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[2.2]Paracyclophane/Dehydroannulene Hybrids: Probing the Aromaticity of the Dehydro[14]annulene Framework

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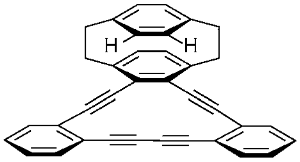
ABSTRACT



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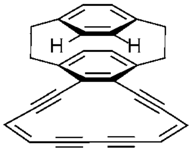

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The synthesis of [2.2]paracyclophane/dehydro[14]annulene hybrids 1 and 2 is reported. Comparison of the proton NMR spectra of 1 and 2 with their open precursors and with related model compounds reveals the pronounced effect of macrocycle formation upon the cyclophane protons H15/H16, which lie above the shielding cone of the diatropic [14]annulene moiety.

An intensely investigated and hotly debated area of dehydroannulene (DA) and dehydrobenzoannulene (DBA) chemistry involves the study of induced ring currents in these macrocycles.[1] With increased benzannelation and higher degrees of unsaturation (i.e., inclusion of triple bonds), many systems become suspect as to whether they can accurately be considered aromatic or anti-aromatic. This issue has been addressed on two fronts. Classically, experimental observations, based mainly on proton NMR data,[2] provide strong evidence for the existence of ring currents in most DAs and DBAs. More recently, theoretical work, specifically nucleus-independent chemical shift (NICS) calculations,[3] has improved our ability to understand this fundamental yet elusive property of these macrocycles.

We recently reported a comprehensive experimental and theoretical investigation of the diatropicity of the octadehydro[14]annulene nucleus.[4] The combination of sensitive alkene proton chemical shifts with consistent calculated data provided compelling evidence for the presence of an induced ring current. Efforts to quantify the strength of the diatropicity of the annulene core fused to dimethyldihydropyrene (DDP), Mitchell's elegant NMR probe for aromaticity,[2] instead afforded inconclusive results.[5] Whereas the computational data supported the aromaticity and thus bond-fixing ability of the octadehydro[14]annulene moiety, the proton chemical shift difference of the DDP internal methyl groups was too

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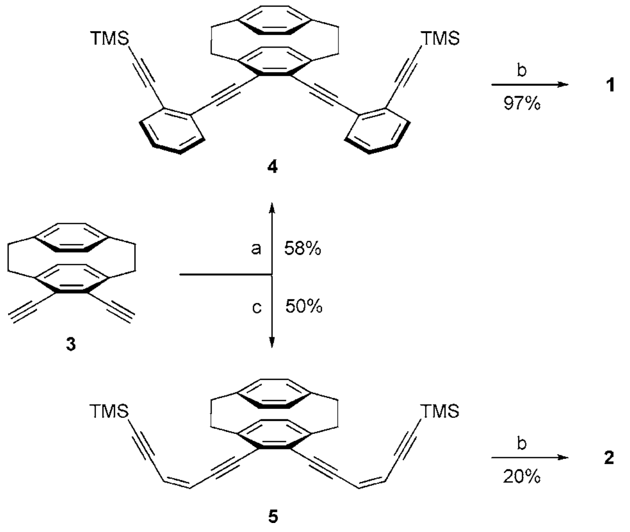
small to derive reliably the relative strength of the ring current in the annulene.

An alternative method for detecting an induced ring current is to place a spectroscopic probe in the shielding cone of the compound in question.[1] Accordingly, we designed molecular hybrids in which the dehydro[14]annulene framework is ortho-fused to one of the benzene decks of [2.2]-paracyclophane (PC), for example, **1** and **2**. In these systems, the cyclophane protons H15/H16 lie above the annulene ring and thus can function as an anisotropy probe. The shielding effect of the aromatic system formed upon cyclization should lead to a marked upfield shift of these protons compared to the corresponding resonances in their acyclic precursors. We report herein the synthesis and spectroscopic analysis of **1** and **2**.

The straightforward route to hybrids **1** and **2** is shown in Scheme 1. Pd-catalyzed cross-coupling of 4,5-diethynyl-[2.2]-paracyclophane (**3**)[6] with 1-iodo-2-(trimethylsilylethynyl)-benzene[7] afforded polyyne **4**, which was subjected to an in situ desilylation−homocoupling procedure[8] to give PC/DBA **1** in 56% overall yield from **3**. An analogous synthetic sequence using (*Z*)-(4-chloro-3-buten-1-ynyl)trimethylsilane[9] provided PC/DA **2**, which proved to be stable only in dilute solutions, in ca. 10% overall yield.

Scheme 1[a]



[a] Reagents: (a) 1-iodo-2-(trimethylsilylethynyl)benzene, Pd(PPh$_3$)$_4$, CuI, NEt$_3$, THF; (b) K$_2$CO$_3$, Cu(OAc)$_2$, CH$_3$OH, CH$_3$CN; (c) (*Z*)-(4-chloro-3-buten-1-ynyl)trimethylsilane, Pd(PPh$_3$)$_4$, CuI, PrNH$_2$, THF.

Slow diffusion of benzene into a dichloromethane solution of **1** furnished single crystals suitable for X-ray structural analysis (Figure 1). Compound **1**[10] crystallizes with two independent molecules in the asymmetric unit, together with one molecule of benzene on a general position and one over an inversion center (both ordered) and one molecule of dichloromethane disordered over an inversion center. The cyclophane moieties display the usual structural features; the rings have a flattened boat shape, with the bridgehead atoms being displaced by ca. 0.15 Å out of the plane of the other four atoms. The annulene ring distortions are closely similar to those of compound **6**,[11] with the four sections C4−C17−C18−C19 etc. being bent inward toward the center of the annulene ring (angles at C17 etc. ca. 168°, at C18 etc. ca. 175°) and the two sections C24−C24′ bent outward from the center (all angles ca. 170°).

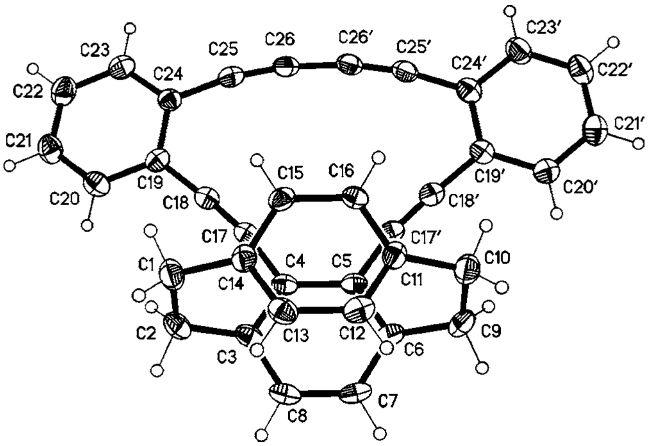


Figure 1. Molecular structure of **1**; one of two independent molecules shown; ellipsoids drawn with 50% probability.

The two independent molecules of **1** are similar but not identical. The cyclophane groups can be fitted well to each other (root mean square deviation = 0.17 Å), but a series of small conformational differences in the annulene rings becomes amplified toward the other ends of the molecules, thus causing the C−C≡C−C≡C−C groups to be mutually displaced by about 1 Å. Taking the cyclophane ring plane C4/C5/C7/C8 as a reference, the atoms C26 and C26′ in one molecule lie 0.25 Å out of this plane in the opposite direction from the ring C11−C16; in the other molecule, the corresponding displacement is 0.58 Å in the same direction as C11−C16. Accordingly, the distances from the hydrogens H15 and H16 to the annulene carbons C17 and C17′ differ somewhat in the solid state, being 3.24 and 3.33 Å in one molecule and 3.15 and 3.12 Å in the other (C−H normalized to 1.08 Å).

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(10) Crystal data for **1**: $C_{36}H_{22}\cdot 0.75C_6H_6\cdot 0.25CH_2Cl_2$, crystal 0.35 × 0.35 × 0.2 mm, triclinic, $P\bar{1}$, $a = 11.903(2)$ Å, $b = 12.782(2)$ Å, $c = 18.785(3)$ Å, $\alpha = 90.687(8)°$, $\beta = 95.682(8)°$, $\gamma = 96.926(8)°$, $V = 2822.5(8)$ Å^3, $Z = 4$, $D_{\mathrm{calcd}} = 1.257$ g cm^{-3}, $\mu = 0.117$ mm^{-1}, $F(000) = 1120$; 25 266 intensities, $2\theta_{\max} = 52.6°$, refinement to $wR2 = 0.186$, $R1 = 0.068$ for 748 parameters and 11 502 unique reflections; max $\Delta\rho = 0.59$ e Å^{-3}, $S = 1.03$. Data were recorded on a Bruker SMART 1000 CCD diffractometer at −140 °C using Mo Kα radiation. The structure was refined anisotropically on F^2 (*SHELXL-97*; Sheldrick, G. M., University of Göttingen, Germany). Hydrogen atoms were included using a riding model.

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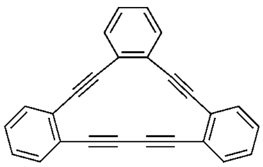

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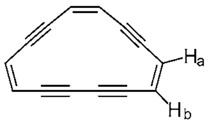

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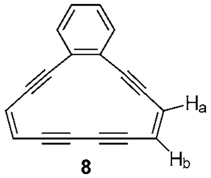

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The close proximity of H15 and H16 to the annulene ring is reflected in the ^{1}H NMR data of **1**. Upon cyclization, H15 and H16 show a distinct upfield shift ($\Delta\delta$ −0.37 ppm) when compared with the analogous resonances in precursor **4**, indicative of a diatropic ring current in the [14]annulene unit (Table 1). The upfield shift is considerably more pronounced in going from **5** to **2** ($\Delta\delta$ −0.92 ppm). Although tempting to ascribe the large difference in chemical shifts to the anisotropy of the triple bonds, the X-ray structure of **4** (see Supporting Information) reveals similar distances between hydrogens H15 and H16 and annulene carbons C17 and C17′; therefore, the marked difference in chemical shifts confirms the existence of a diatropic ring current. It is worthy of note that the other cyclophane arene protons experience either a slight downfield shift (H7/H8: $\Delta\delta$ 0.19−0.25 ppm) due to ring current competition between annulene and benzene rings or essentially no change (H12/H13: $\Delta\delta$ 0.01 ppm).

Table 1. Chemical Shifts (ppm) of the Cyclophane Arene Protons and Chemical Shift Differences (ppm) upon Cyclization[a]

protons	**4**	**1**	**4** → **1**	**5**	**2**	**5** → **2**
H7/H8	6.57	6.76	0.19	6.54	6.79	0.25
H12/H13	6.55	6.54	0.01	6.52	6.53	0.01
H15/H16	7.02	6.65	−0.37	6.93	6.01	−0.92

[a] In $CDCl_3$.

Another sensor that is used to measure the aromaticity of dehydroannulene systems is the vinylic protons H_a and H_b.[4,12] As expected, the alkene protons in **2** are similar to those in **8** (Table 2), though the slight downfield shift of H_a in **2** ($\Delta\delta$ 0.13 ppm) might be the result of possible interaction of H2s/H9s with H19/H19′. Not surprisingly, the alkene protons in **7** are significantly downfield from those in **2**, indicating a decrease in aromaticity in the annulene unit by annelation of aromatic units.

Table 2. Chemical Shifts (ppm) of the Alkene Protons in Precyclized and Cyclized Octadehydro[14]annulenes

proton	pre-**7**[a,b]	**7**[a,b]	pre-**8**[a,b]	**8**[a,b]	**5**[c]	**2**[c]
H_a[d]	6.05	7.92	6.17	7.41	6.17	7.54
H_b[e]	5.90	7.39	5.94	6.73	5.92	6.74

[a] From ref 4. [b] In CD_2Cl_2. [c] In $CDCl_3$. [d] H_a = H19 in **5** and **2**. [e] H_b = H20 in **5** and **2**.

Because of the deshielding effect of the ring current in the [14]annulene, a downfield shift of the vinylic protons upon ring closure is expected. The system with the smallest downfield shift gains the least aromaticity upon annulene formation. Upon cyclization, **7** shows the largest downfield shifts for the vinylic protons ($\Delta\delta$ 1.87 ppm for H_a, 1.49 ppm for H_b). The paracyclophane derivative **2** shows smaller downfield shifts ($\Delta\delta$ 1.37 and 0.82 ppm for H_a and H_b, respectively), indicating a weaker ring current, and are comparable to those observed for the benzannelated system **8** ($\Delta\delta$ 1.24 and 0.79 ppm).

In summary, the synthesis of [2.2]paracyclophane-fused dehydrobenzo[14]annulene **1** and dehydro[14]annulene **2** has been accomplished. The effect of annulene formation on the cyclophane protons which lie over the newly formed 14-membered ring has been studied and confirms the existence of diatropic ring currents in the [14]annulene unit. Furthermore, a stronger effect is observed for the more aromatic compound **2**, indicating that the cyclophane protons might be useful to measure the relative aromaticity of a variety of fused ring systems. Studies are underway to confirm this hypothesis.

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Supporting Information Available: Experimental procedures and copies of ^{1}H NMR data for compounds **1**, **2**, **4**, and **5**; cif files for **1** and **4**. This material is available free of charge via the Internet at http://pubs.acs.org.

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