Neutral [2]catenanes from oxidative coupling of π-stacked components

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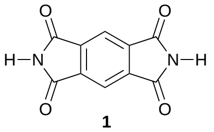
Oxidative dimerisation of bis-acetylenic precursors in the presence of a dinaphtho-crown ether affords neutral [2]catenanes in good yields; the interaction of the complementary donor–acceptor π-systems ensures assembly in a geometry favouring catenane formation.

Recent studies of mechanically interlocked molecules such as catenanes, rotaxanes and knots may be classified according to the nature of the intermolecular association employed in templating their formation. Contemporary organic synthesis has yielded three distinct approaches to such templating: (i) π-stacking of electron-deficient aromatic dications with electronically complementary aromatic molecules,[1] (ii) chelation of metal cations[2] and (iii) amide hydrogen-bonding interactions.[3] Stoddart's methodology for the synthesis of interlocked molecules based on the π-stacking of electron-rich aromatic ethers with electron-poor bipyridinium cations that are generated *in situ* is a landmark in the field.[4,5] Here we describe the synthesis of *neutral* π-stacked interlocked systems from building blocks with pre-programmed recognition characteristics. These systems are structurally and chemically robust, and yet, by virtue of their good solubility characteristics, also amenable to modification using traditional organic chemistry.

The conceptual background to the present work was provided by reports of the inclusion of π-electron-rich aromatic ethers and π-electron-deficient aromatic diimides in a series of donor–acceptor cyclophanes[6] and two self-assembling supramolecular systems.[7] These reports prompted an investigation of some simple co-crystals,[8] such as that formed between pyromellitic diimide **1** and the dialkoxynaphthalene derivative **2**. The solid-state structure of the **1.2** co-crystal reveals alternating stacks of donor (aromatic ether) and acceptor (diimide) molecules; the long axes of the sub-units are approximately perpendicular and a consistent interplanar separation of *ca.* 3.5 Å is maintained between adjacent stack members. These features appeared compatible with the development of a catenane synthesis based on the revealed superstructural design.



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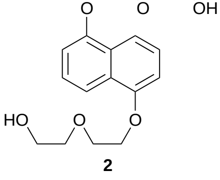

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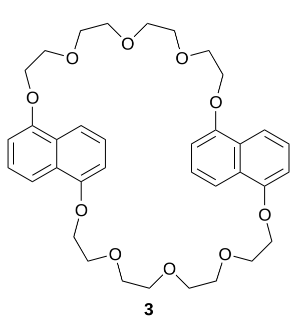

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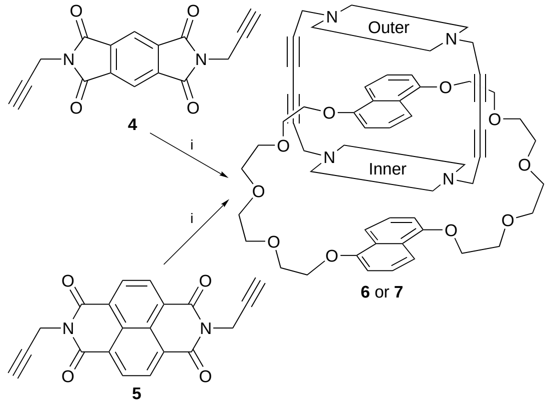
Oxidative coupling of terminal acetylenes has previously been applied to the synthesis of a variety of macrocyclic host systems,[9] including some phenanthroline-based catenates,[10] and the butadiyne linker so generated is ideally suited to bridge the *ca.* 7 Å span demanded by our target structure. A pyromellitimide derivative **4** bearing two terminal acetylenes was readily prepared from the condensation of prop-2-ynylamine with pyromellitic dianhydride. An analogous bis-acetylene **5**, derived from the closely related 1,4,5,8-naphthalenetetracarboxylic dianhydride system, was prepared in 67% yield using an identical procedure (Scheme 1). To link two 1,5-substituted naphthalene residues we selected **3**, available in two steps from 1,5-dihydroxynaphthalene by a modification of a literature route.[11] When a 1:2 molar ratio of **3** and **4** are mixed in dry DMF (50 °C, *ca.* 15 mm crown concentration) an immediate orange colour is established in solution, strongly indicative of charge transfer complex formation. Large excesses of anhydrous CuCl (100 equiv.) and CuCl$_2$ (20 equiv.) were added to effect the coupling process. After 2 days stirring in dry air, the [2]catenane **6** could be isolated from the reaction mixture as an orange–red solid by simple work-up and chromatography. Over several runs conducted on various scales the isolated yield of **6** was in the range 25–33%.‡ Under identical reaction conditions (DMF, 50 °C, 15 mm concentration) a 1 : 2 mixture of **3** and **5** gave the [2]catenane **7** as a purple solid in 29% yield. The increased solubility of this system allowed the reaction to be repeated at room temperature. The isolated yield of **7** rose to 52%, an efficiency comparable with those obtained in previous [2]catenane syntheses.

Fast-ion bombardment mass spectrometry of **6** and **7** reveals peaks at *m/z* 1239 and 1339 respectively, corresponding to the addition of a sodium ion to the catenane structures (M_r = 1216 and 1316 respectively). In both spectra the only other significant peak at high mass occurs at *m/z* 769 ([**3** + Cs]$^+$). This behaviour is a spectral characteristic of catenated structures where the first bond scission leads to unravelling of the interlocked structure.[12] Such fragmentation is not observed under electrospray ionisation conditions where for each structure the only detected peak corresponds to the catenane ($[M + Na]^+$).

At ambient temperature, the ^{1}H NMR spectrum of **6** reveals an AB quartet for the methylene protons of the pyromellitimide macrocycle and upfield shifts of all the aromatic protons relative to the precursors **3** and **4**, as a result of the ordered π-stacking in the molecule. The aromatic pyromellitimide protons appear as a sharp singlet, indicating fast exchange of the inner and outer pyromellitimide sub-units on the chemical shift



Scheme 1 *Reagents and conditions*: i, CuCl, CuCl$_2$, O$_2$, DMF

time scale. In contrast, two clearly resolved sets of multiplets for the naphthalene sub-units of the crown macrocycle are readily identified revealing the comparatively slower rotation of this component. Catenane **7** exhibits a similar ^{1}H NMR spectrum to **6**, indicating similar dynamic behaviour. Variable temperature ^{1}H NMR analysis reveals site exchange processes for **6** that parallel those observed in previously reported systems.[4,5]

Very small single crystals of **6** of a quality apparently suitable for an X-ray structural analysis could be readily grown from deuterated dimethyl sulfoxide ($[^2H_6]Me_2SO$). However, no reflections could be measured for any of these samples when mounted on commercial diffractometers. The structure presented here was obtained by X-ray synchrotron diffraction.§ This radiation source is several orders of magnitude stronger than that employed in routine crystallographic analyses and allowed the structure to be solved with relative ease (Fig. 1).

The two interlocked neutral macrocycles that comprise the catenane adopt a structure where the respective π-rich and π-poor ring systems can align themselves in a similar manner to that observed in the **1.2** co-crystal. Indeed, the validity of the supramolecular design on which the catenane is based is truly revealed when a packing diagram is generated; individual catenane molecules pack one above another to continue the alternating donor–acceptor stack and the typical interplanar spacings of *ca*. 3.4 Å are observed throughout. Hydrogen bonding interactions between the pyromellitimide methylene protons and oxygen donor atoms in the crown polyether chain are also observed, these interactions may prove to play an important role in the templated synthesis. The unit cell contains two catenane molecules and four molecules of $[^2H_6]Me_2SO$ (each disordered over two occupancies). The pyromellitimide ring systems are rotated by 15° relative to each other, inducing a helical twist in this macrocycle, and the connecting butadiyne links are substantially bowed (∠ C–C≡C 169–174°).

[2]Catenanes **6** and **7** represent the first examples of a new class of neutral π-associated interlocked molecules. The electrochemical[13] and photochemical[14] properties of aromatic diimides, and the chemical functionality present in our systems, augur well for the future development of functional and structural derivatives. Indeed, the imide and acetylenic groups are independently reducible and the structural changes so conferred would be likely to alter or destroy the observed π-stacking interactions. Such removal of the templating interaction employed to assemble **6** and **7** would represent an irreversible counterpart to Sauvage's use of transition metal-ion coordination to assemble [*n*]catenates.

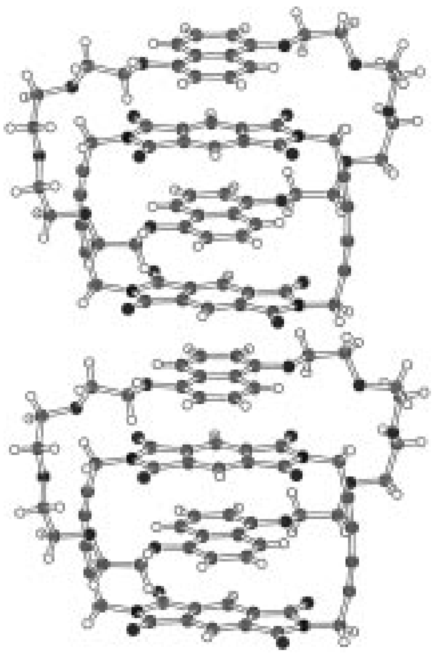


Fig. 1 Ball and stick representation of the solid-state structure of 6

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Footnotes

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‡ *Selected spectroscopic data* for **6**: ^{1}H NMR (400 MHz, $CDCl_3$, 20 °C) 7.13 (d, ^3J 8 Hz, 2 H), 6.90 (s, 4 H), 6.80 (d, ^3J 8 Hz, 2 H), 6.73 (t, ^3J 8 Hz, 2 H), 6.68 (t, ^3J 8 Hz, 2 H), 6.44 (d, ^3J 8 Hz, 2 H), 6.28 (d, ^3J 8 Hz, 2 H), 4.40 (d, AB system, ^2J 18 Hz, 4 H), 4.22 (d, AB system, ^2J 18 Hz, 4 H), 4.12 (m, 4 H), 4.00 (m, 8 H), 3.90–3.85 (m, 20 H); ES–MS (positive-ion) *m/z* 1241.1 ($[M + Na]^+$, 100%), 1256.6 ($[M + K]^+$, 12%).

§ *Crystal data* for **6**.$[^2H_6]Me_2SO$: $C_{68}H_{56}N_4O_{18}$, M_r = 1217.2, triclinic, a = 13.409(3), b = 15.014 (7), c = 16.640(6) Å, α = 100.33(4), β = 90.16(6), γ = 98.76(8)°, V = 1628 Å^3, space group $P\bar{1}$, Z = 2, ρ_{calcd} = 1.40 g cm^{-3}. Crystal of size 0.30 × 0.12 × 0.10 mm. Siemens SMART CCD diffractometer on the single-crystal diffraction station (No. 9.8) at the Daresbury Laboratory Synchrotron Radiation Source (UK): 160 K, λ = 0.6956 Å. Overnight, several series of narrow frames (0.2° in ω) provided coverage of a hemisphere of reciprocal space to θ_{max} 25.8° and corrections were applied for incident beam decay. The structure was solved by direct methods and refined by full-matrix least-squares on F^2; 23612 reflections measured of which 11683 were observed as unique. The structure was refined to R = 0.093, R_w = 0.243, including disordered solvent molecules. Atomic coordinates, bond lengths and angles, and thermal parameters have been deposited at the Cambridge Crystallograpic Data Centre (CCDC). See Information for Authors, Issue No. 1. Any request to the CCDC for this material should quote the full literature citation and the reference number 182/443. Structure ref. code TIDKEW.

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