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Reductive Bergman-Type Cyclizations of Cross-Conjugated Enediynes to Fulvene and Fulvalene Anions: The Role of the Substituent

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Abstract: Various cross-conjugated enediynes undergo "Bergman-type" cycloaromatizations upon reduction with potassium metal, generating anions of fulvenes and fulvalene derivatives. This new anionic cyclization is considerably more facile than the classic Bergman cyclization with linear enediynes, creating highly reactive diradicals at −78 °C. Not all cross-conjugated enediynes yield cyclized dianions upon reduction; some give uncyclized, Y-shaped, cross-conjugated dianions, while others apparently yield radical−anions that either dimerize or persist as monomers. One system yields both a cyclized and an uncyclized dianion. The substituents are thus shown to be a critical factor in determining the outcome of the reduction. Cyclization occurs within a specific "window of opportunity" that is governed by the substituents.

Introduction

Recent years have witnessed a considerable surge in the study of enediyne cyclizations. Many reactions, such as the Bergman,[1] Myers−Saito,[2] Schmittel[3] and Schreiner[4] cyclizations bring about aromatic biradicals, with applications in pharmacology, as these biradicals or their byproducts[5] cause DNA cleavage, ultimately destroying the DNA of viruses and bacteria. The antitumor antibiotic drugs calicheamicin γ_1,[6] dynemicin,[7] and esperamicin A_1[6c−e,8] all become active *p*-benzyne biradical intermediates due to Bergman cyclizations, while a Myers−Saito cyclization is the key step in the mechanism of action of the antitumor agent neocarzinostatin.[9]

Additionally, enediynes serve as precursors for bowl-shaped fullerene fragments[10] and as building blocks of dendritic rods and molecular wires,[11] conjugated polymers,[11,12] carbon allotropes,[12] and radialenes.[13] Linear enediynes (**1**), containing a 1,2-diethynylethylene moiety with six π-electrons, undergo standard Bergman cycloaromatizations (Scheme 1a). Indeed, this is the

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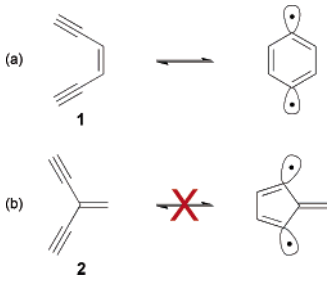
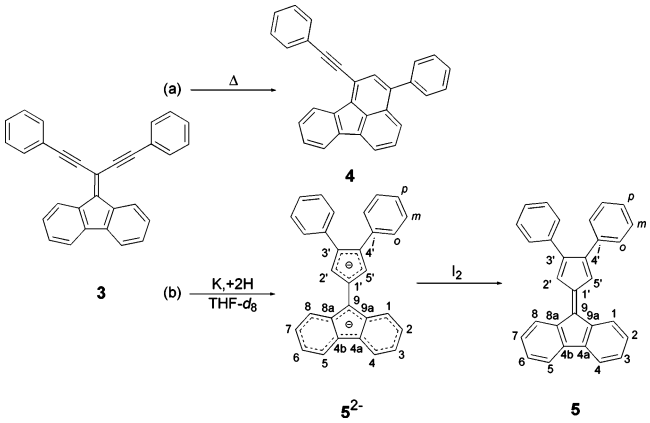
Scheme 1. (a) Standard Bergman Cyclization Observed for a Six π-Electron Linear Enediyne and (b) Not Observed for a Six π-Electron Cross-Conjugated Enediyne



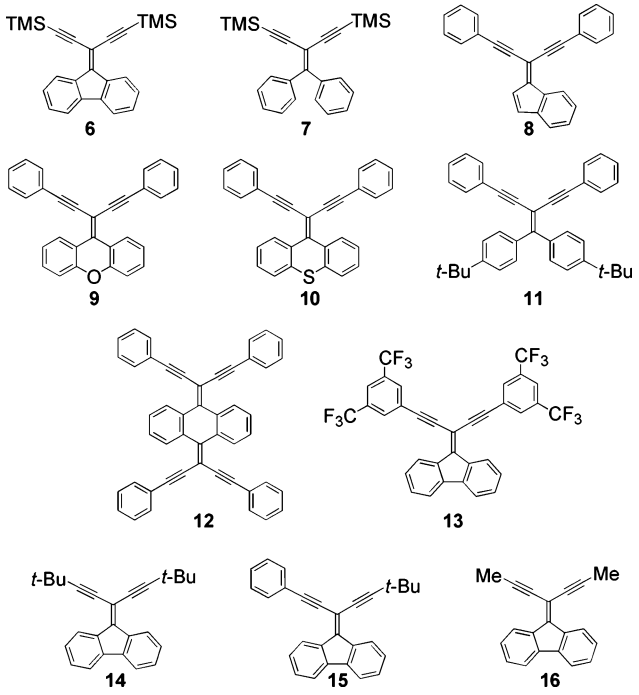
Scheme 2. Cyclizations of **3** under (route a) Thermal Conditions, Resulting in **4**, and (route b) Reductive Conditions, Resulting in 5^{2-}



critical step in forming the benzene biradical that triggers DNA cleavage. The related cycloisomerizations of linear 1,3-dien-5-ynes, forming aromatic six-membered rings, were first reported by Hopf and Musso.[14] The utilization of this reaction for synthesis took a massive leap in the 1990s, and today, these cycloaromatizations are frequently exploited in syntheses of new bowl-shaped PAHs and buckybowls mapping onto fullerene surfaces.[15,16] Cross-conjugated enediynes[17] (Y-enediynes, **2**), however, contain only five π electrons in the longest line of p-orbitals, insufficient for aromatization, and therefore cannot follow this route (Scheme 1b). Under irradiation, however, cyclization has been observed for a triaryl Y-enediyne.[17]

Under thermal conditions, **3** undergoes a "Hopf cyclization"[16] to yield **4** (Scheme 2, route a).[18] However, an anionic cyclization of **3** was recently achieved for the first time, and the resulting product was shown to be entirely different.[19] Reduction by alkali metals results in a new five-membered ring containing *six* π-electrons via a "Bergman-type" cyclization, yielding the dianion $\mathbf{5}^{2-}$. Oxidation with iodine generates the unstable[20] fulvalene **5** (Scheme 2, route b).

Scheme 3. Systems Under Investigation in This Research



While other cyclizations yielding five-membered rings have been previously investigated,[21−23] until now, the closure of **3** to **5** has been the only such anionic "Bergman-type" cyclization observed. The scope and limitations of this transformation, therefore, are not known. We have now found new systems that undergo such a cycloaromatization, thereby demonstrating that the example in route b of Scheme 2 is not a unique occurrence but rather a novel reaction of acetylenes leading to anions of fulvenes, fulvalenes, and even heterocycles.

Methodology.

To determine whether the anionic "Bergman-type" cyclization is a reaction unique to **3**, we reduced 11 more cross-conjugated enediynes, namely, **6**−**16** (Scheme 3). The objective was to examine the reduction of cross-conjugated enediynes differing in size, geometry, π-electron structure, and aromaticity, as well as to probe the ability of heteroatoms and substituents to alter inductive effects. The ultimate goal was to outline which structural features, if any, have a significant effect on this cyclization.

Experimental Section

NMR experiments were carried out using a Bruker DRX-400 spectrometer equipped with a BGUII *z*-gradient, operating at 400.13 and 100.62 MHz for ^{1}H and ^{13}C, respectively. All samples were dissolved in THF-d_8, and the reported chemical shifts were calibrated to the downfield THF signal (δ_H 3.575, δ_C 67.393). Full NMR assignment, obtained by applying standard 1D- and 2D-NMR techniques

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such as COSY, NOESY, HSQCSI, and HMBC, confirmed or refuted the cyclization of the various compounds.

High-resolution mass spectra (DCI in methane) were recorded at 60−70 eV on a VG-Fisons Autospec mass spectrometer.

Monitored Reduction of Samples.

Reduction of **6**−**16** with potassium metal mirrors was carried out under inert conditions at 195 K in NMR tubes with appropriate extensions.[24] After some contact with the alkali metal, the spectra of the neutral species broaden, due to radical−anion formation. Additional contact with the metal yields complex NMR spectra. Further reduction eventually[25] yields a straightforward NMR spectrum of a single species.[26] Full assignments of these species were attained using 1D- and 2D-NMR as mentioned above.

NMR Spectroscopy Data For the Dianions. 6^{2-}: dark olive green solution; δ_H (THF-d_8, 220 K) 7.89 (H-4/5, d, ^3J = 7.7 Hz, 2H), 7.71 (H-1/8, d, ^3J = 8.2 Hz, 2H), 6.83 (H-2/7, dd, $^3J_1$ = 7.4 Hz, $^3J_2$ = 7.1 Hz, 2H), 6.83 (H-3/6, dd, $^3J_1$ = $^3J_2$ = 7.0 Hz, 2H), 0.10 (H-TMS, s, 18H) ppm; δ_C (THF-d_8, 220 K) 132.7 (C-8a/9a), 130.2 (C-2′/5′), 123.0 (C-4a/4b), 119.2 (C-2/7), 119.1 (C-4/5), 115.9 (C-1/8), 108.2 (C-3/6), 91.4 (C-3′/4′), 88.9 (C-9), 36.0 (C-1′), 2.5 (C-TMS) ppm.

7^{2-}: deep red-purple solution; δ_H (THF-d_8, 180 K) 7.68 (H-5/6, d, ^3J = 9.1 Hz, 2H), 6.63 (H-2/9, dd, $^3J_1$ = $^3J_2$ = 7.6 Hz, 2H), 6.34 (H-4/7, dd, $^3J_1$ = $^3J_2$ = 7.1 Hz, 2H), 6.31 (H-1/10, d, ^3J = 9.1 Hz, 2H), 5.57 (H-3/8, dd, $^3J_1$ = $^3J_2$ = 6.5 Hz, 2H), −0.01 (H-TMS, s, 18H) ppm; δ_C (THF-d_8, 180 K) 140.7 (C-5a/5c), 131.1 (C-2′/5′), 128.0 (C-2/9), 126.6 (C-4/7), 119.9 (C-1/10), 116.4 (C-5/6), 106.8 (C-3/8), 93.1 (C-3′/4′), 78.1 (C-5b), 38.9 (C-1′), 1.6 (C-TMS) ppm.

Cyclized dianion of 8: golden-brown solution with lithium, blue-gray solution with sodium, and purple-red solution with potassium; δ_H (THF-d_8, 220 K) 7.86 (H-4, d, ^3J = 7.8 Hz, 1H), 7.39 (H-*o*, d, ^3J = 7.3 Hz, 4H), 7.21 (H-1, d, ^3J = 7.8 Hz, 1H), 7.00 (H-*m*, dd, $^3J_1$ = $^3J_2$ = 7.3 Hz, 4H), 6.74 (H-6, d, ^3J = 2.9 Hz, 1H), 6.72 (H-*p*, t, ^3J = 7.3 Hz, 2H), 6.39 (H-3, dd, $^3J_1$ = 7.8 Hz, $^3J_2$ = 6.9 Hz, 1H), 6.34 (H-2′/5′, s, 2H), 6.30 (H-2, dd, $^3J_1$ = 7.8 Hz, $^3J_2$ = 6.9 Hz, 1H), 5.83 (H-5, d, ^3J = 2.9 Hz, 1H) ppm; δ_C (THF-d_8, 220 K) 143.1 (C-*i*), 130.1 (C-6b), 126.9 (C-*o*), 126.8 (C-*m*), 124.7 (C-4a), 120.2 (C-*p*), 118.6 (C-4), 118.4 (C-1), 116.3 (C-3′/4′), 111.8 (C-6), 111.7 (C-3), 111.5 (C-2), 106.8 (C-6a), 104.3 (C-2′/5′), 103.8 (C-1′), 89.9 (C-5) ppm.

Cyclized dianion of 9: brown solution; δ_H (THF-d_8, 260 K) 7.26 (H-*o*, d, ^3J = 7.6 Hz, 4H), 6.92 (H-*m*, dd, $^3J_1$ = $^3J_2$ = 7.6 Hz, 4H), 6.63 (H-*p*, t, ^3J = 7.6 Hz, 2H), 6.34 (H-1/8, d, ^3J = 7.1 Hz, 2H), 5.93 (H-2′/5′, s, 2H), 5.79 (H-2/7, dd, $^3J_1$ = $^3J_2$ = 7.1 Hz, 2H), 5.22 (H-4/5, d, ^3J = 7.1 Hz, 2H), 5.16 (H-3/6, dd, $^3J_1$ = $^3J_2$ = 7.1 Hz, 2H) ppm; δ_C (THF-d_8, 260 K) 151.9 (C-4a/4b), 143.5 (C-*i*), 137.3 (C-8a/9a), 126.8 (C-*m*), 126.6 (C-*o*), 124.0 (C-2/7), 121.6 (C-1′), 119.6 (C-9), 119.5 (C-*p*), 116.9 (C-3′/4′), 109.8 (C-2′/5′), 109.5 (C-4/5), 108.5 (C-3/6), 106.9 (C-1/8) ppm.

Cyclized dianion of 11: dark reddish-brown solution; δ_H (THF-d_8, 250 K) 7.39 (H-1/4/5/8, d, ^3J = 9.0 Hz, 4H), 7.20 (H-*o*, d, ^3J = 7.5 Hz, 4H), 6.85 (H-*m*, dd, $^3J_1$ = 7.6 Hz, $^3J_2$= 7.5 Hz, 4H), 6.54 (H-2/3/6/7, d, ^3J = 9.0 Hz, 4H), 6.54 (H-*p*, t, ^3J = 7.6 Hz, 2H), 6.04 (H-2′/5′, s, 2H), 1.15 (H-Me, s, 18H) ppm; δ_C (THF-d_8, 250 K) 144.0 (C-*i*), 143.9 (C-4a/4c), 129.4 (C-2a/6a), 126.6 (C-*m*), 126.2 (C-*o*), 124.3 (C-2/3/6/7), 124.2 (C-1′), 118.6 (C-*p*), 118.4 (C-1/4/5/8), 117.5 (C-3′/4′), 108.0 (C-2′/5′), 32.9 (C-*t*-Bu), 32.1 (C-4b), 31.2 (C-Me) ppm.

14^{2-}: dark green-light brown solution; δ_H (THF-d_8, 220 K) 7.88 (H-4/5, d, ^3J = 7.6 Hz, 2H), 7.77 (H-1/8, d, ^3J = 8.1 Hz, 2H), 6.80 (H-2/7, t, $^3J_1$ = $^3J_2$ = 7.4 Hz, 2H), 6.34 (H-3/6, dd, $^3J_1$ = $^3J_2$= 7.1 Hz, 2H), 1.24 (H-Me, s, 18H) ppm; δ_C (THF-d_8, 220 K) 131.8 (C-8a/9a), 121.4 (C-4a/4b), 118.0 (C-4/5), 117.7 (C-1/8), 115.1 (C-2/7), 106.6 (C-9), 106.5 (C-3/6), 96.2 (C-3′/4′), 95.5 (C-2′/5′), 94.5 (C-1′), 33.1 (C-Me), 30.5 (C-*t*-Bu) ppm.

15^{2-}: dark brown-red solution; δ_H (THF-d_8, 220 K) 8.36 (H-8, d, ^3J = 8.1 Hz, 1H), 8.14 (H-1, d, ^3J = 8.1 Hz, 1H), 8.12 (H-5, d, ^3J = 8.1 Hz, 1H), 7.99 (H-4, d, ^3J = 7.6 Hz, 1H), 7.16 (H-7, dd, $^3J_1$ = 8.1 Hz, $^3J_2$ = 7.6 Hz, 1H), 7.02 (H-2, dd, $^3J_1$ = 8.1 Hz, $^3J_2$ = 7.6 Hz, 1H), 6.52−6.58 (H-3, m, 1H), 6.50−6.56 (H-6, m, 1H), 6.21 (H-*o*, d, ^3J = 8.1 Hz, 1H), 5.95 (H-*m*′, dd, $^3J_1$ = 8.1 Hz, $^3J_2$ = 7.1 Hz, 1H), 5.85 (H-*m*, dd, $^3J_1$ = 8.1 Hz, $^3J_2$ = 7.1 Hz, 1H), 1H), 5.27 (H-*o*′, d, ^3J = 8.1 Hz, 1H), 4.65 (H-*p*, t, $^3J_1$ = $^3J_2$ = 7.1 Hz, 1H), 1.31 (H-Me, s, 9H) ppm; δ_C (THF-d_8, 220 K) 138.5 (C-*i*), 135.4 (C-9a), 132.3 (C-9), 131.2 (C-8a), 129.4 (C-*m*), 129.2 (C-*m*′), 120.3 (C-4b), 119.9 (C-4a), 119.1 (C-7), 118.8 (C-5), 118.6 (C-2), 118.2 (C-1), 118.1 (C-4), 117.4 (C-3′), 114.3 (C-8), 113.0 (C-*o*′), 109.0 (C-3), 108.4 (C-*o*), 107.3 (C-4′), 107.1 (C-6), 103.6 (C-2′), 101.5 (C-5′), 97.5 (C-*p*), 95.5 (C-1′), 34.7 (C-*t*-Bu), 33.9 (C-Me) ppm.

Cyclized dianion of 15: dark brown-red solution; δ_H (THF-d_8, 220 K) 7.98 (H-1/8, d, ^3J = 7.6 Hz, 2H), 7.94 (H-4/5, d, ^3J = 7.6 Hz, 2H), 7.52 (H-*o*, d, ^3J = 7.6 Hz, 2H), 7.11 (H-*m*, t, $^3J_1$ = $^3J_2$ = 7.6 Hz, 2H), 6.83−6.88 (H-2/7, m, 2H), 6.82 (H-*p*, t, ^3J = 7.6 Hz, 1H), 6.39 (H-3/6, t, $^3J_1$ = $^3J_2$ = 7.6 Hz, 2H), 6.32 (H-5′, s, 1H), 6.17 (H-2′, s, 1H), 1.48 (H-Me, s, 3H) ppm; δ_C (THF-d_8, 220 K) 147.0 (C-*i*), 129.1 (C-8a/9a), 129.0 (C-*o*), 126.3 (C-*m*), 125.7 (C-3′), 121.9 (C-1′), 120.2 (C-*p*), 120.2 (C-4′), 119.4 (C-4a/4b), 118.5 (C-2/7), 118.1 (C-4/5), 114.4 (C-1/8), 106.9 (C-3/6), 105.3 (C-2′), 102.4 (C-5′), 96.5 (C-9), 33.6 (C-Me), 32.9 (C-*t*-Bu) ppm.

Results and Discussion

Reductions with potassium of the unsymmetrical indenyl derivative **8**, the heterocyclic **9**,[27] the di-*tert*-butyl derivative **11**, and the unsymmetrical **15** all gave rise to NMR patterns indicative of cyclizations similar to that of **5**$^{2-}$. Figure 1 shows the unmistakable difference in the NMR patterns for the dianions formed from **9** and **11**, which undergo the cyclization, compared to that of **6**, which does not.

Key features common to the spectra of dianions formed from **9**, **11**, and all other compounds that underwent cyclization include (a) elimination of the relatively large difference in NMR shifts for protons analogous to H-1 and H-4 in **3** (due to loss of anisotropic effect of the acetylene groups), (b) formation of a relatively upfield[28] singlet in the ^{1}H NMR spectra, and (c) loss of sp-hybridized carbon signals in the ^{13}C NMR spectra. Conversely, the reduced species **6**$^{2-}$, **7**$^{2-}$, and **14**$^{2-}$ still show sp-hybridized carbon signals (slightly shifted upfield) in their ^{13}C NMR spectra, show no singlet in their ^{1}H NMR spectra, and retain the difference for protons analogous to H-1 and H-4 in **3**.[29] Quenching of **6**$^{2-}$, **7**$^{2-}$, and **14**$^{2-}$ with oxygen gives the corresponding neutral starting material in practically quantitative yield.[30] The symmetrical anthracene derivative **12**, the bis[bis-(trifluoromethyl)] derivative **13**, and the "simple" dimethyl derivative **16**, differing from **3** by the two phenyl units, all appear to form stable radical−anions.[31]

Quenching of the cyclization products of **8**, **9**, **11**, and **15** with iodine[32] gave brown oils in very low yield, as demonstrated

(24) Samples of **6**−**16** contained 3−15 mg in ca. 0.7 mL of THF-d_8 to yield 1.09−12.94 mM solutions. An account of the monitored reduction technique can be found: Treitel, N.; Deichmann, M.; Sternfeld, T.; Sheradsky, T.; Herges, R.; Rabinovitz, M. *Angew. Chem., Int. Ed.* **2003**, *42*, 1172. Potassium metal mirrors vacuum distilled into the tube were used instead of lithium wires.

(25) For several compounds, the reduction to a new diamagnetic species took only 2−3 days. For others, it took as long as several weeks.

(26) While this is the general case, diyne **15** yields a mixture of two species. See the text.

(27) The heterocycle **10** appears to undergo this cyclization as well. However, the dianionic cyclized state is much more elusive than that of **9**, making this conclusion somewhat equivocal.

(28) Compared to the resonances for the protons of the aromatic unit receiving the other electron upon reduction. See the text.

(29) Some compounds of this type undergo dimerization via position 1′. This is also in good agreement with their chemical shifts and patterns. See the text and (a) Schlenk, W.; Bergmann, E. *Liebigs Ann. Chem.* **1928**, *463*, 1. (b) Schlenk, W.; Bergmann, E. *Liebigs Ann. Chem.* **1930**, *479*, 40.

(30) In the case of **14**$^{2-}$, the yield was lower.

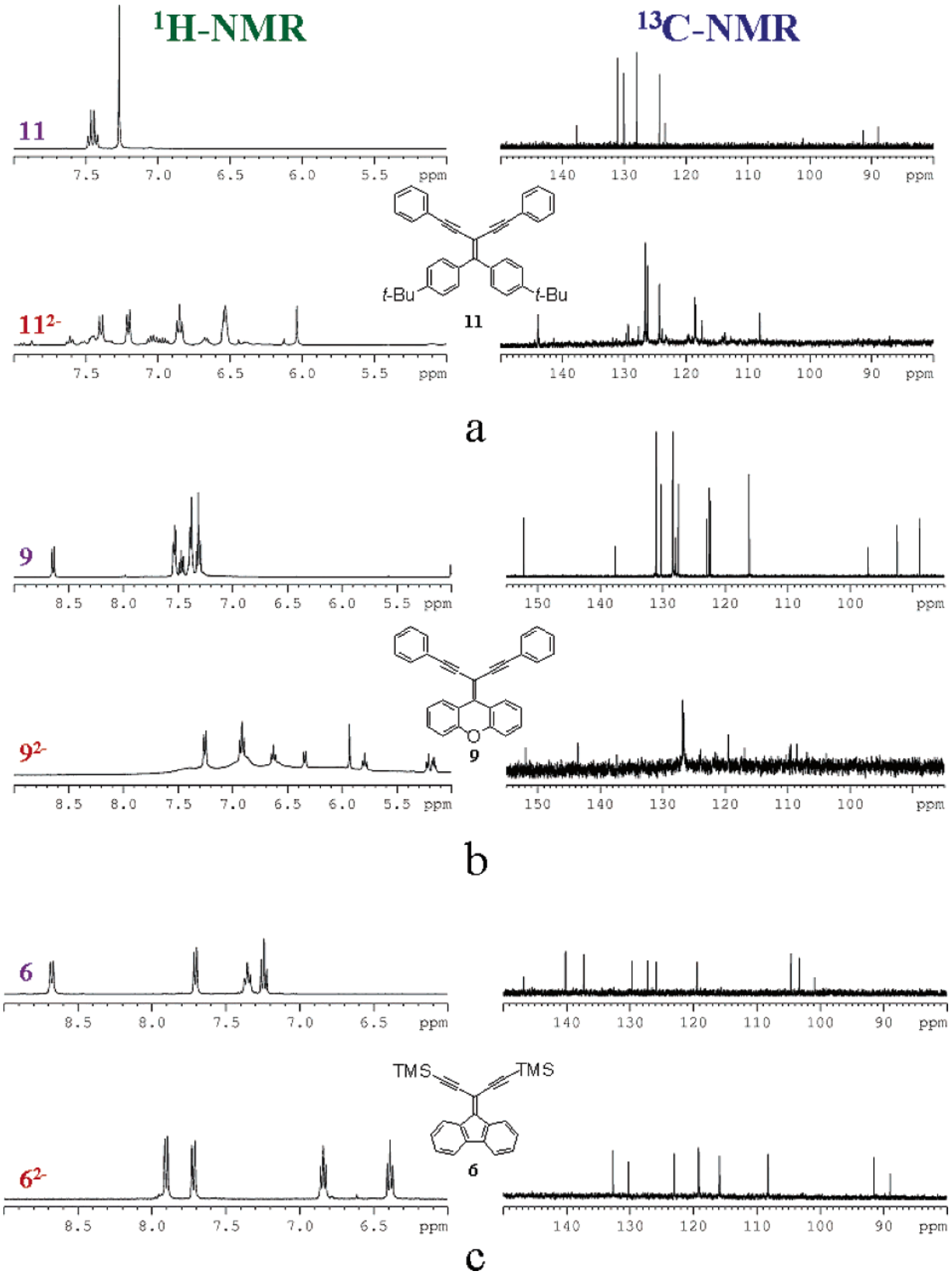
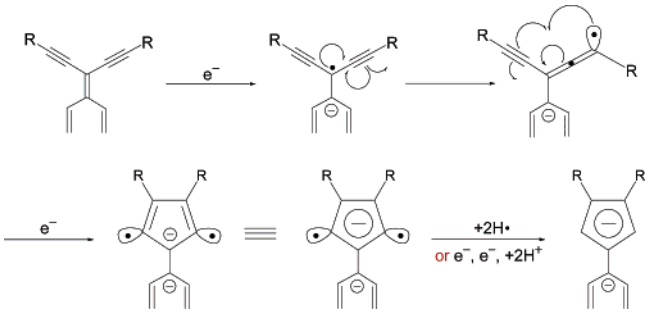


Figure 1. ^{1}H NMR and ^{13}C NMR (THF-d_8) spectra of the cyclic dianionic products, created from (a) **11** and (b) **9**, compared with (c) those of the dianion of **6**, which does not undergo cyclization.

for $\mathbf{5}^{2-}$. These products could be identified as highly unstable fulvenes, fulvalenes, and heterocycles, which are readily oxidized. Therefore, characterization of these species via NMR spectroscopy has not been feasible. However, high-resolution mass spectroscopy of the quench products is in accord with the addition of two protons, just as for $\mathbf{5}^{2-}$. While **8** has a calculated mass of 328.1252 amu, DCI-HRMS analysis[33] of the quench product of the cyclized dianion detected no species with a mass

Scheme 4. Proposed Mechanism for a Reductive "Bergman-Type" Cycloaromatization of a General Cross-Conjugated Enediyne



within 1 amu of this value. On the other hand, addition of two protons yields a calculated mass of 330.1409 amu for the fulvalene product, and a peak was detected experimentally at 330.1404 amu.

The detailed mechanism for this cyclization reaction is not known; however, the overall transformation of a diethynylfulvene to a fulvalene dianion presumably proceeds through an intermediate cyclopentadienide diradical, analogous to the intermediate *p*-benzyne diradicals formed in Bergman cyclizations (see Scheme 1). One plausible sequence of steps for the formation of a cyclopentadienyl ring from a cross-conjugated enediyne (Scheme 4) involves single-electron reduction to a radical−anionic state, followed by formation of a new σ-bond from the bent vinyl radical anion and further reduction, and concluding with hydrogen or proton abstraction.

The exact order of steps in the mechanism notwithstanding, creation of a cyclopentadienylic ring is possible only if the following steps all occur: reduction, cyclization, and proton or hydrogen abstraction. Cyclization in the radical anionic state is presently only a postulate, although we will return to this point later; the particular order in which these steps occur is currently under investigation.

HRMS results for the oxidized dianions after the cyclization indicates that the dianions or diradicals are not quenched by deuterium atoms from the THF-d_8 solvent. Additionally, no deuterium signals in ^{2}D-NMR experiments were observed, excluding those of the solvent, undamaged during the reduction and quench reactions. It is noteworthy that significant precipitate was seen in the tube, after reduction to a new diamagnetic state was completed. Therefore, we postulate that the hydrogen atoms or protons were abstracted from intermediates on pathways to other reduction products, rather than from the solvent.

Why do systems with a common Y-enediyne unit behave so differently during the course of reduction? Two chief factors may govern the outcome of the reaction: charge density on the carbon skeleton and the relative distances between the two sites that may bring about cyclization or form a charged acyclic system. Carbon−carbon intramolecular distances play a key role in the normal Bergman cyclization:[6f,7b,34] in vivo, the cyclization itself takes place after activation brings the carbons at the borders of the enediyne close enough to each other, generating the active benzene biradical.[35] High level calculations should provide insight into the parameters that govern these cyclizations.

Given that compound **3** undergoes cyclization and **14** does not, we thought it might be informative to examine the behavior of compound **15** more closely. In fact, **15** does undergo cyclization, but with a stipulation: unlike the other systems that cyclize, where the result is a clean (or practically clean) cyclized dianion, with **15** one obtains a mixture of both the "open", "plain" $\mathbf{15}^{2-}$ and the cyclized dianionic product (Figure 2), with the uncyclized product being favored, approximately 3:1. This could be the result of **15** possessing partial character of **3** and partial character of **14**.

The uncyclized $\mathbf{15}^{2-}$ shows significant upfield shifts for the phenyl substituent, as far upfield as 4.65 ppm and no farther downfield than 6.21 ppm. This is due to partial conjugation between the phenyl and the enediyne unit, which possesses significant charge density. In turn, this causes the phenyl and fluorenyl units to lose their symmetry, giving rise to a relatively complex spectrum.

The fact that **15** gives both the "open" dianion (**15a** in Figure 2) and a cyclized dianion (**15b** in Figure 2) as two distinct, stable species constitutes strong evidence that the reductive Bergman-type cyclizations described herein are occurring after the first single-electron reduction, at the anion-radical stage (Scheme 4), *not* at the dianion stage. The "open" dianion **15a** is observed to be stable and does not cyclize to give **15b**. The two dianions are not in equilibrium; they are not even isomers. **15b** has already abstracted the two additional hydrogens and would certainly not give them up to go back to **15a**. The most reasonable conclusion is that **15a** and **15b** are both formed *irreversibly* from a common intermediate that represents a branch point along the reaction pathway. That common intermediate is the monoanion radical. In this particular case, fortuitously, the competition between further reduction of the monoanion radical (to make **15a**) and cyclization (to make **15b**) must be nearly equally balanced.

Not all of the enediynes that fail to cyclize, however, are transformed into "open" dianions analogous to **15a**. Close inspection of the ^{13}C NMR spectra given by the new diamagnetic species formed upon reduction of enediynes **6** and **7**, for example, reveals that the monoanion radicals from these cross conjugated enediynes (CCEs) dimerize at position 1′, yielding dianion dimers (Scheme 5).[29] The dimerization is most clearly indicated by the chemical shift of C-1′, which falls in the aliphatic region for the reduction products of **6** and **7** (36.0 and 38.9 ppm, respectively), whereas the chemical shift of C-1′ in the "open," monomeric dianion **15a** comes at 95.5 ppm.

The reductive dimerization of **6** and **7** actually explains why these compounds fail to cyclize. Apparently, dimerization is the kinetically favored pathway in these cases (Scheme 5 route a) and is simply faster than either reduction to the open dianion (route b) or cyclization (route c).

(31) These compounds were all reduced numerous times, under several conditions: at slow and fast rates and at low temperature, room temperature, and under heating. In no case, for any of the enediynes studied, even after months of charging, was a new diamagnetic species observed. Triplet dianions are hypothetically possible, but have been ruled out on account of energy calculations.
(32) In the same manner as for $\mathbf{5}^{2-}$; see ref 19.
(33) Methane gas was used in DCI-HRMS; see the Experimental Section.
(34) For example: (a) Nicolaou, K. C.; Smith, A. L.; Wendeborn, S. V.; Hwang, C. K. *J. Am. Chem. Soc.* **1991**, *113*, 3106. (b) Nicolaou, K. C.; Dai, W. M.; Tsay, S. C.; Estevez, V. A.; Wrasidlo, W. *Science* **1992**, *256*, 1172. (c) Nicolaou, K. C.; Smith, A. L.; Yue, E. W. *Proc. Natl. Acad. Sci. U.S.A.* **1993**, *90*, 5881. (d) Turro, N. J.; Evenzahav, A.; Nicolaou, K. C. *Tetrahedron Lett.* **1994**, *35*, 8089. (e) Schreiner, P. R. *J. Am. Chem. Soc.* **1998**, *120*, 4184. (f) Gaffney, S. M.; Capitani, J. F.; Castaldo, L.; Mitra, A. *Int. J. Quantum Chem.* **2003**, *95*, 706.
(35) See, for instance: (a) Snyder, J. P. *J. Am. Chem. Soc.* **1989**, *111*, 7630. (b) Magnus, P.; Carter, P.; Elliot, J.; Lewis, R.; Harling, J.; Pitterna, T.; Bauta, W. E.; Fortt, S. *J. Am. Chem. Soc.* **1992**, *114*, 2544. (c) Also see ref 5.

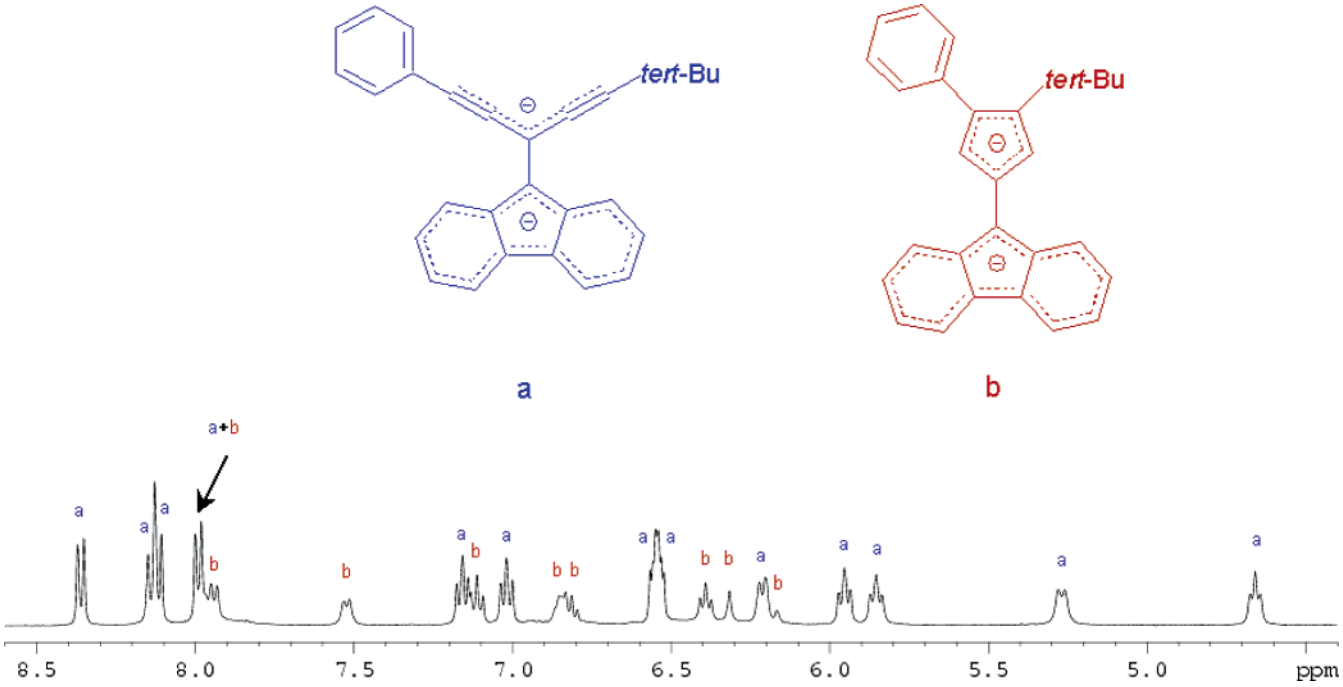
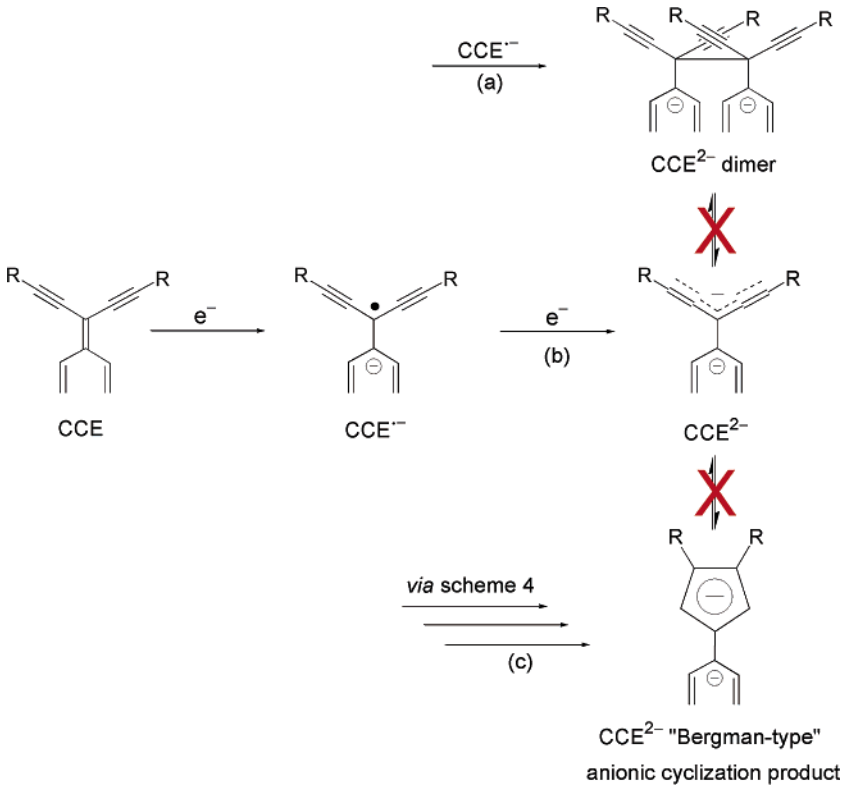


Figure 2. ^{1}H NMR (THF-d_8) of the "open" $\mathbf{15}^{2-}$ [29] (a) and of the cyclization product of the dianion of **15** (b).

Scheme 5. Three Possible Pathways for the Fate of the Monoanion Radical: (route a) Dimerization, Yielding a Dianionic Dimer, (route b) Reduction, Yielding the "Open" Dianion, or (route c) Cyclization and Reduction, Yielding the Cyclopentadienylic Product



Unlike **6** and **7**, however, **14** yields an "open" dianion, analogous to **15a**. The reasoning behind this, presumably, is steric interference; the *t*-Bu groups collide in the dimer dianion of **14**, whereas the longer Si−C bonds in **6** and **7** allow their monoanion radicals to dimerize without steric hindrance.[36] Thus, compounds of this type seem to prefer dimerization (route a),[29] but when steric hindrance becomes a major factor, as in **14**, a different pathway is taken. Depending on the substituents, the end result is either reduction to an "open" dianion (route b) or cyclization followed by reduction, yielding a new five-membered ring (route c).

Once a system follows either pathway b or c, it is impossible for it to "retrace" its steps to get to a different one. Those paths are one-way only, and *no equilibrium* exists between the

(36) Molecular geometries were calculated with PM3 in Spartan 02 (Linux version), Wavefunction, Inc., Irvine, CA.

products of those routes. Pathway a, on the other hand, might be reversible in some cases. In this regard, it is noteworthy that, aside from **15**, *all* the anionic Bergman cyclizations observed to date [i.e., **3**, **8**, **9**, (**10**) and **11**] have phenyl groups on both acetylenes. This is apparently a crucial factor in determining the outcome of the reduction. Perhaps phenyl groups render a pathway reversible, and that may be a prerequisite for success. The bis-TMS and the bis-alkyl compounds all fail for one reason or another. While **12** and **13** also fail, it is difficult to assess their special electronic properties. **15** clearly behaves as a borderline case, with partial bis-phenyl character and partial bis-alkyl character.

As in standard Bergman cyclizations, substituent-inductive effects play a significant role in dictating the result of the reduction.[37] In the Bergman cyclization, formation of an aromatic benzene ring plays a key role; in this anionic "Bergman-type" cyclization, formation of an aromatic cyclopentadienide ring plays an equally important role. By some criteria, the cyclopentadiene anion is actually more aromatic than benzene,[38] and this could, in part, account for why these cyclizations occur at such low temperatures (195 K), whereas neutral systems require 400−500 K for the classic Bergman cyclization. This corresponds to an enormous difference in kinetics.

These findings reinforce those of Kawatkar and Schreiner, who theoretically studied the feasibility of cycloaromatizations of 1,4-pentadiynes.[39] In their theoretical study of "Bergman-like cyclizations", they proposed that σ-accepting capabilities of the specific substituents on the acetylenes drastically affect the energy barriers to cyclization. With appropriate substituents, they postulated that relatively low energy barriers for cyclization are obtainable even when the reaction forms a new ring with antiaromatic character.

Conclusions and Outlook

Various cross-conjugated enediynes undergo anionic cycloaromatizations under reductive conditions, yielding novel anions of fulvenes, fulvalenes, and even heterocycles. In agreement with the view that the aromaticity of the cyclopentadienyl anion exceeds that of benzene,[38] this "Bergman-type" cyclization is more favorable than the classic Bergman cyclization with a linear enediyne, resulting in lower activation energy. The ability to generate a highly reactive diradical under relatively mild conditions may prove useful for various functions, such as the initiation of polymerizations. This new anionic cyclization is a different type of cyclization from the classic Bergman and related cyclizations and from other dianionic cyclizations.[40]

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Supporting Information Available: Syntheses and experimental spectroscopic data for all neutral compounds **6**−**16**, CIF files of **12** and **13**, general crystallographic experimental information for **12**, ORTEP drawings of **12**, and drawings of **13**. This material is available free of charge via the Internet at http://pubs.acs.org.

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(37) For example: (a) Prall, M.; Wittkopp, A.; Fokin, A. A.; Schreiner, P. R. *J. Comput. Chem.* **2001**, *22*, 1605. (b) Alabugin, I. V.; Manoharan, M.; Kovalenko, S. V. *Org. Lett.* **2002**, *4*, 1119. (c) Alabugin, I. V.; Manoharan, M. *J. Am. Chem. Soc.* **2003**, *125*, 4495.
(38) Schleyer, P. v. R.; Maerker, C.; Dransfeld, A.; Jaio, H.; Hommes, N. J. R. v. E. *J. Am. Chem. Soc.* **1996**, *118*, 6317.
(39) Kawatkar, S. P.; Schreiner, P. R. *Org. Lett.* **2002**, *4*, 3643.
(40) Langer, P.; Freiberg, W. *Chem. Rev.* **2004**, *104*, 4125.