Molecular Devices

Donor–Acceptor Pretzelanes and a Cyclic Bis[2]catenane Homologue**

*Yi Liu, Paul A. Bonvallet, Scott A. Vignon, Saeed I. Khan, and J. Fraser Stoddart**

Through its exploitation of noncovalent bonding interactions and self-assembly processes,[1] supramolecular assistance to covalent synthesis[2] has established itself as an efficient means of creating molecules with nanoscale dimensions. For two decades, researchers have harnessed the power of post-assembly covalent modification[2] to produce an array of mechanically interlocked molecular compounds,[3] some of which have been shown to behave as molecular machines[4] and switches[5] on surfaces and at interfaces, respectively. We have developed a template-directed[6] protocol for the construction of [2]catenanes[7] composed of a crown ether containing π-electron-rich aromatic ring systems and a tetracationic cyclophane comprised of two π-electron-deficient bipyridinium units. The kinetically controlled protocol relies on employing the crown ether as the template, around which the cyclophane is formed[8] from reaction of a dicationic salt with *para*-xylylene dibromide. If the crown ether is covalently tethered to this second molecule, then the resulting cyclization(s) could occur either intramolecularly and generate a pretzelane[9] or intermolecularly and generate cyclic or linear oligo/polycatenanes (Figure 1).

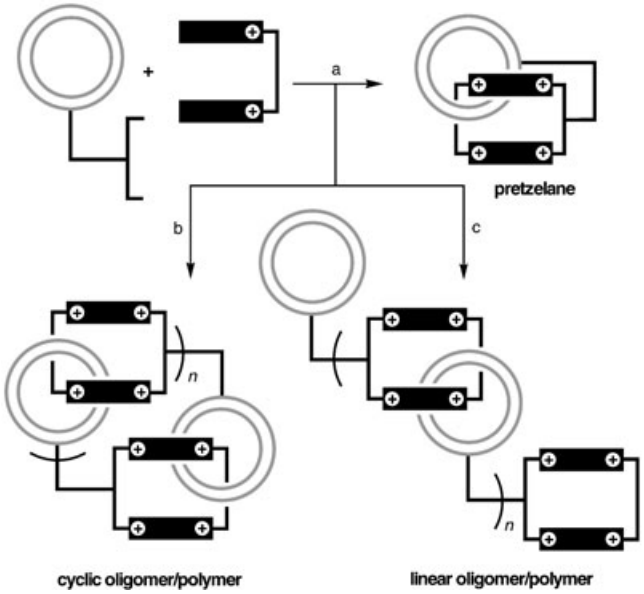


Figure 1. Graphical representations of the formation of a) a pretzelane, b) a cyclic polycatenane, and c) a linear polycatenane. The gray components are π-electron rich and the black (charged) components are π-electron deficient.

Herein, we report the synthesis of two *para*-xylylene dibromide derivatives, which have the same crown ether component[10] tethered by different linkers, and describe the outcome of their reactions with the dicationic salt. It transpires that, when the dibromide contains a longer—and more flexible—linker, a pretzelane is obtained in good yields, as suggested by (dynamic) ^{1}H NMR spectroscopic analyses in solution and confirmed by X-ray crystallographic studies in the solid state. By contrast, when the dibromide contains a shorter—and less flexible—linker, a cyclic bis[2]catenane[11] is obtained as the major product, along with lesser amounts of a pretzelane.

The synthesis of the pretzelanes **7**·4 PF_6 and **10**·4 PF_6 and the cyclic bis[2]catenane **11**·8 PF_6 are outlined in Schemes 1 and 2. Reaction of **1**,[12] which contains a symmetrically positioned carboxyl group, with an excess of **2** gave the alcohol **3**; subsequent esterification of this alcohol with another carboxylic acid derivative **4**[13] afforded the dibromide

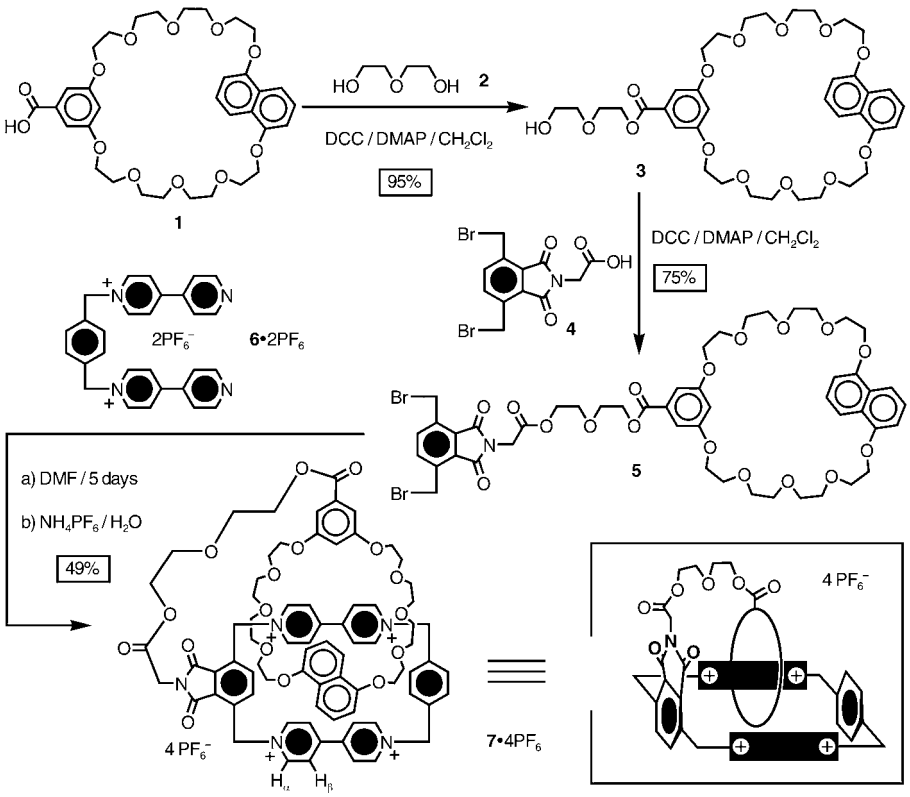
[*] Dr. Y. Liu, Prof. P. A. Bonvallet,[+] S. A. Vignon, Dr. S. I. Khan, Prof. J. F. Stoddart
California NanoSystems Institute and
Department of Chemistry and Biochemistry
University of California, Los Angeles
405 Hilgard Avenue, Los Angeles, CA 90095-1569 (USA)
Fax: (+1) 310-206-1843
E-mail: stoddart@chem.ucla.edu

[+] Present address:
Department of Chemistry
College of Wooster, 943 College Mall
Wooster, OH 44691-2363 (USA)

[**] This work was supported by the Defense Advanced Research Projects Agency (DARPA) and the National Science Foundation (NSF) under equipment grants CHE-9974928 and CHE-0092036.

Supporting information for this article is available on the WWW under http://www.angewandte.org or from the author.

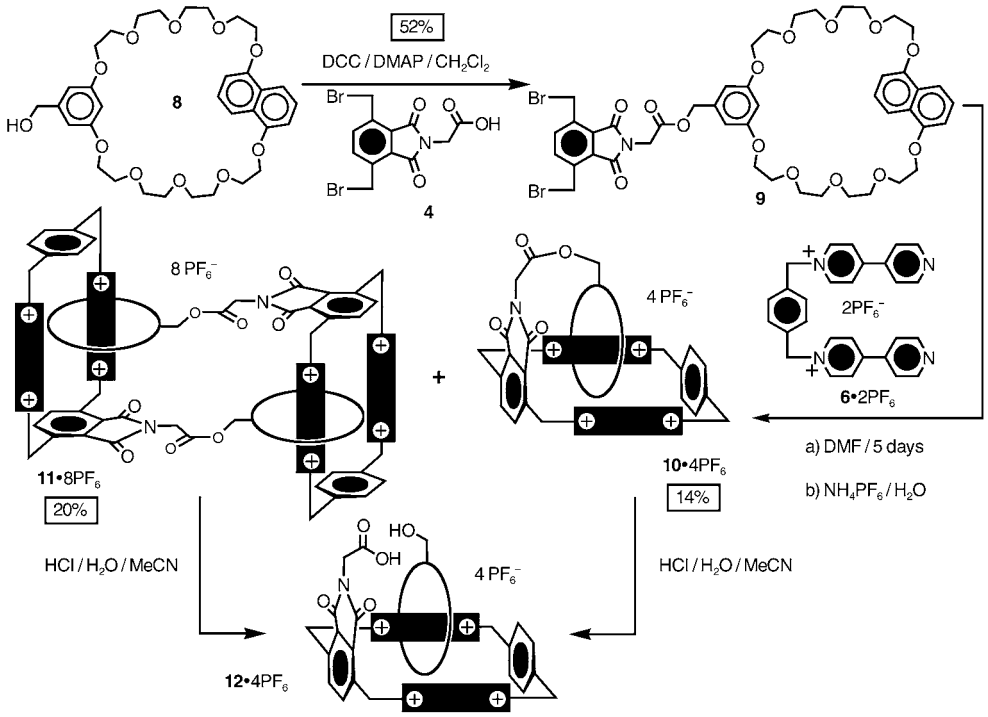
  DOI: 10.1002/ange.200500041



Scheme 1. The synthesis of the pretzelane **7**·4 PF_6. DCC = *N*,*N*′-dicyclohexylcarbodiimide, DMAP = 4-dimethylaminopyridine.

5 as the key intermediate. Formation of **7**·4 PF_6 was achieved in 49% yield by stirring **5** and **6**·2 PF_6[8a] in DMF (*N*,*N*′-dimethylformamide) for five days and then exchanging the counterions. In a similar fashion, the crown ether appended dibromide **9** was obtained from esterification of the crown ether **8**,[14] which carried a hydroxymethyl group, with the carboxylic acid derivative **4**. Treatment of **9** with **6**·2 PF_6 afforded a mixture of **10**·4 PF_6 and **11**·8 PF_6 in yields of 14 and 20%, respectively, after counterion exchange and column chromatography.

The pretzelane **7**·4 PF_6 contains (Figure 2) two elements of chirality, namely, planar chirality associated with the 1,5-dioxynaphthalene (DNP) ring system and helical chirality[15] arising from the relative positioning of the two interlocked rings. This helicity results from the breaking of symmetry in the tetracationic cyclophane by the phthalimido unit. It can be inverted by rotation of this phthalimido unit (process II) or by partial pirouetting of the crown ether (process III). The combination of these two chiral elements gives rise to two enantiomeric pairs of diastereoisomers. One enantiomeric pair, namely, (*pR*)-(*P*)-**7**$^{4+}$ and (*pS*)-(*M*)-**7**$^{4+}$, is characterized by having the oxygen atom on



Scheme 2. The synthesis of the pretzelane **10**·4 PF_6 and the cyclic bis[2]catenane **11**·8 PF_6, followed by the hydrolysis of their esters to generate the common [2]catenane **12**·4 PF_6.

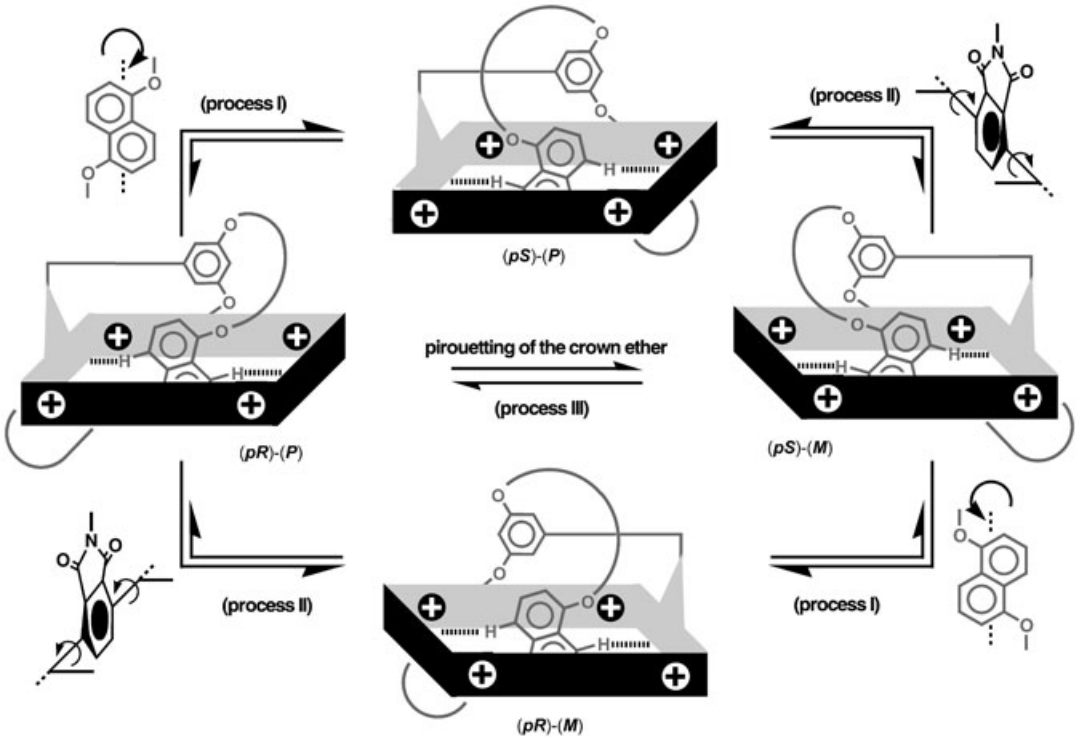


Figure 2. Graphical representations of the four possible stereoisomers of the pretzelane $\mathbf{7}^{4+}$ and the three possible dynamic processes (I, II, and III) associated with their interconversion.

the DNP ring system, which resides on the same side of the mean plane of the tetracationic cyclophane as the diimide group, pointing away from this functional group. In the case of the other enantiomeric pair, (*pS*)-(*P*)-$\mathbf{7}^{4+}$ and (*pR*)-(*M*)-$\mathbf{7}^{4+}$, this oxygen atom points toward the diimide group. Not surprisingly, the (*pR*)-(*P*) diastereoisomer is more stable than the (*pS*)-(*P*) isomer.

The X-ray structural analysis[16,17] of a single crystal obtained by vapor diffusion of $i\mathrm{Pr}_2\mathrm{O}$ into a solution of $\mathbf{7}\cdot 4\,\mathrm{PF}_6$ in MeCN identified the solid-state structure as containing an enantiomeric pair of molecules, namely, (*pR*)-(*P*)-$\mathbf{7}^{4+}$ and (*pS*)-(*M*)-$\mathbf{7}^{4+}$, and confirmed their pretzel-shaped topology (Figure 3). The tetracationic cyclophane is interlocked with the crown ether such that 1) the DNP ring system is sandwiched between the two bipyridinium units, aligned parallel to each other, with 2) one of these two units also sandwiched between the DNP ring system, also parallel, and the resorcinol ring, which is positioned alongside. The mean interplanar separations are 3.4 Å, in keeping with stabilizing π–π-stacking interactions. The conformation of the molecule is also stabilized by CH···O interactions[18] between two of the α protons on the inside bipyridinium unit and the nearby oxygen atoms in the two polyether loops of the crown ether. Furthermore, the molecular conformation is stabilized by yet another CH···O interaction between one of the oxygen atoms in the diethylene glycol linker and one of the hydrogen atoms on the appropriate methylene group at the corner of the tetracationic cyclophane. In addition, there are CH···π interactions between the naphthalene hydrogen atoms on C4 and C8 and their proximal *para*-phenylene rings. There are no discernable intermolecular stacking interactions.

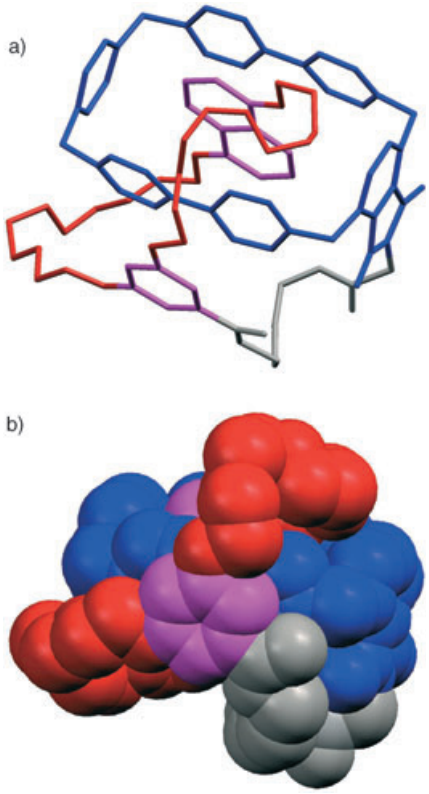


Figure 3. X-ray crystal structure of the pretzelane $\mathbf{7}^{4+}$ illustrated as a) framework and b) space-filling representations of the pretzelane. Purple: the π-donor units in the crown ether; red: the polyethylene glycol chains in the crown ether, blue: the tetracationic cyclophane; gray: the diethylene glycol chain connecting the two macrocycles.

The partial ^{1}H NMR spectrum of (Figure 4a) **7**·4 PF_6, recorded in CD_3CN, can be interpreted as a racemic modification of a single diastereoisomer. The relative stereochemistry and topology of this diastereoisomer can be

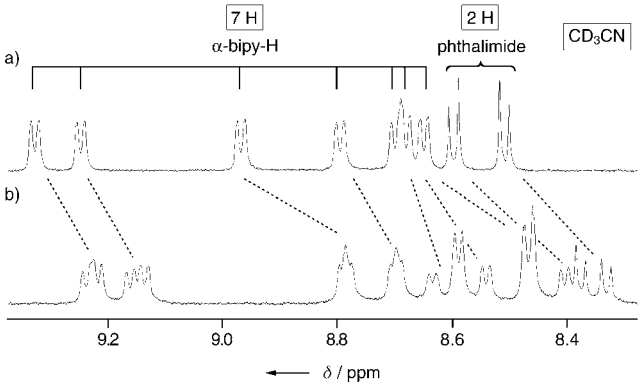


Figure 4. Partial ^{1}H NMR spectra, recorded in CD_3CN at room temperature, showing a) the signals for α-bipyridinium (bipy) and phthalimide protons in **7**·4 PF_6 and b) the change on addition of four equivalents of the chiral shift reagent Me_2NH_2·(*R*)-BINPHAT.

assigned by 2D ROESY spectroscopic analysis[19] to be the same one ((*pR*)-(*P*)-$\mathbf{7}^{4+}$/(*pS*)-(*M*)-$\mathbf{7}^{4+}$) as that observed in the solid state. The presence of these enantiomers was confirmed by recording the ^{1}H NMR spectrum (Figure 4b) in CD_3CN in the presence of a chiral shift reagent, dimethyl ammonium bis(tetrachlorobenzenediolato)mono((*R*)-[1,1′]-binaphthalenyl-2,2′-diolato)phosphate(v)[20] (Me_2NH_2·(*R*)-BINPHAT). Addition of four equivalents of Me_2NH_2·(*R*)-BINPHAT to a solution of **7**·4 PF_6 in CD_3CN results in the resonances for seven of the eight α-bipyridinium protons and the two phthalimido protons not only undergoing changes in chemical shift but also separating into two independent sets of equal intensity signals, which is commensurate with the formation of diastereoisomeric salts in approximately equal amounts.

Dynamic ^{1}H NMR spectroscopic analysis was performed on this pretzelane in CD_3SOCD_3. At room temperature, all of the protons are heterotopic and so give rise to well-resolved signals, thus indicating that any degenerate exchange processes are slow on the ^{1}H NMR timescale. Heating a CD_3SOCD_3 solution of **7**·4 PF_6 up to 120 °C (Figure 5a–d) causes the resonances[21] to begin to coalesce as a result of several site-exchange processes, including 1) reorientation (process I) of the DNP ring system outside the cyclophane's cavity, 2) a 180° rotation (process II) of the phthalimido unit about the $-CH_2ArCH_2-$ axis, and 3) pirouetting (process III) of the crown ether whereby its resorcinol unit moves from one bipyridinium unit around the tetracationic cyclophane to the other one. Since neither process I nor II are associated with degeneracy, they must occur as a pair, namely, processes I + II. The occurrence of this highly coordinated process is not unreasonable on the basis of a molecular modeling study: it suggests that the DNP ring system has to leave the cyclophane's cavity so that process II can occur.

Probe protons were chosen in $\mathbf{7}^{4+}$ to measure kinetic and thermodynamic data separately for processes I + II and

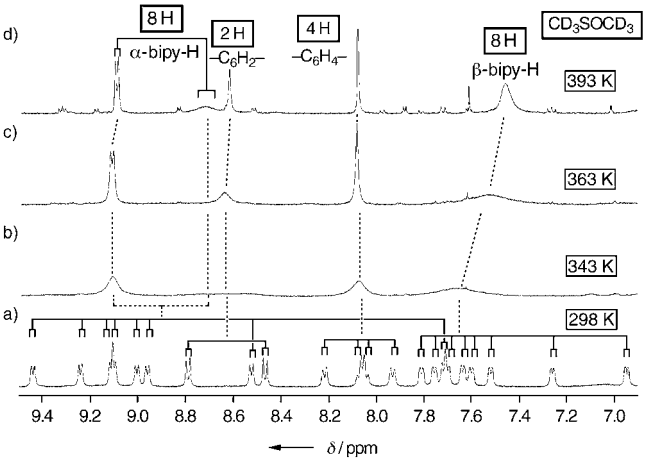


Figure 5. Partial ^{1}H NMR spectra of a solution of **7**·4 PF_6 in CD_3COCD_3 at a) 298, b) 343, c) 363, and d) 393 K, thus indicating the coalescence of the α- and β-bipyridinium protons and the phenylene protons. The unmarked, low-intensity peaks observed at 393 K are a result of decomposition of **7**·4 PF_6 at this temperature.

process III. The two diastereotopic protons on the 5-substituted resorcinol ring only undergo site exchange when processes I and II operate in tandem, while the two diastereotopic protons on the phthalimido unit experience site exchange as a result of process III. Spin-saturation transfer experiments[22] performed at 301 K on these two pairs of probe protons gave[23] ΔG values of 17.5 and 17.6 kcal mol^{-1}. The fact that these free energy barriers ($\Delta G^{\neq}$) are virtually identical (within experimental error) suggests that one process (I) is rate-limiting and that one or both of the other two processes (II and III) follow quickly.

In the case of **10**·4 PF_6 and **11**·8 PF_6, ESI mass spectrometry provided unambiguous evidence for their monomer–dimer relationship. Although they both reveal peaks at *m*/*z* 1681, 768, and 464 (Table 1), the charges carried by these ion fragments are different: the peaks for the former (**10**·4 PF_6) are singly, doubly, and triply charged, thus corresponding to the loss of one, two, and three PF_6^- ions, respectively, from a pretzelane-like constitution with a molar mass of 1826 Da, while the peaks for the latter (**11**·8 PF_6) are doubly, quadruply, and sextuply charged, thus corresponding to the loss of two, four, and six PF_6^- ions,[24] respectively, from a compound with a molar mass of 3652 Da

Table 1: Characterization[a] of **10**·4 PF_6 and **11**·8 PF_6 by ESI mass spectrometry.

Compounds	Number of PF_6^- counterions lost						
	1	2	3	4	5	6	7
10·4 PF_6	1681	768	464	312	–	–	–
(M_r = 1826)	(0.5)	(61)	(100)	(31)			
11·8 PF_6	–	1681	1072	768	586	464	377
(M_r = 3652)		(0.5)	(15)	(100)	(78)	(84)	(18)

[a] Data are presented as *m*/*z* ratio and (relative abundance (%)). Molecular weight and *m*/*z* values apply to the average mass of any isotope distribution and are based on a scale in which ^{12}C = 12.000.

and the constitution of a cyclic bis[2]catenane. To verify their mechanically interlocked topology, both compounds were subjected to acid-catalyzed hydrolysis of the ester linkage between the macrocyclic polyether and the tetracationic cyclophane. Heating **10**·4 PF_6 and **11**·8 PF_6 in CD_3CN/D_2O solutions at 70 °C for one day in the presence of one drop of HCl afforded a single product,[25] namely, the [2]catenane **12**·4 PF_6 in each case. These observations provide chemical proofs of the mechanically interlocked topologies of **10**·4 PF_6 and **11**·8 PF_6.

This exploratory study has established that the pretzelane topology can be generated[26] using appropriately CH···O-augmented donor–acceptor interactions as the recognition motif for templating the syntheses of dynamic pretzelanes. The fact that the barrier to enantiomerization between (*pR*)-(*P*)-**7**$^{4+}$ and (*pS*)-(*M*)-**7**$^{4+}$ is approximately 17.5 kcal mol^{-1} augurs well for introducing electrochemically switchable, metastable diastereoisomerism into bistable pretzelanes in which one of the bipyridinium units in the tetracationic cyclophane is replaced with a chemically modified one.

Experimental Section

7·4 PF_6: A solution of **5**[27] (0.45 g, 0.41 mmol) and the dicationic salt **6**·2 PF_6[8a] (0.39 g, 0.55 mmol) in DMF (10 mL) was stirred at room temperature for 5 days. Diethyl ether (200 mL) was added to the reaction mixture to ensure precipitation of the crude product. The precipitate was isolated by vacuum filtration and subjected to column chromatography on silica gel (MeOH/aqueous NH_4Cl (2 M)/$MeNO_2$, 7:2:1). Purple fractions containing the product were combined and concentrated. Solid NH_4PF_6 was added to the residue to precipitate **7**·4 PF_6 as a purple solid (0.39 g, 49 %). M.p. 195 °C (decomp); ^{1}H NMR (CD_3CN, 500 MHz, 298 K): δ = 9.27 (d, J = 6.6 Hz, 1 H), 9.19 (d, J = 6.6 Hz, 1 H), 8.88 (d, J = 6.6 Hz, 1 H), 8.73 (d, J = 6.6 Hz, 1 H), 8.65–8.59 (m, 3 H), 8.54 (d, J = 8.3 Hz, 1 H), 8.43 (d, J = 8.3 Hz, 1 H), 8.05 (d, J = 8.1 Hz, 1 H), 8.00–7.92 (m, 3 H), 7.43 (dd, J = 8.1, 2.4 Hz, 1 H), 7.41 (dd, J = 8.1, 2.4 Hz, 1 H), 7.38 (dd, J = 8.1, 2.4 Hz, 1 H), 7.36 (dd, J = 8.1, 2.4 Hz, 1 H), 7.28 (dd, J = 8.1, 2.4 Hz, 1 H), 7.27 (dd, J = 8.1, 2.4 Hz, 1 H), 7.00 (dd, J = 8.1, 2.4 Hz, 1 H), 6.95 (t, J = 1.5 Hz, 1 H), 6.81 (t, J = 1.5 Hz, 1 H), 6.67 (d, J = 13.7 Hz, 1 H), 6.62–6.60 (m, 2 H), 6.29 (d, J = 7.9 Hz, 1 H), 6.24 (d, J = 7.9 Hz, 1 H), 6.02 (t, J = 7.9 Hz, 1 H), 5.91–5.85 (m, 3 H), 5.78–5.73 (m, 4 H), 5.71 (t, J = 1.5 Hz, 1 H), 5.61 (t, J = 7.9 Hz, 1 H), 4.86 (d, J = 17.1 Hz, 1 H), 4.83 (dd, J = 12.5, 2.5 Hz, 1 H), 4.62 (dd, J = 12.5, 2.5 Hz, 1 H), 4.54 (d, J = 17.1 Hz, 1 H), 4.52–3.45 (m, 36 H), 3.29 (dd, J = 11.4, 2.5 Hz, 1 H), 3.07 (dd, J = 11.4, 2.5 Hz, 1 H), 2.50 (d, J = 8.1 Hz, 1 H), 2.44 ppm (d, J = 8.1 Hz, 1 H); MS(ESI): m/z 1783.4 $[M-PF_6]^+$, 818.9 $[M-2PF_6]^{2+}$, 497.6 $[M-3PF_6]^{3+}$; HRMS(ESI): m/z calcd for $C_{77}H_{81}N_5O_{17}P_3F_{18}$ $[M-PF_6]^+$: 1782.4547, found: 1782.4559.

10·4 PF_6 and **11**·8 PF_6: A solution of **9**[27] (0.31 g, 0.31 mmol) and **6**·2 PF_6[8a] (0.22 g, 0.31 mmol) in DMF (10 mL) was stirred at room temperature for 5 days. The solvent was removed under reduced pressure and the residue was subjected to column chromatography on silica gel. The fractions containing **10**·4 PF_6 were collected using MeOH/aqueous NH_4Cl (2 M)/$MeNO_2$ (7:2:1) as the eluent. The second set of fractions, containing **11**·8 PF_6, were collected using MeOH/aqueous NH_4Cl (2 M)/$MeNO_2$ (2:2:1) as the eluent. Solid NH_4PF_6 was added to the residues to precipitate **10**·4 PF_6 (76 mg, 14 %) and **11**·8 PF_6 (113 mg, 20 %) as brown solids.

10·4 PF_6: M.p. 232 °C (decomp); ^{1}H NMR ([D_6]DMSO, 500 MHz, 363 K): δ = 9.13–9.06 (m, 6 H), 8.69 (s, 2 H), 8.38 (br s, 2 H), 8.12 (s, 4 H), 7.83 (br s, 2 H), 7.81 (d, J = 7.9 Hz, 2 H), 7.66 (d, J = 6.6 Hz, 2 H), 7.59 (m, 4 H), 7.37 (t, J = 7.9 Hz, 2 H), 6.97 (d, J = 7.9 Hz, 2 H), 6.64 (br s, 2 H), 6.44 (s, 1 H), 6.22–5.80 (m, 8 H), 5.30–3.44 ppm (m, 36 H).

11·8 PF_6: M.p. 244 °C (decomp); ^{1}H NMR ([D_6]DMSO, 500 MHz, 363 K): δ = 9.22 (d, J = 6.4 Hz, 8 H), 9.01–8.78 (m, 8 H), 8.78 (s, 4 H), 8.17 (s, 8 H), 7.84–7.60 (m, 12 H), 7.10–6.93 (m, 4 H), 6.53 (s, 4 H), 6.35 (br s, 4 H), 6.30 (d, J = 8.3 Hz, 8 H), 5.90 (br. s, 8 H), 5.83 (br s, 4 H), 5.49 (s, 2 H), 5.34 (s, 4 H), 5.07 (s, 4 H), 4.45 (br s, 8 H), 4.28 (br s, 8 H), 4.11 (br s, 8 H), 4.01 (br s, 8 H), 3.93–3.46 (m, 32 H), 2.58 ppm (d, J = 8.3 Hz, 4 H).

Received: January 6, 2005
Published online: April 14, 2005

Keywords: catenanes · molecular devices · pretzelanes · self-assembly · template synthesis

[1] a) J. S. Lindsey, *New J. Chem.* **1991**, *15*, 153 – 180; b) D. Philp, J. F. Stoddart, *Angew. Chem.* **1996**, *108*, 1242 – 1286; *Angew. Chem. Int. Ed. Engl.* **1996**, *35*, 1154 – 1196; c) D. N. Reinhoudt, M. Crego-Calama, *Science* **2002**, *295*, 2403 – 2407.

[2] M. C. T. Fyfe, J. F. Stoddart, *Acc. Chem. Res.* **1997**, *30*, 393 – 401.

[3] a) G. Schill, *Catenanes, Rotaxanes, and Knots*, Academic Press, New York, **1971**; b) *Molecular Catenanes, Rotaxanes, and Knots* (Eds.: J.-P. Sauvage, C. Dietrich-Buchecker), Wiley-VCH, Weinheim, **1999**.

[4] a) V. Balzani, A. Credi, F. M. Raymo, J. F. Stoddart, *Angew. Chem.* **2000**, *112*, 3484 – 3530; *Angew. Chem. Int. Ed.* **2000**, *39*, 3348 – 3391; b) V. Balzani, A. Credi, M. Venturi, *Molecular Devices and* Machines—A *Journey into the Nano World*, Wiley-VCH, Weinheim, **2003**; c) A. H. Flood, R. J. A. Ramirez, W.-Q. Deng, R. P. Muller, W. A. Goddard III, J. F. Stoddart, *Aust. J. Chem.* **2004**, *57*, 301 – 322.

[5] a) D. W. Steuerman, H.-R. Tseng, A. J. Peters, A. H. Flood, J. O. Jeppesen, K. A. Nielsen, J. F. Stoddart, J. R. Heath, *Angew. Chem.* **2004**, *116*, 6648 – 6653; *Angew. Chem. Int. Ed.* **2004**, *43*, 6486 – 6491; b) A. H. Flood, A. J. Peters, S. A. Vignon, D. W. Steuerman, H.-R. Tseng, S. Kang, J. R. Heath, J. F. Stoddart, *Chem. Eur. J.* **2004**, *10*, 6558 – 6564; c) A. H. Flood, J. F. Stoddart, D. W. Steuerman, J. R. Heath, *Science* **2004**, *306*, 2055 – 2056.

[6] a) *Templated Organic Synthesis* (Eds.: F. Diederich, P. J. Stang), Wiley-VCH, Weinheim, **1999**; b) J. F. Stoddart, H.-R. Tseng, *Proc. Natl. Acad. Sci. USA* **2002**, *99*, 4797 – 4800.

[7] a) P.-L. Anelli, P. R. Ashton, R. Ballardini, V. Balzani, M. Delgado, M. T. Gandolfi, T. T. Goodnow, A. E. Kaifer, D. Philp, M. Pietraszkiewicz, L. Prodi, M. V. Reddington, A. M. Z. Slawin, N. Spencer, J. F. Stoddart, C. Vicent, D. J. Williams, *J. Am. Chem. Soc.* **1992**, *114*, 193 – 218; b) H.-R. Tseng, S. A. Vignon, P. C. Celestre, J. F. Stoddart, A. J. P. White, D. J. Williams, *Chem. Eur. J.* **2003**, *9*, 543 – 556.

[8] a) M. Asakawa, W. Dehaen, G. L'abbé, S. Menzer, J. Nouwen, F. M. Raymo, J. F. Stoddart, D. J. Williams, *J. Org. Chem.* **1996**, *61*, 9591 – 9595; b) G. Doddi, G. Ercolani, S. Franconeri, P. Mencarelli, *J. Org. Chem.* **2001**, *66*, 4950 – 4953; c) G. Ercolani, P. Mencarelli, *J. Org. Chem.* **2003**, *68*, 6472 – 6473; d) C. D'Acerno, G. Doddi, G. Ercolani, S. Franconeri, P. Mencarelli, A. Piermattei, *J. Org. Chem.* **2004**, *69*, 1393 – 1396.

[9] a) R. Jäger, T. Schmidt, D. Karbach, F. Vögtle, *Synlett* **1996**, *8*, 723 – 725; b) C. Yamamoto, Y. Okamoto, T. Schmidt, R. Jäger, F. Vögtle, *J. Am. Chem. Soc.* **1997**, *119*, 10547 – 10548; c) F. Vögtle, O. Safarowsky, C. Heim, A. Affeld, O. Braun, A. Mohry, *Pure Appl. Chem.* **1999**, *71*, 247 – 251; d) A. Mohry, H. Schwierz, F. Vögtle, *Synthesis* **1999**, *10*, 1753 – 1758; e) C. Heim, D. Udelhofen, F. Vögtle in *Molecular Catenanes, Rotaxanes and Knots* (Ed.: J.-P. Sauvage, C. Dietrich-Buchecker), Wiley-VCH, **1999**, pp. 177 – 222; f) C. Reuter, A. Mohry, A. Sobanski, F. Vögtle, *Chem. Eur. J.* **2000**, *6*, 1674 – 1682; g) Y. Qian, E. Vogel, A. H. Parham, M. Nieger, M. Bolte, R. Fröhlich, P. Saarenketo, K.

Rissanen, F. Vögtle, *Eur. J. Org. Chem.* **2001**, *21*, 4041 – 4049; h) M. O. Vysotsky, M. Bolte, I. Thondorf, V. Böhmer *Chem. Eur. J.* **2003**, *9*, 3375 – 3382.

[10] Q. Zhang, D. G. Hamilton, N. Feeder, S. J. Teat, J. M. Goodman, J. K. M. Sanders, *New J. Chem.* **1999**, *23*, 897 – 903.

[11] Acyclic bis[2]catenanes are known; for example: a) P. R. Ashton, A. S. Reder, N. Spencer, J. F. Stoddart, *J. Am. Chem. Soc.* **1993**, *115*, 5286 – 5287; b) P. R. Ashton, J. A. Preece, J. F. Stoddart, M. S. Tolley, *Synlett* **1994**, 789 – 792; c) P. R. Ashton, J. Huff, I. W. Parsons, J. A. Preece, J. F. Stoddart, M. S. Tolley, D. J. Williams, A. J. P. White, *Chem. Eur. J.* **1996**, *2*, 123 – 136; d) N. Armaroli, M. A. J. Rodgers, P. Ceroni, V. Balzani, C. O. Dietrich-Buchecker, J.-M. Kern, A. Bailal, J.-P. Sauvage, *Chem. Phys. Lett.* **1995**, *241*, 555 – 558.

[12] S. Menzer, A. J. P. White, D. J. Williams, M. Belohradsky, C. Hamers, F. M. Raymo, A. N. Shipway, J. F. Stoddart, *Macromolecules* **1998**, *31*, 295 – 307.

[13] Y. Liu, A. H. Flood, R. M. Moskowitz, J. F. Stoddart, *Chem. Eur. J.* **2005**, *11*, 369 – 385.

[14] P. R. Ashton, I. Baxter, S. J. Cantrill, M. C. T. Fyfe, P. T. Glink, J. F. Stoddart, A. J. P. White, D. J. Williams, *Angew. Chem.* **1998**, *110*, 1344 – 1347; *Angew. Chem. Int. Ed.* **1998**, *37*, 1294 – 1297.

[15] For a discussion of the chirality and the assignment of absolute chiralities to helices and planes, see the Supporting Information.

[16] CCDC-258912 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

[17] Crystal data for compound **7**·4 PF_6 ($C_{77}H_{81}N_5O_{17}P_4F_{24}$·5 MeCN): $M_r = 2133.62$, triclinic, space group $P\bar{1}$, $a = 14.443(1)$, $b = 14{,}692(1)$, $c = 24.274(2)$ Å, $\alpha = 96.324(1)$, $\beta = 95.790(1)$, $\gamma = 110.893(1)°$, $V = 4728.4(6)$ Å^3, $T = 120$ K, $Z = 2$, red platelike needles of approximate size $0.4 \times 0.2 \times 0.18$ mm, $\rho_{calcd} = 1.499$ g cm^{-3}, $\mu(Mo_{K\alpha}) = 0.198$ mm^{-1}, 42 599 reflection measured on Bruker Smart 1000 CCD diffractometer. 22 159 independent reflections, semi-empirical absorption correction from equivalents, F^2 refinement, 1355 parameters, R_1/wR_2 $[I > 2\sigma(I)] = 0.08/0.23$, $R_1/wR_2 = 0.11/0.26$ (all data).

[18] F. M. Raymo, M. D. Bartberger, K. N. Houk, J. F. Stoddart, *J. Am. Chem. Soc.* **2001**, *123*, 9264 – 9267.

[19] The assignment of relative stereochemistry to the more stable diastereoisomer of **7**·4 PF_6 using 2D ROESY is described in the Supporting Information. Also, the fact that the H-4 and H-8 protons on the dioxynaphthalene unit resonate at very high field ($\delta = 2.25$ and 2.28 ppm) indicates that this ring system is located inside the cavity of the tetracationic cyclophane.

[20] J. Lacour, A. Londez, C. Goujon-Ginglinger, V. Buss, G. Bernardinelli, *Org. Lett.* **2000**, *2*, 4185 – 4188.

[21] The pretzelane **7**·4 PF_6 begins to decompose at 120 °C in CD_3SOCD_3 solution.

[22] a) M. Feigel, H. Kessler, D. Leibfritz, *J. Am. Chem. Soc.* **1979**, *101*, 1943 – 1950; b) B. E. Mann, *J. Magn. Reson.* **1977**, *25*, 91 – 94.

[23] $\Delta G^{\neq}$ values were calculated from the rate constants k_{ex} by using the Eyring equation $\Delta G^{\neq} = R T_c \ln(k_{ex} h / k_b T_c)$, in which R is the gas constant, h is the Planck constant, and k_b is the Boltzmann constant.

[24] Furthermore, the ESI mass spectrometry of **11**·8 PF_6 also contains peaks showing the loss of three, five, and seven PF_6^- ions.

[25] The synthesis and characterization of the common [2]catenane **12**·4 PF_6 are described in the Supporting Information.

[26] A comparison of the outcomes summarized in Schemes 1 and 2 indicated that the length of the tether between the crown ether and the tetracationic cyclophane is a key parameter in determining the results of the template-directed cyclization. The longer and more flexible linker (Scheme 1) favors pretzelane formation. Higher homologues are not observed, thus reflecting the well-established fact that the entropic cost associated with generating polymeric assemblies as a result of the kinetically controlled supramolecular assistance to covalent synthesis is simply too high: small cycles are much preferred over large ones and their acyclic counterparts; see: a) R. Kramer, J.-M. Lehn, A. Marquis-Rigault, *Proc. Natl. Acad. Sci. USA* **1993**, *90*, 5394 – 5398; b) P. R. Ashton, A. N. Collins, M. C. T. Fyfe, P. T. Glink, S. Menzer, J. F. Stoddart, D. J. Williams, *Angew. Chem.* **1997**, *109*, 59 – 62; *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 59 – 62; c) D. L. Caulder, K. N. Raymond, *Angew. Chem.* **1997**, *109*, 1508 – 1510; *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 1440 – 1442; d) S. J. Cantrill, G. J. Youn, J. F. Stoddart, D. J. Williams, *J. Org. Chem.* **2001**, *66*, 6857 – 6872.

[27] The syntheses of **5** and **9** are described in the Supporting Information.

