Synthesis of 1,6-Didehydro[10]annulene. Observation of Its Exceptionally Facile Rearrangement To Form the Biradical 1,5-Dehydronaphthalene

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Contribution No. 8745, Arnold and Mabel Beckman
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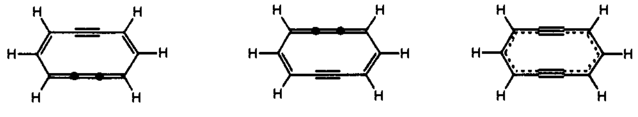
Received October 14, 1992

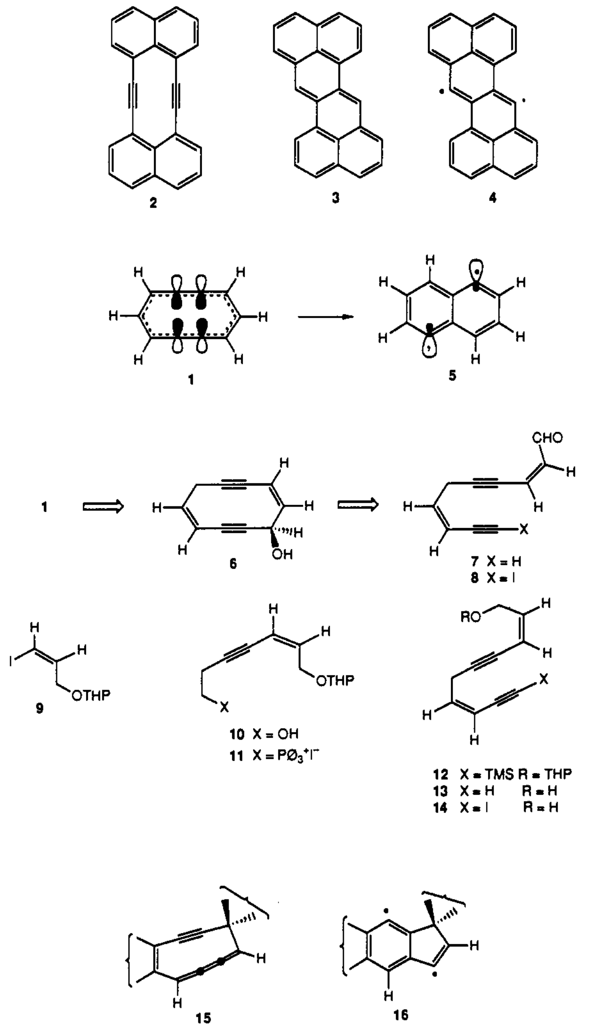
1,6-Didehydro[10]annulene (**1**) has been recognized as an intriguing organic molecule for more than 40 years.[1] Notwithstanding its structural simplicity and nominal aromaticity, neither the parent hydrocarbon nor any derivative of this $C_{10}H_6$ isomer has been prepared to date, although several laboratories have described efforts toward this end.[2,3] Notable among these are the contributions of Sondheimer et al.[2a,c,e] and Staab et al.[2b,f] directed toward the synthesis of the hydrocarbon **2**. Though the latter molecule does not formally represent a derivative of **1**, it is nevertheless of considerable interest in the present context that all attempts to produce this substance led not to **2**, but instead to the hydrocarbon zethrene (**3**), a result which led the Sondheimer and Staab groups to invoke explicitly the biradical **4** via the proposed intermediate **2**.[2e,f] In retrospect, this hypothesis presages much of the biradical-forming cycloaromatization chemistry to follow in later years,[4] although it should be noted that the putative hydrocarbon **2** was never observed and that the conditions of these experiments (copper salts, pyridine reflux) allow for alternative interpretations of the data. We were drawn to consider the hydrocarbon **1** in light of its potential thermal conversion to the biradical 1,5-dehydronaphthalene (**5**), a reactive intermediate of considerable interest in its own right.[5] In this communication we describe the first preparation of **1** and document its exceptionally facile conversion to 1,5-dehydronaphthalene (**5**) (Chart I).

Acetylenic alcohol **6** was chosen as the immediate synthetic precursor to **1** in view of the presumed facility of both the dehydration reaction that would transform **6** to **1** and the intramolecular acetylide–aldehyde addition reaction of substrate **7**, envisioned to provide **6**. However, all attempts to cyclize **7** via a metal acetylide intermediate met with failure, a result attributed to the extreme base sensitivity of **7** and, as later discovered, of **6** as well. Chromium(II)-mediated reaction of the iodo aldehyde **8**, in contrast, proved to be an effective closure method;[6] the iodo aldehyde cyclization precursor was synthesized as follows. (*Z*)-Vinyl iodide **9**[7] was coupled with 3-butyn-1-ol in tetrahydrofuran (THF) at 23 °C (($(Ph_3P)_2PdCl_2$, CuI, Et_3N) to afford the (*Z*)-enyne **10** in 79% yield.[8] Transformation of **10** to the corresponding mesylate,[9] the resultant mesylate to the iodide (LiI, THF, 55 °C), and finally the iodide to the phosphonium salt **11** (1.0 equiv of triphenylphosphine, acetonitrile, 80 °C) proceeded smoothly in 68% yield. Wittig reaction of the ylide derived from **11** (1 equiv of *n*-butyllithium) with (trimethylsilyl)propionaldehyde (1.02 equiv) in THF at −78 °C provided the bis-enyne **12** (71%) as a 4.3:1 mixture of *Z* and *E* isomers at the newly-formed olefinic bond, respectively. Sequential deprotection of functional groups

Chart I



Representations of 1,6-Didehydro[10]annulene (**1**)



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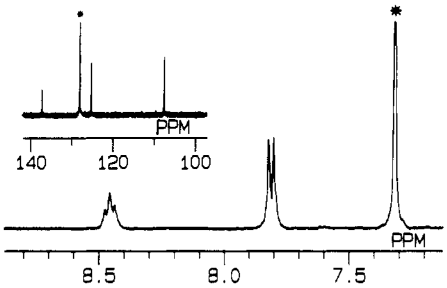

Figure 1. ^{1}H NMR spectrum of **1** (2:1 THF-d_8/CD_2Cl_2, −75 °C, 400 MHz): δ 8.45 (t, 2 H, J = 8.3 Hz, H5 and H10), 7.81 (d, 4 H, J = 8.3 Hz, H1, H4, H6, H9). Inset: ^{13}C NMR spectrum of **1** (CD_2Cl_2, −90 °C, ^{1}H-decoupled, 100 MHz): δ 137.1 (2 C, C5, and C10), 125.1 (4 C, C2, C3, C7, and C8), 107.5 (4 C, C1, C4, C6, and C9). Assignments verified by selective ^{1}H-decoupled ^{13}C NMR.

within **12** (trichloroacetic acid, acetonitrile–water, 23 °C, THPO → HO, 88%; triethylamine trihydrofluoride, methanol, 55 °C, TMSC≡C → HC≡C, 97%) then afforded **13**. Iodination of **13** to form **14** was readily achieved by the method of Hofmeister et al. employing *N*-iodosuccinimide (1.02 equiv) and silver nitrate (0.1 equiv) in acetone (0–23 °C, 81%).[10] Oxidation of **14** with the Dess–Martin periodinane (2.5 equiv, dichloromethane, 23 °C) provided the iodo aldehyde **8** in 85% yield.[11] Treatment of a dilute solution of **8** in rigorously deoxygenated THF at 0 °C with chromium(II) chloride (2,5 equiv) doped with nickel(II) chloride (0,01%) for 3 h afforded the cyclization product **6** in 40% yield after purification by flash column chromatography.[6] Due to the extreme sensitivity of **6** toward adventitious decomposition when neat, this product was typically handled in solution in the presence of a free radical inhibitor.

Initial studies designed to transform **6** to **1** via the corresponding mesylate[9] established that **1** has no appreciable lifetime above −40 °C. For example, treatment of **6** with methanesulfonic anhydride and triethylamine in deoxygenated THF-d_8 at −40 °C led to slow disappearance of the starting material with concomitant formation of 1,5-dideuterionaphthalene (^{1}H NMR analysis, $t_{1/2} \approx 1.5$ h); signals attributable to the presumed intermediate mesylate or to **1** were not observed, leading to the conclusion that mesylate formation is rate-determining and that cyclization of **1** to the biradical **5** is rapid at −40 °C. By contrast, variable-temperature NMR analysis of the reaction of **6** with trifluoromethanesulfonic anhydride and triethylamine at −90 °C showed clean and rapid conversion of **6** to a product assigned as **1**. ^{1}H and ^{13}C NMR data (Figure 1) are consistent with static or time-averaged D_{2h} symmetry for **1** at −90 °C. The proton-decoupled ^{13}C NMR spectrum consists of three singlets whose chemical shifts are approximated by averaging the anticipated chemical shifts for corresponding carbons in the two canonical resonance structures. The ^{1}H NMR chemical shifts show clear evidence of a diamagnetic ring current, supporting the notion that **1** is an "aromatic" compound (Figure 1). Samples of **1** were stable for extended periods at −90 °C but at higher temperatures cyclized readily to form naphthalene (50–85% yield, varying with the medium). In deuterated solvents, incorporation of deuterium was evident at the 1 and 5 positions of naphthalene. The kinetics for the cyclization reaction was determined in CD_2Cl_2 in the presence of 1,4-cyclohexadiene (0,6 M) and found to be first-order ($k = (4.6 \pm 0.9) \times 10^{-4}\ s^{-1}$, $\Delta G^* = 16.3 \pm 0.1$ kcal/mol, −51 ± 1 °C, 85% yield of naphthalene). Thus, the half-life for cyclization of **1** at −51 °C is ~25 min, making this the most rapid biradical-forming cycloaromatization yet reported. The next most rapid cyclization of which we are aware is that of the neocarzinostatin cumulene intermediate (**15** → **16**, $t_{1/2} \approx 2$ h at −38 °C, $\Delta G^* = 18.0 \pm 0.1$ kcal/mol).[4d-f] With the assumption that both processes have negligible entropies of activation, the free energies of activation may be compared directly, leading to a 1.7 kcal/mol lower barrier for cyclization of **1** versus **15**. This is an interesting and unexpected outcome because it would appear that **15** is the more strained molecule. It should be pointed out that the exceedingly facile cyclization of **1** to **5** does not argue against the aromatic stabilization of the former. The stability usually associated with an aromatic compound relates to a reaction pathway in which aromaticity is invariably lost in transition; in the case of **1**, aromaticity is not disrupted in the transformation to **5**.

In conclusion, it seems both reasonable and useful to classify the biradical-forming cycloaromatization reactions into two categories: those involving cycloaromatization to form a biradical syn about the newly-formed σ bond, of which the Bergman reaction[4a-c] may be considered prototypical, and those involving cycloaromatization to form a biradical anti about the newly-formed σ bond,[2e,f,4d-i] perhaps now best illustrated by the transformation of **1** to **5**. Though rigorous comparisons are not possible, it would appear that the latter class of cyclization is generally a more facile reaction. On the basis of ab initio calculations it has been suggested that this effect has its origin in the differences in in-plane π–π repulsion in the two systems, this being exacerbated in the former class and diminished in the latter.[12] Finally, with regard to the enediyne antibiotics, it will clearly be of interest to design a molecule which will undergo a transformation analogous to **1** → **5** after an appropriate "chemical activation" step; perhaps such a molecule already exists in nature.

Acknowledgment. Generous financial assistance from the David and Lucile Packard Foundation, Pfizer Inc., and American Cyanamid Company is gratefully acknowledged.

Supplementary Material Available: Listings of IR and ^{1}H and ^{13}C NMR spectral data for **6** and synthetic precursors to **6** (4 pages). Ordering information is given on any current masthead page.

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High-Intensity, Argon Ion Laser-Jet Photochemistry. Reactions between Transient Species: The Addition of Diphenylcarbene to the Photoenol of 2-Methylbenzophenone

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Received June 15, 1992

In principle, reactions between short-lived photochemical transients, transient–transient reactions, offer many possibilities for novel chemistry. Transient–transient reactions between identical species, such as radical coupling, are well-known, and while their efficiencies are enhanced at higher light intensities, they can frequently be observed at lower light levels in the absence of competing processes.[1] In contrast, very few examples of

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