An Unusual Charge Umpolung: Synthesis of the Bay Region Diketone 2,3:10,11-Dibenzoperylene-1,12-dione

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Received August 3, 1998

Introduction

The oxidations of polycyclic aromatic hydrocarbons (PAHs) are of interest for reasons ranging from purely synthetic[1] to purely environmental. PAHs are an important class of environmental contaminants produced in the combustion of fuels and other organic matters.[2] Some are relatively potent mutagens and carcinogens as they bind covalently to DNA through enzymatic bay region activation. The role of the bay region stems from the steric crowding which protects the substituting groups on the edges of the bay segment from detoxification and thus guarantees the survival of the group and the attack on the DNA. The need for oxidized PAHs, on one hand, and the relative difficulties in oxidizing bay region positions, on the other, resulted in the development of long multistep reaction sequences. The relative reactivities of PAHs toward oxidations depend on the type of oxidant used and on the availability of the position of attack. In some cases, oxidations will result in the substitution on one carbon as with the peroxide oxidation of benzo[*a*]anthracene[3] or will result in a *para* diketone as observed with the CrO_3 oxidation of the compound.[4] *Ortho* diketones are formed on the most reactive double bond of the aromatic compound while *para* diketones are believed to form via a two-step attack on two separate transannular positions. For a given attack to proceed at an activated carbon, the electronic structure of the substrate should display a partial localization of the electrons at that carbon atom maintaining a low degree of localization energy. PAHs suffering from molecular overcrowding such as phenanthrene, perylene, and their benzannelated analogues have been converted to diketones **1**, **2**, and **3**. The more interesting 4,5-phenanthrenequinone was found to be unstable and decomposed on synthesis.[5]

In the course of our study of PAH polyanions, we measured the distribution of charge densities at various bay regions of benzannelated perylenes such as **4** and **5**. Unlike the relatively uniform distribution of charge over the neutral system, the corresponding dianions $\mathbf{4}^{2-}$ and $\mathbf{5}^{2-}$ exhibit a high electron density at their bay regions as is schematically shown in Figure 1. In this Note, we describe the most efficient synthesis to date of 2,3:10,11-dibenzoperylene-1,12-dione **6** from dianion $\mathbf{4}^{2-}$.

Results and Discussion

Compound **4** was synthesized in two steps from 9-bromophenanthrene **7** as shown in Scheme 1. Coupling of **7** with 9-phenanthrylmagnesium bromide by a nickel−phosphine-catalyzed reaction in THF[6] afforded 9,9′-biphenanthryl[7] **8** in 52% yield. Nearly quantitative cyclization to **4** was achieved when **8** was treated with potassium metal in distilled 1,2-dimethoxyethane, followed by $CdCl_2$ oxidation. Formation of dianion $\mathbf{4}^{2-}$ proceeded smoothly in THF-d_8 under high vacuum conditions. Dianion $\mathbf{4}^{2-}$, deeply violet in color, exhibited a nicely resolved ^1H NMR spectrum at 240 K, shown in Figure 2b.

On the basis of both semiemperical and estimated charge densities extracted from the ^{13}C NMR spectrum of the dianion,[8] charge densities were determined to be highest at C_1 (C_{12}) followed by $C_{3'}$ ($C_{13'}$) and with C_4 (C_9) showing only smaller charge densities (Table 1). Charge distribution comparison with that of perylene dianion $\mathbf{9}^{2-}$ reveals great similarities in the distribution and magnitude of charge densities. The presence of two annelated benzene rings does not alter the charge profile of the perylene segment to a great extent. These high charge densities at the bay region positions of $\mathbf{9}^{2-}$ permitted substitution at these position and the total synthesis of hexabenzocoronene.[9]

Further evidence for the high charge localization (36% of the total charge) at only one bay region of $\mathbf{4}^{2-}$ comes directly from the chemical shift difference observed for the C_6 and C_1 carbons and protons, situated in the two bay regions of $\mathbf{4}^{2-}$. While the ^{13}C NMR chemical shift difference between the two carbons amounts to only 0.1 ppm in the neutral species **4**, this same shift difference is measured at 29.2 ppm in the corresponding dianion $\mathbf{4}^{2-}$. Furthermore, these chemical shifts are larger than those reported for the bay region carbons of the perylene derivatives[10] i.e., benzo[*ghi*]perylene[11] and their dianions. This difference in chemical shifts stems from the combined effects imposed by concentration of a large charge density at the bay region and an enlargement of the

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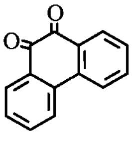

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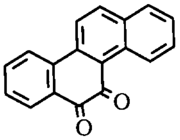

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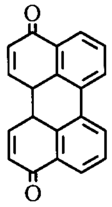

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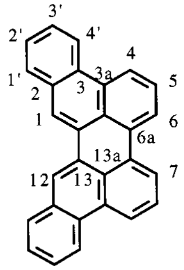

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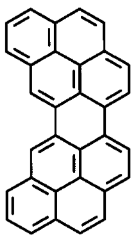

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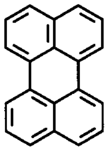

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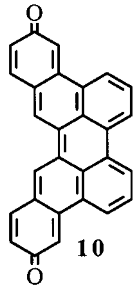

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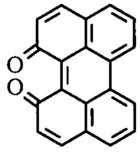

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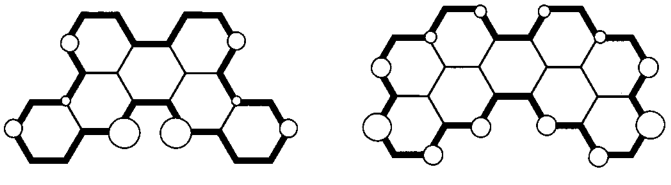
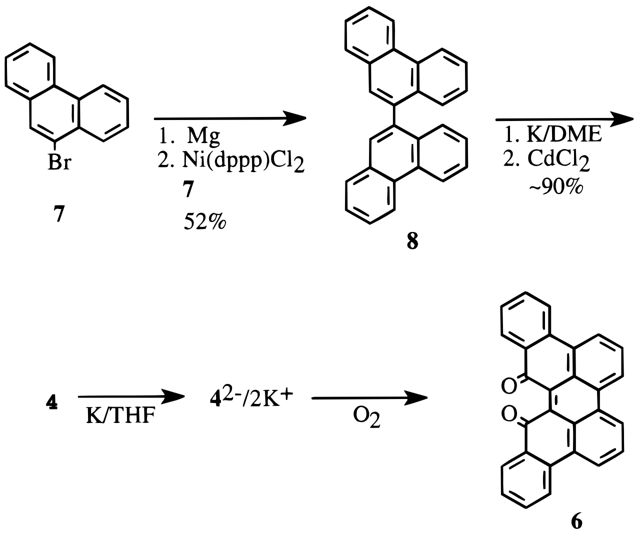


4^{2-} 5^{2-}

Figure 1. Charge densities as calculated by AM1.

Scheme 1: Synthesis of Diketone 6



surface for charge delocalization as a direct result of benzannelation. Bond length alternations as predicted by AM1 calculations show that upon reduction of **4** the $C_{13}-C_{14}$ bond length is reduced from 1.476 Å in the neutral species to 1.409 Å in the anionic species $\mathbf{4}^{2-}$. This decrease in bond length is larger than that of the equivalent bond $C_{6a}-C_{6b}$ for which the bond length is shortened by only 0.019 Å. Hence, the severe repulsion expected between the bay protons should be minimized for protons H_6 and H_7 and be reinforced for H_1 and H_{12}. The resulting polarization of the σ-bonds causes the upfield shifts in the ^{13}C NMR spectrum for the bay region carbons[12] to 84.2 and 122.0 ppm for C_1 and C_{6a}, respectively, as compared with the corresponding carbons in the perylene dianion (98.1 ppm). The ^1H NMR spectrum of $\mathbf{4}^{2-}$ indicates, however, that the opposite effect expected for the proton shifts is not manifested. The resonances of H_1 and H_{12} show the *most upfield shift*. While both H_1, H_{12} and H_6, H_7 pairs exhibit upfield shifts on reduction, a shift of 4.32 ppm measured for H_1 and H_{12} is clearly a direct consequence of excess charge residing at this bay region. A normal upfield shift of 1.9 ppm attributed directly to the reduction process is observed for bay protons H_6 and H_7.

Oxidation of anions by oxygen or air usually results in the retrieval of the neutral hydrocarbon. However, when $\mathbf{4}^{2-}$ is brought in contact with oxygen, diketone **6** is formed in nearly quantitative yields via an addition–elimination sequence. Previous attempts to synthesize quinone **6** via chromic acid oxidation of **4** resulted in the isolation of only 18% of the desired quinone **6**.[13] With semiemperical calculations indicating significant charge densities at C_1, C_{12} along with $C_{3'}$ and $C_{13'}$, such conversion is expected to produce diketone **10** as well. The formation of diketone **6** exclusively from the oxygen-mediated transformation points to the much higher charge density at these positions. In fact, oxidation of **5** under similar conditions did not yield any quinone.

Further evidence for such behavior comes from the oxidation of the parent perylene **9**. Oxidation of **9** results exclusively in the "*para*" quinone **3**[14] when carried out with chromic acid and in quinone **11** when the oxidation

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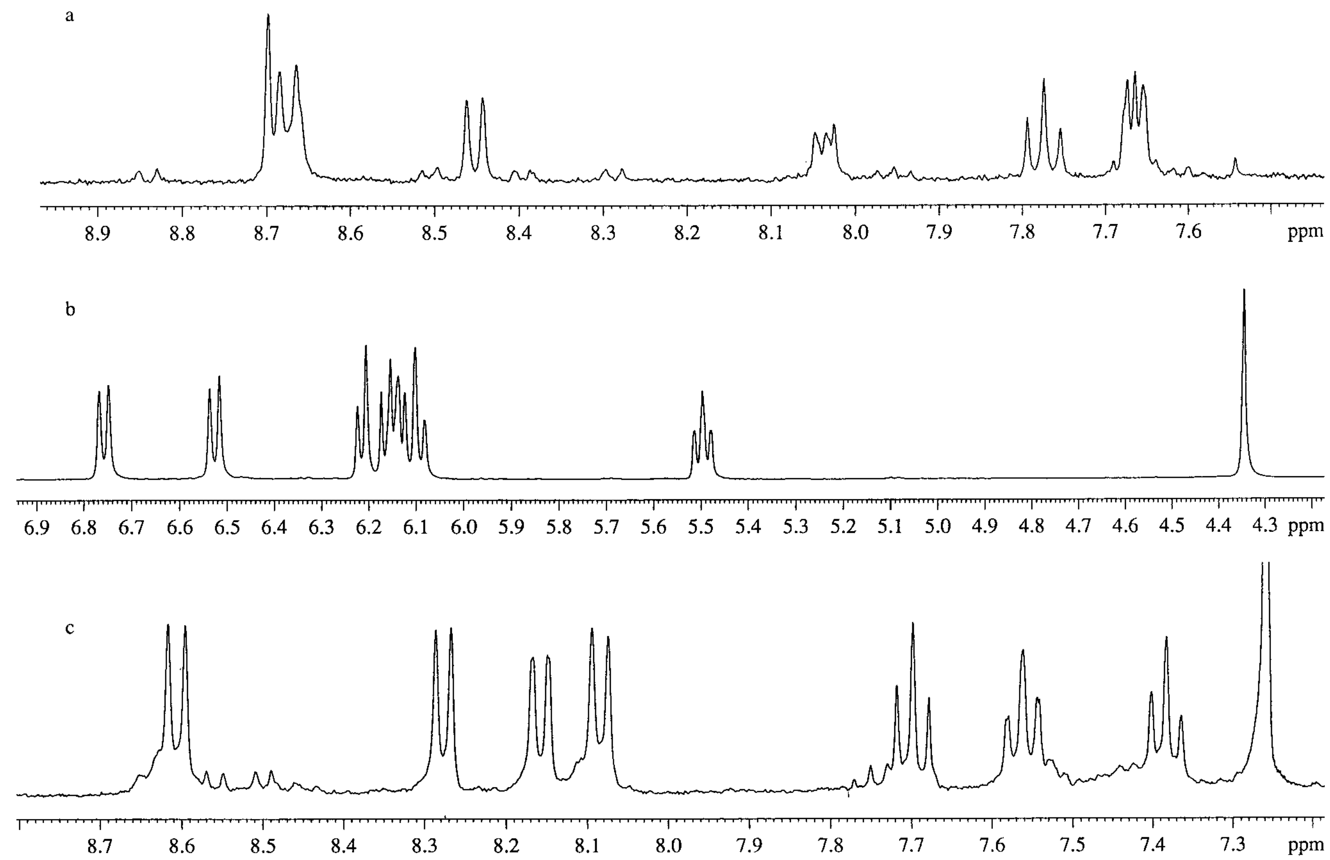

Figure 2. (a)^{1}H NMR of hydrocarbon **4** at 240 K. (b) ^{1}H NMR of the **4**$^{2-}$/2K$^+$ salt at 240 K. (c) 600 MHz ^{1}H NMR of diketone **6** at 298 K.

Table 1. Charge Densities As Calculated by AM1 and Measured from the ^{13}C NMR of Dianion 4^{2-}/2K$^+$

atom	AM1	^{13}C NMR
1,12	**−0.288**	**−0.357**
2,11	+0.044	+0.045
3,10	−0.160	−0.113
3a,9a	+0.058	+0.042
4,9	**−0.252**	**−0.182**
5,8	−0.135	−0.056
6,7	−0.200	−0.080
6a,6b	−0.035	+0.053
13,14	+0.014	−0.130
14a,13a	−0.015	+0.026
1′,11′	−0.193	−0.045
2′,12′	−0.104	−0.028
3′,13′	**−0.300**	**−0.177**
4′,14′	−0.058	+0.003

is executed under electron-transfer conditions in the presence of a photochemical enzyme.[15]

Conclusions

Under normal reductive conditions the localization of charge at the bay region in systems such as **4** is kept to minimum as a result of close proximity of the C−H bonds and the tendencies toward bond polarizations. This charge “Umpolung” observed to exist upon reduction of a PAH system is an important tool for the synthesis of bay region quinones. The generality of this dianion-to-quinone conversion and other synthetic aspects of this conversion are currently being investigated with other aromatic hydrocarbons containing similar bay region carbons.

Experimental Section

General Methods. All chemicals were obtained from Aldrich Chemical Co. and were used after proper purification. THF, THF-d_8, and DME were distilled from potassium. Ni(dppp)Cl$_2$ was synthesized according to a published procedure.[16] All reactions were performed under argon and were monitored by TLC and analyzed by UV light. ^{1}H and ^{13}C NMR spectra were acquired on Bruker 400 and 600 MHz spectrometers and were assigned by several 2D correlation techniques.

9,9′-Biphenanthryl (8). 9-Bromophenanthrene **7** (0.50 g, 1.95 mmol) in 25 mL of a dry 1:1 mixture of ether and toluene was treated with Mg turnings (activated with iodine) and was left to reflux for 12 h under argon. The slightly colored milky solution was than delivered in small portions into a separate flask already containing 0.30 g (1.17 mmol) of **7** and Ni(dppp)-Cl$_2$ dissolved in 25 mL of dry THF. At the end of the addition (15 min), the deep red solution is stirred at 65 °C for 10 h. Extraction with a 1:1 mixture of toluene/dichloromethane (3 × 100 mL) affords 0.215 g of **8** as an off-white solid, mp = 183−185 °C;[7] ^{1}H NMR (400 MHz, THF-d_8) $\delta = 7.38$ (t, $^3J = 6.70$ Hz, H$_7$), 7.50 (dd, $^3J = 7.30$, $^4J = 0.82$ Hz, H$_8$), 7.65 (m, H$_6$), 7.67 (m, H$_2$), 7.73 (t, $J = 5.67$ Hz, H$_3$), 7.86 (s, H$_{10}$), 7.92 (dd, $^3J = 6.82$, $^4J = 1.10$ Hz, H$_1$), 8.81 (d, $J = 6.80$ Hz, H$_4$), 8.82 (d, $J = 6.82$ Hz, H$_5$); ^{13}C NMR $\delta = 123.0$ (C$_4$), 123.2 (C$_5$), 126.9 (C$_6$), 127.0 (C$_9$), 127.2 (C$_3$), 127.3 (C$_2$), 127.9 (C$_8$), 128.9 (C$_{10}$), 129.1 (C$_1$), 130.7 (C$_{4a}$, C$_{4b}$), 132.0 (C$_{10a}$), 132.6 (C$_{8a}$), 137.5 (C$_7$); MS (DI) $m/z = 354$ (M$^+$, 100%).

2,3:10,11-Dibenzoperylene (4). Into a dry flask containing 30 mL of distilled DME, 0.200 g (0.560 mmol) of **8** is added and dissolved prior to the addition of 0.30 g of potassium metal cut into small cubes. The reaction is allowed to stir at room temperature for 10 h and upon removal of unreacted potassium metal is treated with 0.50 g of solid CdCl$_2$. The now pale yellow

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solution is stirred for an additional 10 h at which time it is poured into water and extracted with toluene. Usual workup results in the isolation of 180 mg of an orange solid characterized as compound **4**: mp = 330−332 °C (several lit. values[17]); ^{1}H NMR (400 MHz, THF-d_8) $\delta = 7.64$ (m, $H_{1'}$), 7.65 (m, $H_{3'}$), 7.75 (t, H_5), 8.01 (t, $H_{2'}$), 8.42 (d, H_6), 8.64 (m, H_4, $H_{4'}$), 8.67 (s, H_1); ^{13}C NMR $\delta = 121.8$ (C_1), 121.9 (C_6), 123.0 (C_4), 123.2 ($C_{4'}$), 127.2 ($C_{1'}$), 127.4 ($C_{3'}$), 127.5 (C_5), 127.6 (C_{6a}), 129.4 ($C_{2'}$), 130.5 (C_{14a}), 131.6 (C_{13}), 132.6 (C_3), 132.7 (C_2), 135.7 (C_{3a}); MS (DI) m/z = 176 (34.9%), 352 (M^+, 100%).

2,3;10,11-Dibenzoperylene Dianion (4^{2-}). The deep violet dianion was prepared from 4 to 5 mg of hydrocarbon **4** and potassium metal according to previously published procedures:[18] ^{1}H NMR (600 MHz, THF-d_8, 240 K) $\delta = 4.35$ (H_1), 5.48 ($H_{3'}$), 6.08 ($H_{1'}$), 6.12 ($H_{2'}$), 6.15 (H_5), 6.21 (H_4), 6.52 (H_6); ^{13}C NMR (240 K) $\delta = 81.6$ (C_1), 104.8 (C_4), 109.1 ($C_{3'}$), 113.6 (C_6), 120.1 ($C_1{}'$), 121.3 (C_5), 121.7 (C_3), 121.8 (C_{13}), 126.6 ($C_{2'}$), 128.6 (C_{6a}), 131.9 (C_{14a}), 139.4 (C_2), 142.2 (C_{3a}); UV (THF) $\lambda_{max} = 569$ nm.

2,3:10,11-Dibenzoperylene-1,12-dione (6). To a solution of dianion **4**$^{2-}$/2K$^+$ is bubbled a stream of dry oxygen gas while maintaining the solution at 0 °C. The solution is kept under an atmosphere of oxygen as the temperature is raised to room temperature and the color of the dianion fades. Evaporation of the filtered solution affords quinone **6** as the sole product. Under wet oxygen conditions, quinone **6** may be accompanied by varying quantities of the 1,12-dihydro-**4**.

Spectral data for **6**: mp = 340 °C (lit.[19] mp 336 °C); ^{1}H NMR (600 MHz, THF-d_8) $\delta = 7.56$ (ddd, $^3J = 7.27$, $^3J = 7.26$, $^4J = 1.00$ Hz, $H_{2'}$), 7.74 (ddd, $^3J = 7.25$, $^3J = 7.20$, $^4J = 1.47$ Hz, $H_{3'}$), 7.87 (dd, $^3J = 7.50$, $^3J = 8.32$ Hz, H_5), 8.25 (ddd, $^3J = 7.59$, $^4J = 0.90$, $^5J = 0.47$ Hz, $H_{4'}$), 8.33 (ddd, $^3J = 7.35$, $^4J = 1.43$, $^5J = 0.5$ Hz, $H_{1'}$), 8.45 (d, $^3J = 7.36$ Hz, H_4), 8.78 (d, $^3J = 8.16$ Hz, H_6); ^{13}C NMR $\delta = 123.3$ ($C_{4'}$), 124.0 (C_4), 124.3 (C_6), 126.7 (C_{14a}), 128.1 ($C_1{}'$), 128.8 ($C_{2'}$), 129.3 (C_5), 129.4 (C_{3a}), 131.6 (C_{6a}), 133.5 ($C_{3'}$), 133.7 (C_2), 135.4 (C_{14}), 135.8 (C_3), 187.2 (C_1); UV (THF) λ_{max} = 439, 406, 371 nm; MS (DI) m/z = 382 (M^+).

Acknowledgment. We are grateful for the financial support from the German−Israel Foundation for Scientific Research and Development (G.I.F). We also thank the Wolfson Foundation for making the 600 MHz NMR facilities available.

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