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A high yielding template-directed synthesis of the first fluorenone-containing [2]catenane

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Abstract—A new crownophane containing both 2,7-dioxyfluorenone and 1,5-dioxynaphthalene moieties bridged by triethylene glycol units has been synthesized and used as a highly efficient template for the preparation of the first fluorenone-containing [2]catenane incorporating a cyclobis(paraquat-*p*-phenylene) tetracation as a second macrocyclic component.

The potential opportunity of using noncovalently interlocked molecules such as catenanes and rotaxanes for the design of molecule-level machines and electronic devices[1–4] has attracted significant attention toward the synthesis and chemistry of these supramolecules.[5–7] One of the most fruitful approaches to catenanes is template-directed synthesis based on template assistance of one macrocycle for the formation of the second macrocycle.[8–11] As a powerful recognition tool for the efficient template-directed syntheses of catenanes incorporating bipyridinium-based components mechanically interlocked with dioxyarene-based polyether components, a combination of the stabilizing effects of [C–H···O] hydrogen bonds, [π–π] stacking, and [C–H···π] interactions have been successfully employed.[5–7] The electrostatic component plays a dominant role in these interactions, and in the case of polar subsystems included in the macrocyclic host framework, it is possible to identify recognition efficiency and determine the complexes stabilization energy within the limits of the electrostatic energy term.[12] This immediately suggests that the introduction of aromatic units containing electron-rich polar groups in the framework of one macrocyclic component can reinforce ion–dipole interactions with the positively charged second component and hence enhance the efficiency of the catenation process. Being interested in this simple opportunity of optimizing the template effect of the donor component, we have synthesized fluorenonocrownophane **3** for the first time as a template for the formation of the cyclobis(paraquat-*p*-phenylene) tetracation ($CBPQT^{4+}$) as the second macrocyclic component of the [2]catenane.

Macrocyclization of bistosylate **1**[13] with bisphenol **2**, under high dilution conditions, gave after work-up and chromatographic purification over silica gel, the crownophane **3**.[14] Employing the strategy developed by Raymo and Stoddart[7] the catenation of **3** was carried out with a 2-fold excess of the bis(bipyridinium) derivative **4**·$2PF_6$ and 1,4-bis(bromomethyl)benzene **5** under atmospheric pressure to afford the [2]catenane **6**·$4PF_6$ in a yield of 91%, after counterion exchange[15] (Scheme 1). The yield of **6**·$4PF_6$, one of the highest ever obtained for the catenanes, reflects a very efficient preorganization of the reactants, evidently augmented by electrostatic interaction between the fluorenonocrownophane **3** carbonyl group and the bipyridinium dication **4**·$2PF_6$, or its monoalkylated intermediate, in addition to conventional noncovalent interactions. Thus, the fluorenone unit is superior to other dioxyarene derivatives in this self-assembly process.

Keywords: Catenanes; Cyclophanes; Fluorenonophanes; Self-assembly; Template synthesis.
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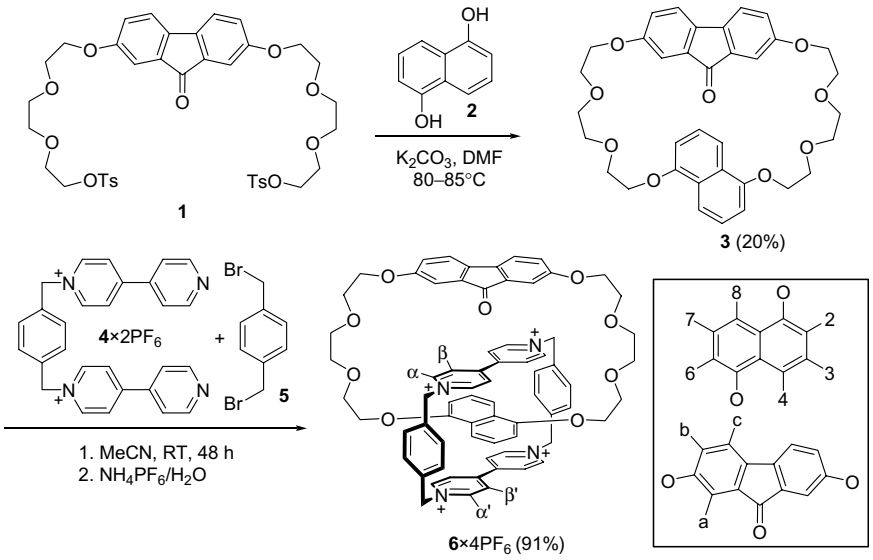

Scheme 1. Synthesis of crownophane **3** and [2]catenane **6**·4PF_6.

The X-ray crystal structure of the [2]catenane **6**·4PF_6 shows that the 1,5-dioxynaphthalene ring of **3** is located inside the cavity of the tetracationic cyclophane, while the fluorenone unit is positioned outside (Fig. 1).[16] The fluorenone carbonyl group is almost centered with respect to the plane of the internal bipyridinium unit at a distance of 3.74 Å from its centroid. This immediately indicates a considerable dipole–charge interaction between them that undoubtedly is an important stabilization component of the catenane **6**·4PF_6 structure. The mean interplanar separation distances between the 1,5-dioxynaphthalene ring and the internal and external bipyridinium units are 3.29 and 3.31 Å, respectively. The separation between the fluorenone fragment and the internal bipyridinium unit is 3.39 Å. Such distances in the donor–acceptor array, coupled with the near parallel alignments and considerable degree of overlap of all the aromatic moieties of the catenane, indicate their involvement in strong face-to-face π–π stacking interactions. The dioxynaphthalene unit is oriented orthogonally to the planes of the paraxylyl rings and its hydrogen atoms in positions 4 and 8 are located at distances of 2.54 and 2.58 Å, respectively, from the aromatic centre which clearly specifies the presence of [C–H···π] interactions. There are the two bifurcated [C–H···O] hydrogen bonds between diametrically opposite α-CH groups of the internal bipyridinium unit and the central oxygen atoms of the polyether linkages.

Inspection of the packing of the [2]catenane **6**·4PF_6 (Fig. 2) reveals that molecules form centrosymmetric π-stacked dimer pairs involving the partial overlap of fluorenone units. These dimers contain molecules of different planar chirality, (p*R*) and (p*S*), associated with the local C_{2h} symmetry of the 1,5-dioxynaphthalene unit.

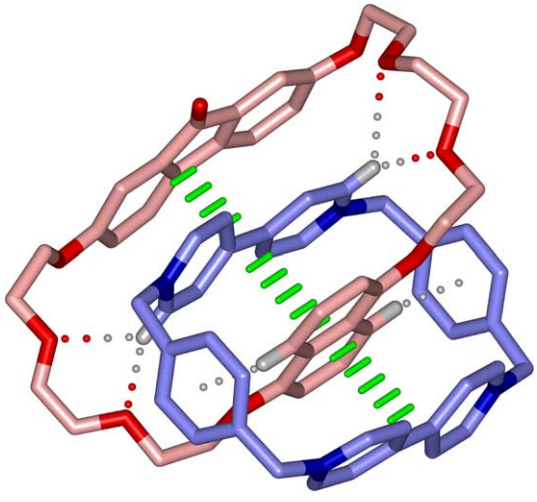

Figure 1. Polytube representation of the solid-state structure of [2]-catenane **6**·4PF_6. For clarity carbon atoms of the crownophane are shown in pink and the carbon atoms of the tetracationic cyclophane in blue; oxygen atoms are depicted in red, nitrogen atoms in dark blue, and selected hydrogen atoms in gray. Water molecules and counterions are not shown. Dots and green bars show hydrogen and π–π stacking interactions, respectively.

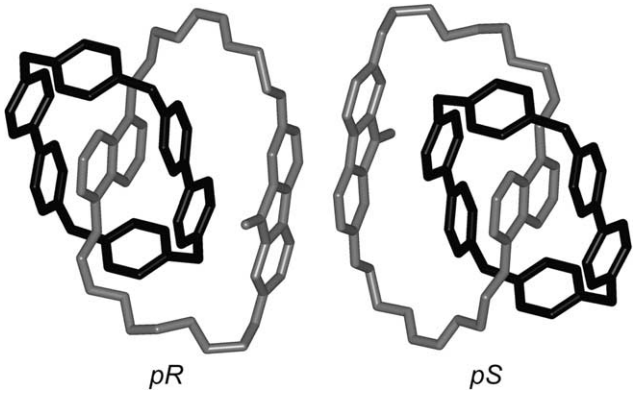

Figure 2. One of the 'enantiomeric pairs' formed by the [2]catenane **6**·4PF_6 in the crystal state.

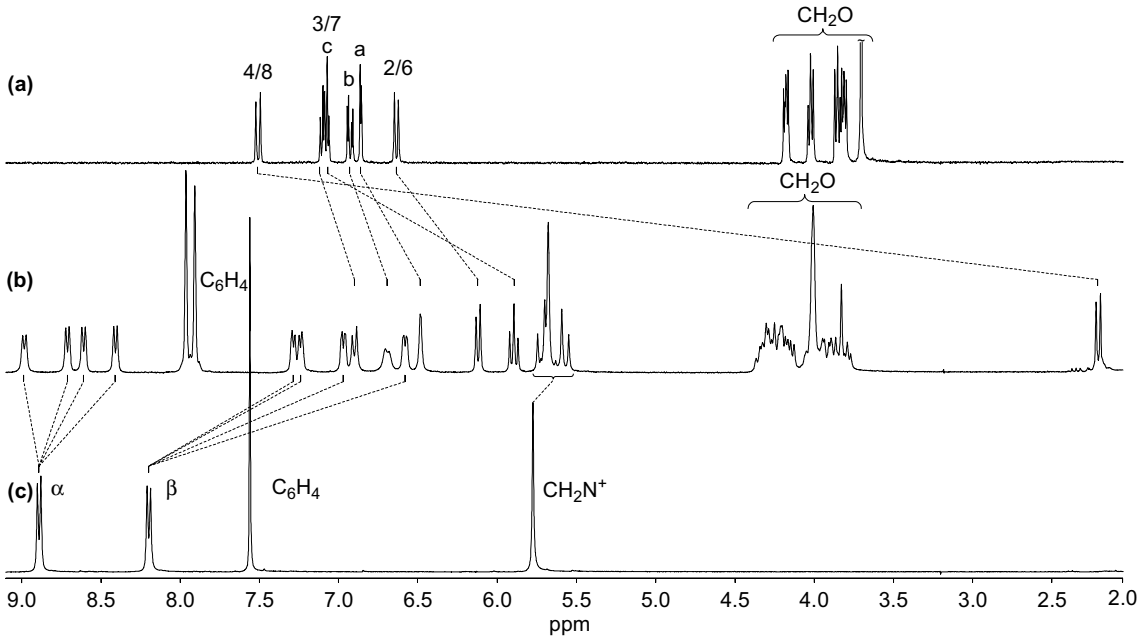

Figure 3. ^{1}H NMR spectra (300 MHz, CD_3CN, 293 K) of (a) **3**, (b) **6**·4PF_6, and (c) $CBPQT^{4+}$. The designated protons are depicted on the structural formula in Scheme 1.

Thus, the crystals contain equal numbers of molecules of opposite chirality.

Comparison of the ^{1}H NMR spectrum (CD_3CN, 293 K) of the crownophane **3** with that of [2]catenane **6**·4PF_6 (Fig. 3) shows upfield shifts for the 2,7-dioxyfluorenone protons ($\Delta\delta = -0.38$, -0.24, and -0.18 ppm for the Ha, Hb and Hc protons, respectively). The most significant upfield shifts were due to the 1,5-dioxynaphthalene protons ($\Delta\delta = -0.52$, -1.19, and -5.30 ppm for the symmetry-related pairs of protons H-2/6, H-3/7, and H-4/8, respectively).

The very high upfield shift for the H-4/8 protons of the naphthalene unit, together with the downfield shift of the *p*-phenylene protons of the tetracationic component ($\Delta\delta = +0.39$ ppm), indicates the edge-to-face [C–H$\cdots\pi$] interaction between the H-4/8 hydrogen atoms of the naphthalene and *p*-phenylene rings, as observed in the solid state, and unambiguously confirms the location of the dioxynaphthalene ring inside the cavity of $CBPQT^{4+}$ in solution. There are no signals in the spectrum of **6**·4PF_6 arising from an occupied fluorenone unit, suggesting that the catenane exists exclusively as one 'frozen' translational isomer. The sharp, well-resolved signals of the dioxynaphthalene protons suggest slow circumrotation of the neutral macrocycle through the cavity of the tetracationic cyclophane on the ^{1}H NMR timescale. As a result of imposing the local C_{2h} symmetry of the 1,5-dioxynaphthalene unit upon both the 'inside' and 'outside' bipyridinium units, their α/α′ and β/β′ protons give rise to eight sets of signals. This, coupled with two, partially overlapped, AB quartets of the 'inside' and 'outside' CH_2N^+ protons and two singlets of the *p*-phenylene moiety protons, indicates slow circumrotation of the tetracationic cyclophane through the cavity of the neutral macrocycle on the ^{1}H NMR timescale. Integrally, analysis of the ^{1}H NMR spectrum reveals that in solution the [2]catenane **6**·4PF_6 is a highly ordered system in which all the major motions of its separate macrocyclic components are slow or non-existent on the ^{1}H NMR timescale even at a room temperature.

In conclusion, a new binding motif based on the simple concept of reinforcement of the host–guest electrostatic interaction demonstrates for the first time that fluorenonophanes, and very likely, similar crownophanes containing aromatic units with electron-rich polar groups, can be used as efficient templates for the synthesis of catenanes with high yields. We hope that this template motif extends opportunities for supramolecular synthesis and will be useful for construction of interlocked molecules of different types.

Acknowledgements

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References and notes

1. Balzani, V.; Credi, A.; Raymo, F. M.; Stoddart, J. F. *Angew. Chem., Int. Ed.* **2000**, *39*, 3348–3391.
2. Balzani, V.; Credi, A.; Venturi, M. *Molecular Devices and Machines—A Journey into the Nano World*; Wiley-VCH: Weinheim, 2003.
3. Collin, J.-P.; Dietrich-Buchecker, C.; Gaviña, P.; Jimenez-Molero, M. C.; Sauvage, J.-P. *Acc. Chem. Res.* **2001**, *34*, 477–487.
4. Schalley, C. A.; Beizai, K.; Vögtle, F. *Acc. Chem. Res.* **2001**, *34*, 465–476.

5. *Molecular Catenanes, Rotaxanes and Knots*; Sauvage, J.-P., Dietrich-Buchecker, C. O., Eds.; Wiley-VCH: Weinheim, 1999.
6. Amabilino, D. B.; Stoddart, J. F. *Chem. Rev.* **1995**, *95*, 2725–2828.
7. Raymo, F. M.; Stoddart, J. F. *Chem. Rev.* **1999**, *99*, 1643–1664.
8. Stoddart, J. F.; Tseng, H.-R. *Proc. Natl. Acad. Sci. U.S.A.* **2002**, *99*, 4797–4800.
9. Hubin, T. J.; Busch, D. H. *Coord. Chem. Rev.* **2000**, *200–202*, 5–52.
10. Jäger, R.; Vögtle, F. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 930–944.
11. Raehm, L.; Hamilton, D. G.; Sanders, J. K. M. *Synlett* **2002**, 1743–1761.
12. Müller-Dethlefs, K.; Hobza, P. *Chem. Rev.* **2000**, *100*, 143–167, and references therein.
13. Lukyanenko, N. G.; Kirichenko, T. I.; Lyapunov, A. Yu.; Bogaschenko, T. Yu.; Pastushok, V. N.; Simonov, Yu. A.; Fonari, M. S.; Botoshansky, M. M. *Tetrahedron Lett.* **2003**, *44*, 7373–7376.
14. A solution of **1** (7.84 g, 10 mmol) and **2** (1.60 g, 10 mmol) in DMF (400 mL) was added dropwise over 10 h to a stirred suspension of K_2CO_3 in DMF (600 mL) under argon at 80 °C and heating was maintained for a further 40 h. The reaction mixture was filtered and the residue was washed with DMF. The combined filtrate was evaporated to dryness and the residue was dissolved in benzene, filtered, washed with 5% aqueous HCl, 5% aqueous NaOH, water, and brine and then dried over $MgSO_4$. The solvent was removed under reduced pressure and the residue was subjected to column chromatography (SiO_2, $CHCl_3$/MeOH, 100:1) to afford pure **3**, after crystallization from ethanol, as an orange solid (1.17 g, 20%). Mp 152 °C; ^{1}H NMR (300 MHz, CD_3CN): δ 3.71 (s, 8H), 3.79–3.88 (m, 8H), 3.99–4.05 (m, 4H), 4.15–4.21 (m, 4H), 6.64 (d, 2H, J = 7.5 Hz), 6.86 (d, 2H, J = 2.2 Hz), 6.93 (dd, 2H, J = 2.5, 8.1 Hz), 7.08 (d, 2H, J = 8.1 Hz), 7.09 (t, 2H, J = 8.1 Hz), 7.51 (d, 2H, J = 8.7 Hz); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 67.4, 68.2, 69.6, 69.9, 71.1, 105.2, 110.6, 114.3, 120.0, 121.0, 124.7, 126.4, 135.5, 137.2, 154.0, 158.9, 193.0; UV/vis (MeCN): λ_{max} (ε): 225 (59,000), 270 (72,000), 296 (14,000), 311 (12,000), 324 (7000), 468 (320); MS (EI, 70 eV): *m*/*z* (%) = 600 (100) [M^+], 300 (7), 212 (2), 160 (5); Anal. Calcd for $C_{35}H_{36}O_9$: C, 69.99; H, 6.04%. Found: C, 69.87; H, 6.09%.
15. To a solution of **3** (120 mg, 0.2 mmol) and **4**·2PF_6 (282 mg, 0.4 mmol) in MeCN (15 mL) was added **5** (132 mg, 0.5 mmol) and the reaction mixture was stirred at room temperature for 48 h. The solvent was removed in vacuo, and the resulting violet solid was washed with $CHCl_3$ (20 mL), dissolved in H_2O (75 mL) and insoluble polymeric materials were removed by filtration. A saturated aqueous solution of NH_4PF_6 was added until no further precipitation occurred. The precipitate was filtered off, washed with H_2O (20 mL) and dried in vacuo. Recrystallization from MeCN/*i*-PrOH (4:3, v/v) gave **6**·4PF_6 as dark violet crystals (309 mg, 91%). Mp > 300 °C (decomp.); ^{1}H NMR (300 MHz, CD_3CN): δ 2.21 (d, 2H, J = 8.4 Hz), 3.74–4.39 (m, 24H), 5.57 (d, 2H, J = 13.1 Hz), 5.68 (t, 4H, J = 14.0 Hz), 5.74 (d, 2H, J = 13.1 Hz), 5.90 (t, 2H, J = 8.1 Hz), 6.12 (d, 2H, J = 7.8 Hz), 6.48 (br s, 2H), 6.58 (dd, 2H, J = 1.9, 6.2 Hz), 6.69 (br d, 2H, J = 7.2 Hz), 6.90 (d, 2H, J = 8.4 Hz), 6.97 (dd, 2H, J = 2.2, 6.8 Hz), 7.24 (dd, 2H, J = 1.0, 5.0 Hz), 7.29 (dd, 2H, J = 1.3, 5.0 Hz), 7.91 (s, 4H), 7.96 (s, 4H), 8.41 (d, 2H, J = 6.2 Hz), 8.61 (d, 2H, J = 6.5 Hz), 8.71 (d, 2H, J = 6.2 Hz), 8.99 (d, 2H, J = 6.5 Hz); ^{13}C NMR (75.5 MHz, CD_3CN):δ 66.1, 69.1, 69.2, 70.9, 71.7, 72.5, 72.6, 105.1, 109.2, 112.0, 120.2, 122.4, 124.6, 125.3, 125.9, 126.0, 126.7, 129.2, 131.9, 132.0, 132.9, 136.0, 136.9, 137.2, 137.6, 144.2, 144.4, 145.0, 145.6, 146.1, 151.9, 160.5, 192.8; UV/vis (MeCN): λ_{max} (ε): 221 (58000), 264 (86000), 515 (1300); MS (FAB): *m*/*z* (%) = 1555 (48) [M^+–PF_6], 1410 (100) [M^+–2PF_6], 1265 (16) [M^+–3PF_6]; Anal. Calcd for $C_{71}H_{68}F_{24}N_4O_9P_4 \cdot 3H_2O$: C, 48.58; H, 4.25; N, 3.19%. Found: C, 48.45; H, 4.47; N, 3.12%.
16. Crystal data for [**6**·4PF_6]·$(H_2O)_3$: $C_{71}H_{74}F_{24}N_4O_{12}P_4$, M_r = 1755.2, triclinic, space group P–1, a = 13.789(1), b = 13.825(1), c = 20.547(1) Å, α = 81.60(1), β = 83.25(1), γ = 89.71(1)°, U = 3847.7(4) Å^3, Z = 2, D_{calcd} = 1.546 g cm^{-3}, μ = 0.220 mm^{-1}, F(000) = 1836. Final residuals (for 1020 parameters) were $R1$ = 0.1002 and $wR2$ = 0.2103 for 2779 with $I > 2\sigma(I)$. Residual electron density was 0.770 and −0.351 eÅ^{-3}. Crystallographic data (excluding structure factors) for the structures in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication number CCDC 244184. Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK [fax: +44(0)-1223-336033 or e-mail: deposit@ccdc.cam.ac.uk].