in accord with the fact that the bisdehydro-[12]annulene, isomer A, possesses 12 out-of-plane π -electrons and, therefore, does not comply with Hückel's rule.

A molecular model of bisdehydro-[12]annulene, isomer A, seen from two different directions, is shown in *Figure 31*. From the picture on the left it can be seen that the *trans*-double bond is perpendicular to the plane of the rest of the ring. The picture on the right, in which the molecule is looked at in the direction of the main plane, shows that two sets of protons are equivalent to each other on each side of the molecule.

We return now to bisdehydro-[12]annulene, isomer B, the n.m.r. spectrum of which is presented in *Figure 32*. It is evident that only one band at 5.58τ appears, which is assigned to all eight protons of the molecule. It should be noted that this compound is presumably also not planar, but exists in a twisted form, as indicated in *Figure 32*. Although this structure possesses two

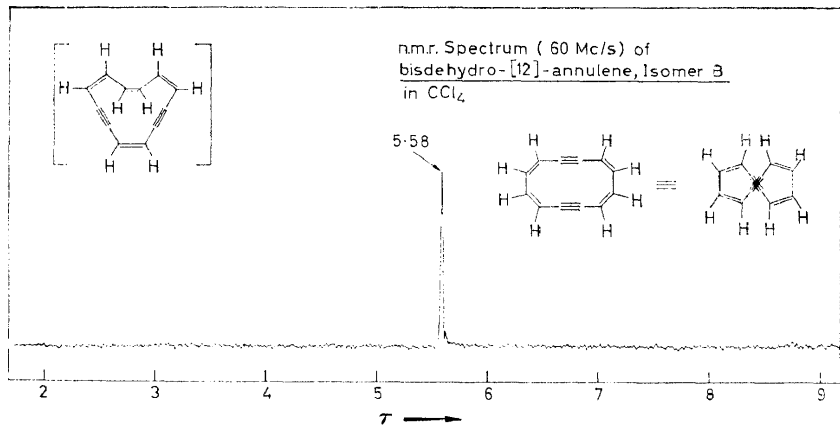


Figure 32

different types of protons, it is not unreasonable to assume that these merge into one band due to their similar chemical shifts. The only remaining structure which can reasonably be considered for this isomer is the one shown in brackets in the left part of *Figure 32*, and it is extremely unlikely that this structure should show only one band in the n.m.r. Once more there is no sign of any ring current, in agreement with the fact that Hückel's rule is not obeyed.

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Whether the bisdehydro-[12]annulenes can be partially hydrogenated to [12]annulene is an important question, to which no definite answer can be given at present. Both the isomers of bisdehydro-[12]annulene on partial hydrogenation in benzene solution over a palladium catalyst produced complex mixtures, which on careful chromatography on alumina gave yellow fractions showing a well-defined ultraviolet maximum at *ca.* 300 m μ . We believe these fractions most probably to contain [12]annulene, since the infrared spectrum of the yellow oil obtained by evaporation no longer showed an acetylene band at about 4.60 μ , and full hydrogenation led mainly to cyclododecane. However, these chromatography fractions on being hydrogenated after a few days standing gave mainly a hydrocarbon which differed from cyclododecane, but which has not yet been identified. If the material absorbing at *ca.* 300 m μ is indeed [12]annulene, this annulene is obviously an unstable compound which undergoes a ready transannular reaction on standing. This work is not yet complete and is being continued.

This brings me to the end of the account of our work in this field. It has of course not been possible to include everything that I would have liked. A summary is given in *Figure 33* of all the annulenes and dehydro-annulenes which have been prepared by us, these being indicated by a plus sign.

Ring-size	Annulene	Dehydro-annulene
10*	—	—
12	+ (?)	+ (2) (2)
14*	+	+ (1) (2)
16	+	+ (2) (2) (2) (2)
18*	+	+ (3)
20	+	+ (1) (2)
22*	—	—
24	+	+ (3) (4)
26*	—	—
28	—	+ (2)
30*	+	+ (3) (5)

Figure 33

The ring-sizes which obey Hückel's rule are marked by an asterisk, and the number of acetylenic bonds in the dehydro-annulenes is indicated by a number in parentheses. By far the most interesting series which has not been discussed is the cyclic C₁₀-series, and we are occupied now in attempting to prepare fully conjugated members of this series. As can be seen from *Figure 33*, the conjugated compounds which have been prepared by us and which have not been discussed because of lack of time are three members in the C₂₀-series^{29, 30}, a tridehydro-[24]annulene, a bisdehydro-[28]annulene, as well as three members in the C₃₀-series^{14, 17, 20, 21, 30}.

Quite recently, a number of significant observations regarding the chemistry of the aromatic annulenes and dehydro-annulenes has been made. For instance, they can be nitrated under carefully defined conditions, and they form complexes with compounds such as trinitrobenzene. This work is still in progress and has not yet reached a stage where it is justified to describe it in detail. So far, the question of the aromatic nature of the annulenes

and dehydro-annulenes has been investigated by means of n.m.r. spectroscopy and X-ray crystallography. Other means are of course available for this study, such as determination of the electron spin resonance spectra, the heats of combustion, the diamagnetic anisotropy, *etc.*, and it is intended to carry out some of these determinations.

In summary, the work described in this lecture has provided experimental confirmation of our theoretical ideas regarding aromaticity in conjugated cyclic substances. It has also shown that it is not justified to equate aromaticity with benzene-like stability and chemical behaviour, since aromatic compounds have been prepared which do not at all show this type of behaviour.

In conclusion, I should like to pay tribute to the scientists who have carried out all the experiments described, namely Dr Reuven Wolovsky, Dr Yehiel Gaoni, Dr Yaacov Amiel and Dr David-Ben-Efraim. In this lecture I have acted as a spokesman for this group. It will be appreciated that the work involved very considerable experimental difficulties, and the successful outcome is a tribute to the skill, enthusiasm and perseverance of these scientists. In addition, I would like to express my thanks to Dr Lloyd Jackman, now Professor in the University of Melbourne, Australia, who cooperated generously in the determination and interpretation of the n.m.r. spectra.

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