Antiaromatic Rings

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The Isomers of [12]Annulyne and their Reactive Relationships to Heptalene and Biphenyl[**]

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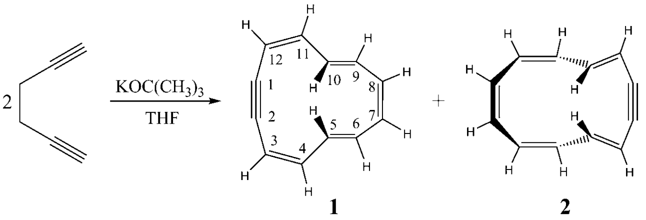
The colorful and interesting chemistry of the annulenes represents a still living vestige ("Renaissance of Annulene Chemistry")[1] of the days of the intense investigation of small hydrocarbon ring systems.[2] The smallest possible "antiaromatic" dehydrogenated annulene, [8]annulyne,[3] can be trapped as its radical anion, thus avoiding destabilization due to the π-electron count rule, and can be studied by EPR spectroscopy.[3] The situation turns out to be much more complex and intriguing in the case of the [12]annulyne system.

[12]Annulyne, which can be thought of as the double ring expanded *o*-benzyne,[4] is the smallest "antiaromatic" annulyne (4*n* π-electrons) capable of isomerization and having internal protons. The [12]annulynes are also subject to destabilization from the π-electron count rule, but upon one-electron reduction they undergo, much to our amazement, rearrangement to form either the radical anion of biphenyl or of heptalene, depending upon the particular isomer being reduced.

It was recently reported that the facile base condensation of 1,5-hexadiyne with potassium *tert*-butoxide in tetrahydrofuran (THF) leads directly to the formation of two isomers of [12]annulyne:[5] 5,10-di-*int*-di-*trans*-[12]annulyne (**1**) and 4,11-di-*int*-di-*trans*-[12]annulyne[6] (**2**) in a 1:1 ratio (Scheme 1).



Scheme 1. Base condensation of 1,5-hexadiyne in THF.

Since the products from the base condensation of hexadiyne vary with ion association conditions,[7] we thought that we might be able to establish the conditions whereby the remaining possible symmetrical isomers of [12]annulyne (6,9-di-*int*-di-*trans*-[12]annulyne and the all *cis*-[12]annulyne) would be revealed.

1,5-Hexadiyne was exposed to a mixture of potassium *tert*-butoxide and [18]crown-6 in an evacuated sealed apparatus using the same procedure that produced **1** and **2**,[5] except that the [D$_8$]THF solvent system was replaced with perdeuterated benzene. Cooling an attached NMR sample tube causes the C_6D_6 and any volatile products to cleanly distill into the tube, which can subsequently be sealed from the apparatus. The now clear, colorless, freshly distilled C_6D_6 solution exhibits a ^{1}H NMR signal revealing two new $C_{12}H_{10}$ isomers: **3** (6,9-di-*int*-di-*trans*-[12]annulyne) and **4** (a cumulene structure with four additional *cis* double bonds) (Figure 1). The "impurity" signal at $\delta = 5.6$ ppm is greatly diminished as is the ratio [**3**]/[**4**] when the solution is distilled through a column warmed to 150 °C. These products are clearly kinetically controlled and ion association, in the intermediates, plays a role.

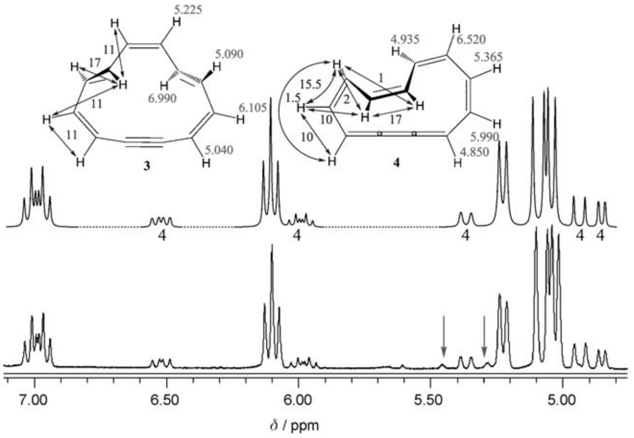


Figure 1. Lower: ^{1}H NMR spectrum (25 °C, 400 MHz) obtained from $KOC(CH_3)_3$ initiated condensation of hexadiyne in C_6D_6. Upper: Computer simulated spectra of the major species (**3**) and minor species (**4**) generated using the *J* splittings (arrows; in Hz) and chemical shifts (in ppm). The ratio [**3**]/[**4**] is 5. As the temperature is elevated up to 85 °C the only observable change in the spectrum is a slight increase in the ratio [**3**]/[**4**] and some decomposition. The arrows in the spectrum point out two small impurity resonances. Replacing C_6D_6 with [D$_{12}$]cyclohexane gives the same spectrum.

The internal protons of **3** appear at $\delta = 6.99$ ppm. This is close to the conventional aromatic region for benzenoid systems, which suggests some paratropicity. Downfield shifts were also observed for the internal protons of **1** and **2** at $\delta = 6.87$ and 6.63 ppm, respectively. The paratropic shifts are not as prominent in **4**, because the C–C bond angle strain prevents the approach to planarity.

The requirement that the larger three bond *J* couplings apply across a true double bond demands that compound **4** be

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in an all *cis* cumulene Kekulé structure (1,2,3,5,7,9,11-cyclododecaheptaene). Such a structure, that fits well to the NMR data, was indeed found using the B3LYP/6-31G* protocol.

To see if the compound with the highest solution electron affinity (presumably **3**) could be trapped as its corresponding radical anion and observed by EPR spectroscopy (as was [8]annulyne), dehydrated hexamethylphosphoramide (HMPA)[8a,b] was distilled into the C_6D_6 solution. Subsequently, the 50:50 HMPA/C_6D_6 solution was briefly exposed to a potassium metal mirror yielding a paramagnetic solution. In summary, treatment of 1,5-hexadiyne with $KOC(CH_3)_3$ in benzene followed by the addition of HMPA and reduction with potassium metal leads to an radical anion solution exhibiting a very strong, well resolved EPR signal due to the radical anion of biphenyl (Figure 2, upper panel). When the same experiment is carried out using [18]crown-6 in place of HMPA the biphenyl radical anion is not formed, but that of heptalene is (Figure 2, lower panel).

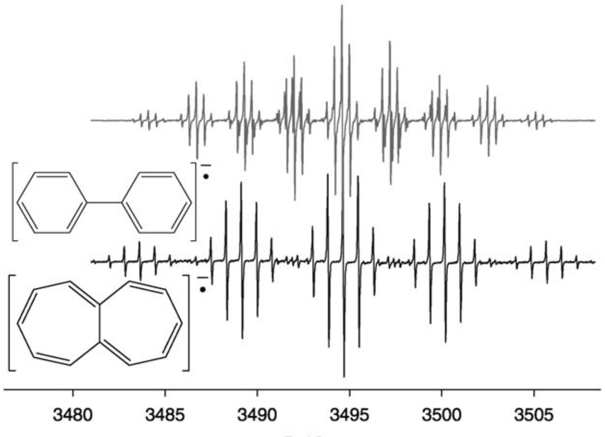


Figure 2. Upper: X-band EPR spectrum of the radical anion measured about 1 h after the one-electron reduction of the isomers of [12]annulyne that were produced by the $KOC(CH_3)_3$ initiated condensation of hexadiyne in benzene. This spectrum is due to the radical anion of biphenyl. Lower: X-band EPR spectrum of the radical anion measured after one-electron reduction of the isomers of [12]annulyne that were produced by $KOC(CH_3)_3$ initiated condensation of hexadiyne in THF. This spectrum is due to the radical anion of heptalene.

It was strongly anticipated that the one-electron reduction of the **3**+**4** mixture would initially lead to the formation of **3**$^{\bullet-}$, as **3** is much more planar than is **4**. However, once **3**$^{\bullet-}$ is formed electron transfer to **4** would lead to its radical anion, which could immediately rearrange to the radical anion of biphenyl. B3LYP/6-31+G* analysis of **4**$^{\bullet-}$ reveals non-classical π-p_y–π-p_z interactions which can readily evolve into σ bonds. Analogously, biaryl radical anions have been produced by one-electron reduction of tetraphenylmethane, triphenylamine, triphenylboron, triphenyl phosphine oxide, phenyl ethers, diphenylsilanes, trinapthyl borane, biarylureas, etc.[9]

In an attempt to actually observe the radical anion of **3** prior to biphenyl$^{\bullet-}$ formation, the reduction was carried out in the proximity of the EPR spectrometer with the sample immediately (within 1 min) placed into the cavity of the X-band spectrometer. Indeed, a radical anion intermediate was observed in the presence of biphenyl$^{\bullet-}$, but it is (surprisingly) not that of **3**. Further, it could be clearly seen that the concentration of this new radical anion (**5**$^{\bullet-}$) is decreasing during the course of the scan, while that of the biphenyl radical anion is growing at its expense.

Complete analysis of this new spectrum reveals that it is due to a system exhibiting ten individual electron–proton hyperfine interactions, indicating a $C_{12}H_{10}$ with C_1 symmetry. The validity of our measured a_H values (Figure 3) is illustrated in an expanded view of this spectrum (see inset of Figure 3).

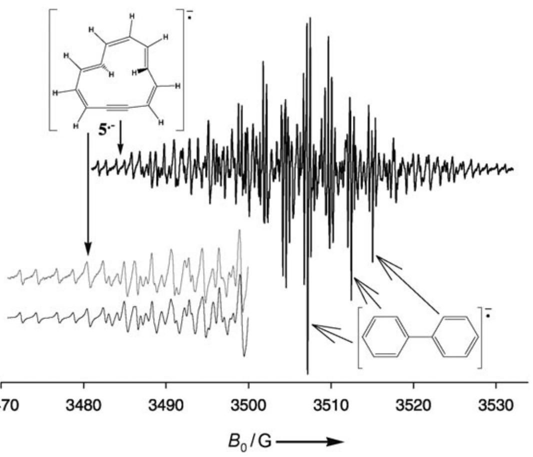
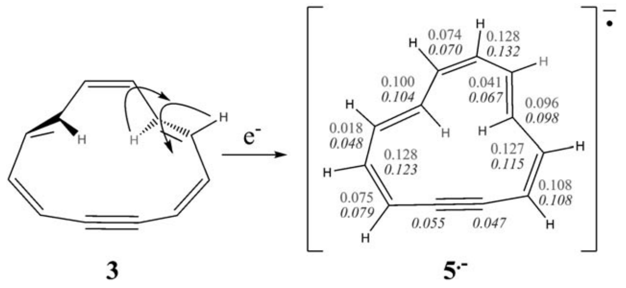


Figure 3. Upper: X-band EPR spectrum of the radical anions measured immediately after the one-electron reduction of the isomers of [12]annulyne that yielded the NMR spectrum shown in Figure 1. The simulation (lower panel) was generated using a 1:7 mixture of **5**$^{\bullet-}$ to biphenyl$^{\bullet-}$. Note that the concentration of the [12]annulyne anion radical is decreasing relative to that of the biphenyl during the EPR scan. Anion radical **5**$^{\bullet-}$ is clearly asymmetric, as ten different electron–proton couplings (each from a single proton) were used in the simulation: 0.98, 2.245, 4.085, 4.145, 5.37, 5.49, 5.95, 7.02, 7.04, and 7.06 G with a line width of 0.17 G. The first 16 G of the EPR spectrum and the computer generated simulation are shown in the upper and lower inset spectra, respectively.

We found a conformer of $C_{12}H_{10}$ that conforms to this set of EPR coupling constants (spin densities), which can be easily formed by the bond rotations illustrated in Scheme 2. The B3LYP/6-31+G* predicted carbon p_z spin densities for **5**$^{\bullet-}$ (shown in italics in Scheme 2) are in good agreement[7c] with the experimental spin densities (upright numbers in Scheme 2) obtained from the a_H values (Figure 3) and the McConnell relationship ($a_H = Q\rho$ with $Q = 55$ G).[3,7,10] The unsymmetric form of **5**$^{\bullet-}$ is predicted (B3LYP/6-31+G*) to be nearly planar because of the attenuated conflict between the internal protons. This fully conjugated system is the kinetically controlled reduction product, and it can be formed by the facile bond rotations indicated by arrows in Scheme 2. Electron transfer from **5**$^{\bullet-}$ ($\mathbf{5}^{\bullet-}+\mathbf{4} \rightleftharpoons \mathbf{5}+\mathbf{4}^{\bullet-}$) produces a finite concentration of **4**$^{\bullet-}$.

The Q value and spectral width (Figure 3) is unusually large suggesting an unusually efficient transfer of spin from the π to the σ system.[10] The proposed structure for **5**$^{\bullet-}$ is



Scheme 2. Reduction of 6,9-di-*int*-di-*trans*-[12]annulyne leads to the formation of the 5,9-di-*int*-di-*trans*-[12]annulyne anion radical, which can accommodate a much more planar morphology.

supportive of such an interaction, because C(1) is only 2.42 Å from the nearest internal proton. The p_y–1s overlap increases the efficiency of spin transfer from the π to the σ system.

Although DFT-predicted s orbital spin densities are not adequate for accurate coupling constant predictions, a comparison of the sum of all of the H atom 1s spin densities over a homologous series should lead to a general understanding of the efficiency of the π to σ spin transfer. A survey of the possible isomers of [12]annulyne reveals one with an extraordinarily large set of negative s orbital spin densities. The predicted total hydrogen spin density in **5**$^{\bullet-}$ is −0.0451 which is, indeed, an unusually large negative number. The same calculation yields predicted total hydrogen spin densities for **1**, **2**, and **3** that are all close to −0.022. In total there are, in principle, five possible unsymmetrical (needed to obtain ten non-equivalent electron–proton couplings) structures with one internal proton and 40 with two internal protons. Not all are stable, and only one (**5**$^{\bullet-}$) is predicted to have the spin density profile supporting the proposed structure for the observed radical anion.

Thus, it appears that one-electron reduction of the mixture in HMPA produces an anion system that has access (through electron transfer) to the all-*cis* cumulene conformation, **4**$^{\bullet-}$ (Figure 4). Once the radical anion in this conformation is formed, the system undergoes immediate transformation to the radical anion of biphenyl.

In stark contrast, when a THF/HMPA or THF containing [18]crown-6 solution of **1** and **2** is briefly exposed to a potassium metal mirror, the solution becomes dark purple and yields a strong well-resolved EPR signal due to, not biphenyl$^{\bullet-}$, but the radical anion of heptalene (Figure 2, lower panel). Further, no intermediate system could be observed, even when EPR analysis was carried out immediately. Also, when a THF containing [18]crown-6 solution of **3** and **4** is briefly exposed to a potassium metal mirror heptalene$^{\bullet-}$ is again formed. Keep in mind that HMPA effectively prevents ion association, and [18]crown-6 simply forms a host–guest complex with the cation leaving the crown–cation complex ion associated with the radical anion.[8c] In the presence of ion association **4**$^{\bullet-}$, which can rearrange to biphenyl$^{\bullet-}$, is not formed. Ion association inhibits electron transfer to **4** and promotes the formation of heptalene$^{\bullet-}$.

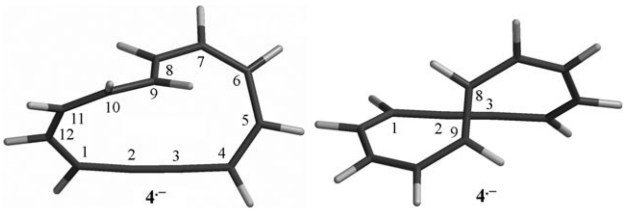
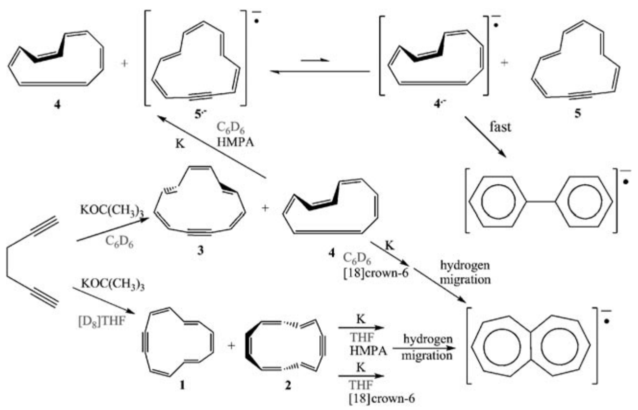


Figure 4. B3LYP/6-31+G* computed structures of **4**$^{\bullet-}$. In the radical anion of the all-*cis*-[12]cumannulene the p orbitals in the 2/9 and 3/8 positions could evolve into σ bonds while the central double bond in the cumulene moiety reduces to a single σ bond. The predicted distances C(2)–C(9) and C(3)–C(8) are both 3.08 Å. Actually the C(2)–C(8) and C(3)–C(9) distances are only 3.05 Å, but they are not arranged in mutual configurations for proper orbital overlap. Keep in mind that the transformation need not be concerted.

In solution, intramolecular reactions of [6]annulyne are practically non-existent,[4c] while those of its twelve carbon counterpart are vast. Based upon solvent choice, two different pairs of isomers come from the base condensation of hexadiyne, and, upon reduction (after HMPA addition), the distinct isomer pairs rearrange very differently: one to biphenyl$^{\bullet-}$ and one to heptalene$^{\bullet-}$ (Scheme 3). On the other hand, both pairs are reduced to form heptalene$^{\bullet-}$ when ion association is present. Perhaps the intermolecular chemistry of [12]annulyne will prove to be as practicable and interesting as that of [6]annulyne. Now that these four [12]annulynes are readily available, this can be investigated. We are still in the process of unraveling the mechanistic details of the strong solvent effect, but to borrow a recent quote from Whitesides: "It is a poor decision to regard chemistry as the conversion of reactants to products rather than the conversion of reactants and solvent to products."[11] This is certainly true in the case of the [12]annulyne system and probably in many other, yet to be observed, annulyne systems. The small resonances between $\delta = 5.6$ and 5.7 ppm in Figure 1 are apparently due to heptalene; this is also a topic of current investigation.



Scheme 3. Base condensation of hexadiyne and reduction of the products leads to different radical anion systems, depending on the solvent system.

Experimental Section

Preparation of NMR samples: A break tube with fragile ends containing 120 μL of 1,5-hexadiyne (50% in pentanes) was added to tube A in Figure 5. Next 112 mg of potassium *tert*-butoxide was also added to tube A. Then, a vacuum was applied to the system, and approximately 1 mL of perdeuterated benzene or perdeuterated cyclohexane, which was stored in an evacuated bulb containing "NaK_2", was distilled onto the potassium *tert*-butoxide. The apparatus was then sealed from the vacuum system at B, while the benzene solution was kept frozen in liquid nitrogen. The apparatus was brought to ambient temperature and vigorously shaken so as to break the tube containing the 1,5-hexadiyne. After a period of about 1 h, the U tube was immersed in a hot oil bath (150 °C), and the attached NMR tube was immersed in ice water. This caused the solvent and reaction mixture to cleanly distill into the NMR tube, which could then be sealed from the apparatus and submitted to NMR analysis (see Figure 1). Some heptalene appears to be formed during the reaction. Neutral heptalene is unstable at elevated temperatures, and the warm U tube diminishes the resonance from the (what we believe to be) heptalene.

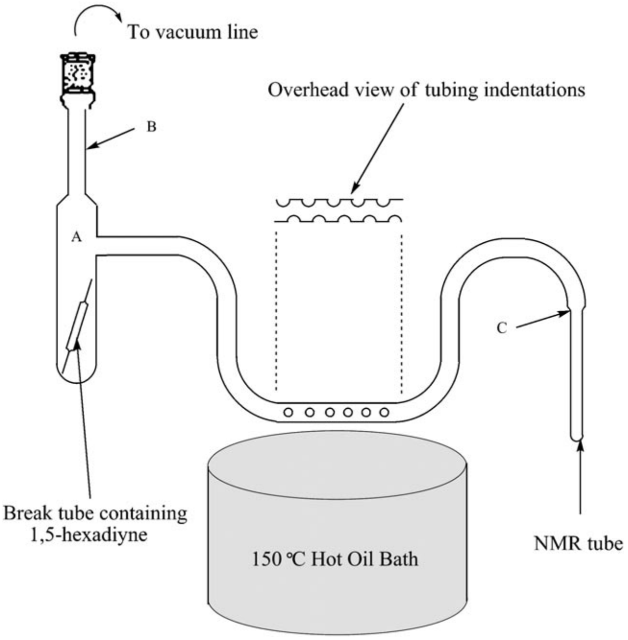


Figure 5. Apparatus used for the generation of the [12]annulynes.

Preparation of EPR samples: A glass tube with fragile ends containing 120 μL (0.39 mmol) of 1,5-hexadiyne (50 % in pentanes) was carefully placed into tube A (Figure 6) along with 50 mg (0.45 mmol) of potassium *tert*-butoxide. Then approximately 2 g of potassium metal was added to test tube D, and the apparatus was sealed at point E. The apparatus was then evacuated, and the potassium metal was distilled to create a mirror in tube C. Tube D was sealed from the apparatus at point I. Approximately 1 mL of benzene (C_6D_6) was then distilled from an evacuated bulb containing "NaK_2" into tube A, and the apparatus was sealed from the vacuum system at point F. The apparatus was then vigorously shaken, at ambient temperature, to rupture the tube containing the 1,5-hexadiyne. This resulted in a thick tan colored solution, which was distilled directly into cooled tube B. Tube A was then sealed from the apparatus at point G. The apparatus was then reconnected to the vacuum system and the break seal was ruptured. This allowed the distillation of approximately 1 mL of dehydrated hexamethylphosphoramide (HMPA) into tube B. The apparatus was then sealed from the vacuum system at point H. The apparatus was then tilted to allow the solution to come into contact with the potassium mirror resulting in the reduction of the [12]annulynes. The EPR tube could then be filled with the reduced mixture and submitted to X-band EPR analysis. When the spectrum is recorded immediately, that shown in Figure 3 is obtained. However, if there is a delay, only the EPR spectrum of the biphenyl radical anion can be observed (see Figure 2, upper panel). If THF instead of benzene is distilled into tube A, the only EPR spectrum that can be observed is that due to the radical anion of heptalene (lower spectrum in Figure 2).

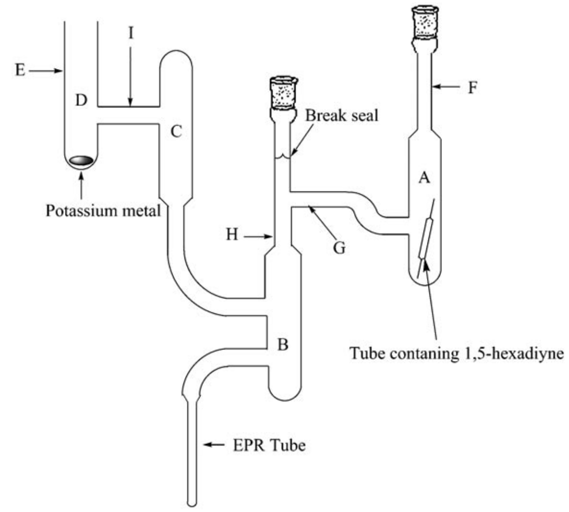


Figure 6. Apparatus used for the generation of the [12]annulynes and their subsequent one-electron reduction. When THF serves as the primary solvent, the radical anion observed upon EPR analysis is that of heptalene. However, when benzene serves as the primary solvent, EPR analysis reveals only the radical anion of biphenyl (see Figure 2).

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