

Self-Assembling Cyclophanes and Catenanes Possessing Elements of Planar Chirality**

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Abstract: Cyclobis(paraquat-1,5-naphthalene) has been prepared by a template-directed synthesis. As a result of the presence of the two chiral planes generated by its 1,5-disubstituted naphthalene residues, this compound can exist in three different stereoisomeric forms, an achiral (*RS*) form and two chiral forms, (*RR*) and (*SS*). Although the racemic modification could not be separated from the *meso* isomer, dynamic NMR spectroscopy together with molecular modeling indicate a diastereoisomeric ratio of 3:1 in favor of the (*RR/SS*) form. In addition, a couple of [2]catenanes in which the π -electron-deficient cyclobis(paraquat-1,5-naphthalene) component is interlocked with one of the π -electron-rich macrocyclic

polyethers bis-*p*-phenylene[34]crown-10 (BPP34C10) or bis-1/5-dinaphtho[38]crown-10 (1/5DN38C10) self-assemble with diastereoselectivities in the range 50–60%. Relative stereochemical assignments for the different stereoisomeric forms have been achieved by dynamic NMR spectroscopy. In both [2]catenanes, the diastereoisomers in which the tetracationic cyclophanes have local D_2 symmetry predominate. When the dynamic processes occurring within the [2]catenane containing the 1/5DN38C10 macrocycle are slow on the

NMR timescale, a third element of planar chirality can be observed. This element is associated with the inside 1,5-dioxynaphthalene residue belonging to the crown ether and is orthogonal to the two chiral planes already present within the skeleton of the tetracationic cyclophane component. After repeated fractional crystallizations, single crystals were obtained, and one was subjected to X-ray crystallography. The 1,5-disubstituted naphthalene residues in both the cyclobis(paraquat-1,5-naphthalene) and the 1/5DN38C10 components were found to have (*SS*) chirality; that is, the [2]catenane undergoes spontaneous resolution on crystallization.

Keywords: catenanes • chirality • pseudorotaxanes • self-assembly • template synthesis

Introduction

There are numerous ways^[1] of introducing chirality into cyclophanes and hence into catenanes, in which they are incorporated as components. Here, we describe the introduction of elements of planar chirality^[2] into cyclobis(paraquat-*p*-phenylene)^[3] **1**⁴⁺ (Figure 1) and show how this chirality can be incorporated into the [2]catenanes^[4] **2**⁴⁺ and **3**⁴⁺.

Cyclobis(paraquat-1,5-naphthalene) **4**⁴⁺, in which the two *p*-phenylene spacers present in **1**⁴⁺ have been replaced by 1,5-disubstituted naphthalene spacers (as elements of planar chirality), can exist in three different stereoisomeric forms (Figure 2): an achiral (*RS*) form with C_{2h} symmetry in which the naphthalene spacers are eclipsed with respect to each other, and chiral (*RR*) and (*SS*) forms with D_2 symmetry in which the naphthalene spacers are staggered with respect to each other. The rotation of the naphthalene spacers around an axis defined by their ring-junction carbon atoms allows interconversion between the different diastereoisomers and inversion between the enantiomers. From an inspection of

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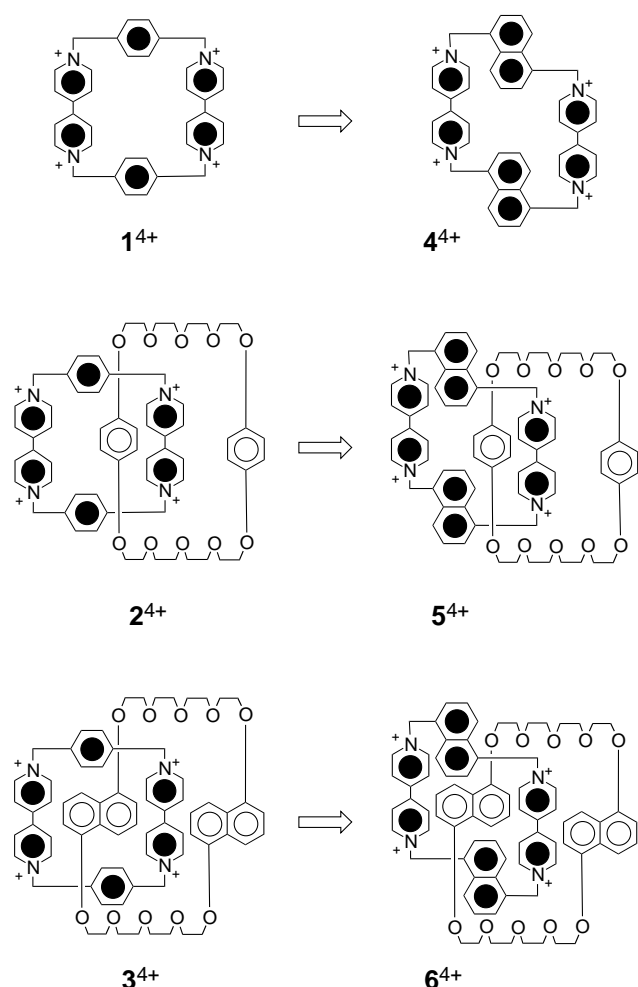


Figure 1. Introducing elements of planar chirality into the tetracationic cyclophane 1^{4+} and into the [2]catenanes 2^{4+} and 3^{4+} .

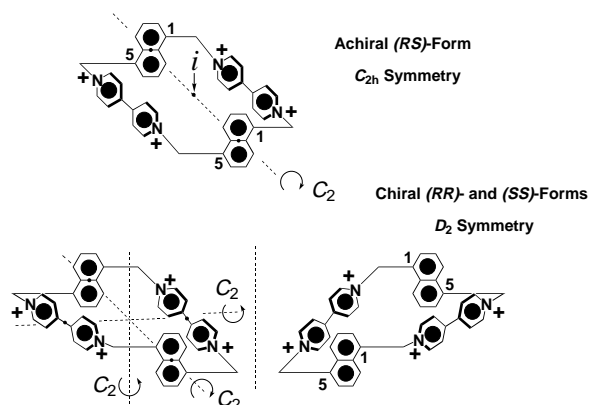


Figure 2. The different stereochemical forms of cyclobis(paraquat-1,5-naphthalene) 4^{4+} .

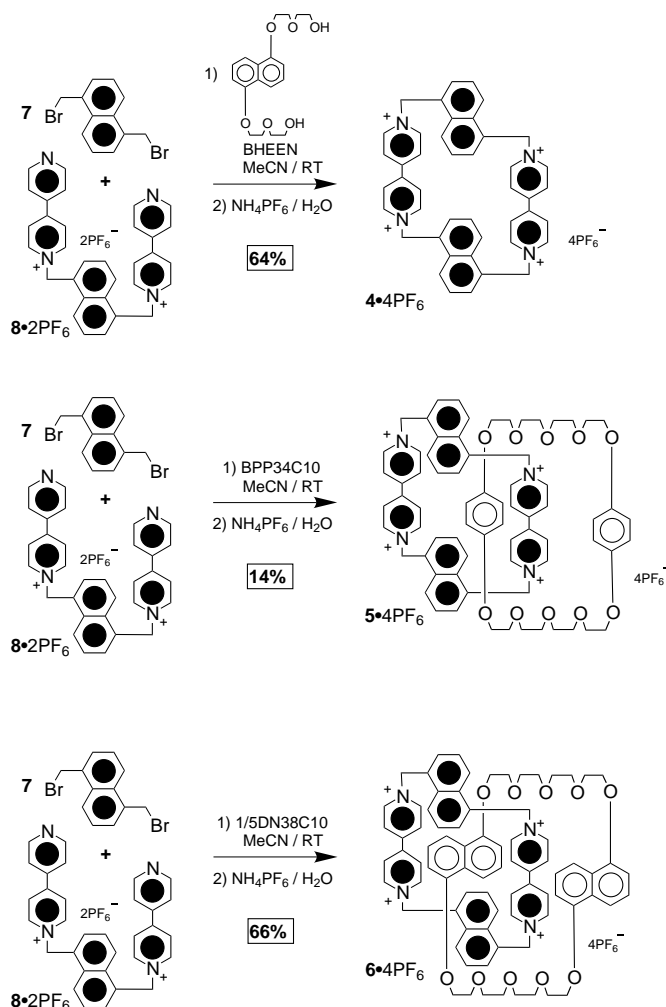
CPK space-filling molecular models (vide infra, molecular modeling) such a process, however, appears not to be possible because of the unfavorable steric interactions that would occur between the H-4/8 protons of the naphthalene spacers and the bipyridinium units in the tetracationic cyclophane

during the interconversion between the different diastereoisomers.^[5]

We report how this tetracationic cyclophane can be self-assembled in the presence of either bis-*p*-phenylene[34]-crown-10 (BPP34C10) or bis-1,5-dinaphtho[38]crown-10 (1/5DN38C10) to afford the [2]catenanes 5^{4+} and 6^{4+} with two and four planes of chirality, respectively.

Results and Discussion

Synthesis and complexation studies: Reaction of excess 4,4'-bipyridine with 1,5-bis(bromomethyl)naphthalene^[6] (**7**) in MeCN yielded the pure dicationic salt $8 \cdot 2PF_6$ in 30% yield, after purification by column chromatography and counterion exchange. Cyclobis(paraquat-1,5-naphthalene) $4 \cdot 4PF_6$ was obtained by reacting approximately equimolar amounts of **7** and $8 \cdot 2PF_6$ in the presence of excess (6 mol equiv) template 1,5-bis[2-(2-hydroxyethoxy)ethoxy]naphthalene^[7] (BHEEN), Scheme 1. The cyclophane, which was isolated in 64% yield after chromatography and counterion exchange, was not obtained when the reaction was repeated under exactly the



Scheme 1. Template-directed syntheses of the tetracationic cyclophane $4 \cdot 4PF_6$ and the [2]catenanes $5 \cdot 4PF_6$ and $6 \cdot 4PF_6$.

same conditions but without the template. When BPP34C10 and 1/5DN38C10 were present in threefold molar excess in separate reaction mixtures containing **7** and **8**·2PF₆⁻, the [2]catenanes **5**·4PF₆⁻ and **6**·4PF₆⁻ were subsequently isolated in yields of 14 and 66%, respectively. The remarkable difference in these yields might reflect, in part at least, the much better binding of BHEEN than of 1,4-bis[2-(2-hydroxyethoxy)ethoxy]benzene^[4a] (BHEEB) by the tetracationic cyclophane **4**·4PF₆⁻. See Scheme 2 for the association constants (K_a) and the derived ΔG° values. Similar differences have also been noted^[3] for cyclobis(paraquat-*p*-phenylene) (**1**⁴⁺), where the K_a value ($>5000\text{M}^{-1}$) for the 1:1 complex with BHEEN is considerably higher than that ($K_a = 2220\text{M}^{-1}$) for the 1:1 complex with BHEEB. Further evidence for complexation between i) BHEEB or ii) BHEEN with **4**·4PF₆⁻ comes from X-ray crystallography carried out on complexes with 1:1 and 2:1 stoichiometries, respectively.

Solid-state structures of complexes with cyclobis(paraquat-1,5-naphthalene): Single crystals suitable for X-ray structural analysis of the [2]pseudorotaxane containing BHEEB were grown by vapor diffusion of *i*Pr₂O into a solution containing **4**·4PF₆⁻ ($6 \times 10^{-4}\text{M}$) and BHEEB (10^{-2}M) in MeCN. The X-ray analysis of the complex (Figure 3) shows the structure of the tetracationic component to be disordered, with each 1,5-disubstituted naphthalene spacer exhibiting a C_2 -flipping about an axis passing through the two methylene substituents. As the complex crystallizes in the uniquely determinable centrosymmetric space group $P2_1/c$, the average distribution of atoms throughout the unit cell must have C_i symmetry. The occupancies of the two orientations of the 1,5-disubstituted naphthalene units are each 50%; therefore it is not possible to establish whether we have a superimposition of the two enantiomeric forms of the tetracationic cyclophane, or a C_2 disorder of the achiral form (about an axis passing through

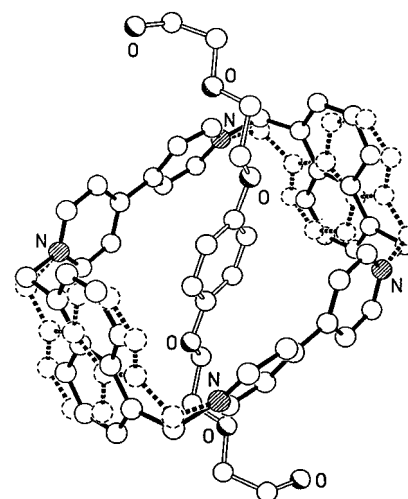
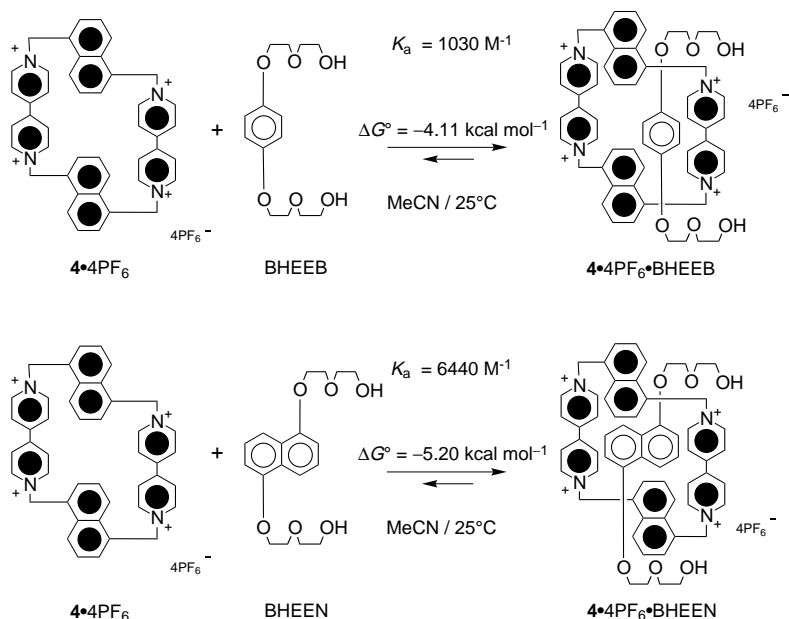


Figure 3. The structure of **4**·4PF₆⁻·BHEEB in the solid state.

the centers of the two bipyridinium unit), or a contribution of all three. There is only one orientation observed for the hydroquinone ring of BHEEB, which is sandwiched symmetrically between the two bipyridinium units (which exhibit twist and bow distortions each of 28°) with a mean interplanar separation of ca. 3.62 Å between the π -electron-rich and π -electron-deficient components. The OC₆H₄O axis of the thread is inclined by 51° with respect to the mean plane of the tetracationic cyclophane. Secondary complex stabilization is achieved by weak C–H⋯O hydrogen bonds between diametrically opposite β -pyridinium hydrogen atoms and the proximal central oxygen atom of each polyether chain (C⋯O, H⋯O distances, and C–H⋯O angle of 3.13, 2.43 Å, and 129°, respectively). The only dominant intercomplex interaction is a face-to-face π -stacking of the 1,5-disubstituted naphthalene spacers of the tetracationic cyclophanes (mean interplanar separation 3.42 Å) of lattice-translated complexes. There are no major hydrogen-bonding interactions involving the terminal hydroxyl groups of BHEEB. The only approach to this oxygen atom is an intermolecular contact of 2.63 Å to one of the methylene hydrogen atoms of the tetracationic cyclophane.

Single crystals suitable for X-ray structural analysis of the [2]pseudorotaxane containing BHEEN were grown by vapor diffusion of *i*Pr₂O into a solution containing **4**·4PF₆⁻ ($6 \times 10^{-4}\text{M}$) and BHEEN (10^{-2}M) in MeCN. The X-ray analysis of the complex reveals the formation of a 1:2 complex between **4**⁴⁺ and BHEEN (Figure 4), a stoichiometry analogous to that observed^[3] for the complexation of 1,5-dioxynaphthalene acyclic polyethers by the tetracationic cyclophane **1**⁴⁺ in the solid state. The two independent BHEEN threads are orientated with their 1,5-dioxynaphthalene ring systems positioned on crystallographically independent inversion centers. As in the case of the 1:1 complex formed between **4**⁴⁺ and BHEEB, **4**⁴⁺ exhibits rotational disorder of its two 1,5-disub-



Scheme 2. Complexation of BHEEB and of BHEEN by the tetracationic cyclophane **4**·4PF₆⁻.

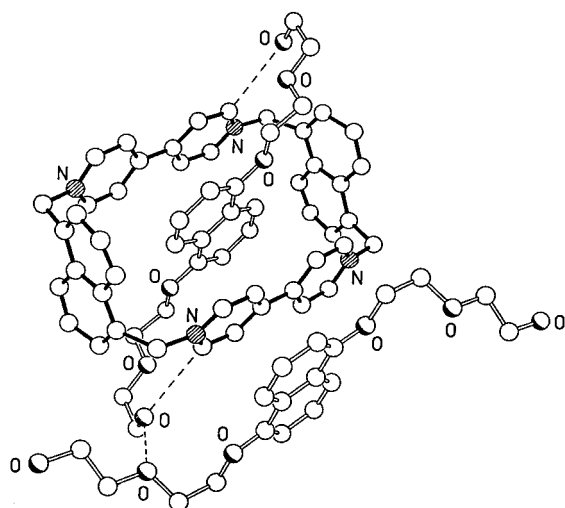


Figure 4. The 1:2 complex formed between $4 \cdot 4\text{PF}_6$ and BHEEN in the solid state.

stituted naphthalene spacers, thereby precluding the resolution of the isomers present (only one of the possible isomeric forms is illustrated in Figure 4). The twisting and bowing parameters of the bipyridinium units are 9° and 17° , respectively. The $\text{OC}_{10}\text{H}_6\text{O}$ axes of the 1,5-dioxynaphthalene rings of the inside and alongside BHEEN threads are inclined by 63° and 41° , respectively, with respect to the mean plane of the tetracationic cyclophane. The mean interplanar separation between the inside 1,5-dioxynaphthalene ring system and the bipyridinium units of the tetracationic cyclophane is 3.44 \AA . As the alongside 1,5-dioxynaphthalene ring system is positioned on an inversion center, it is sandwiched (π - π stacked) symmetrically between symmetry-related tetracationic cyclophanes (mean interplanar separation 3.42 \AA). The 1:2 complex is stabilized further by i) C-H \cdots O hydrogen bonds between one of the α -pyridinium hydrogen atoms and the terminal hydroxyl oxygen atom of the inside BHEEN (C \cdots O, H \cdots O distances, and C-H \cdots O angle of 3.16 , 2.25 \AA , and 159° , respectively), and ii) inter-thread O-H \cdots O hydrogen bonds from the hydroxyl group of the inside BHEEN to the central oxygen atom of the polyether chain of the alongside BHEEN (O \cdots O, H \cdots O distances and O-H \cdots O angle of 2.68 , 1.95 \AA , and 148° , respectively). The effect of the combined π -donor- π -acceptor stacking and intercomponent O-H \cdots O hydrogen bonding is to create an overall pseudopolyrotaxane chain (Figure 5). Adjacent hydrogen-bonded pseudopolyrotaxane chains are aligned with the 1,5-disubstituted naphthalene spacers of the tetracationic cyclophane components parallel but slightly off set with respect to that of the next (mean interplanar separation and centroid-centroid distance between the 1,5-disubstituted naphthalene ring systems of 3.34 and 4.60 \AA).

^1H NMR spectroscopic investigation of the cyclophane and of the [2]catenanes: The ^1H NMR spectrum (400 MHz) of $4 \cdot 4\text{PF}_6$ in CD_3COCD_3 at 304 K (Figure 6) reveals the presence of two sets of resonances in a 3:1 ratio corresponding to the diastereoisomers shown in Figure 2. The separate signals for these diastereoisomers are clearly evident only in

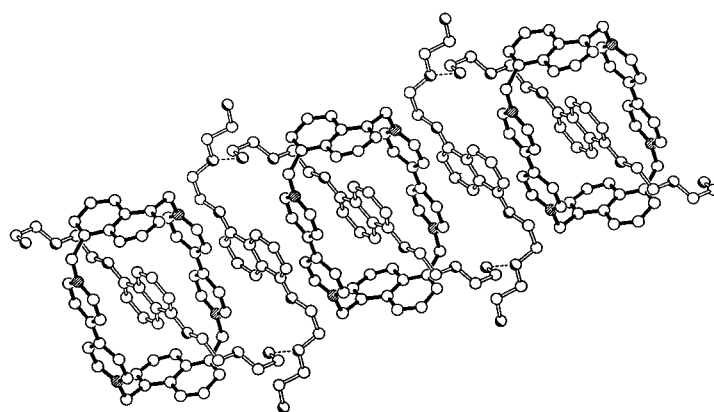


Figure 5. The hydrogen-bonded pseudopolyrotaxane chain formed by $4 \cdot 4\text{PF}_6$ and BHEEN in the solid state.

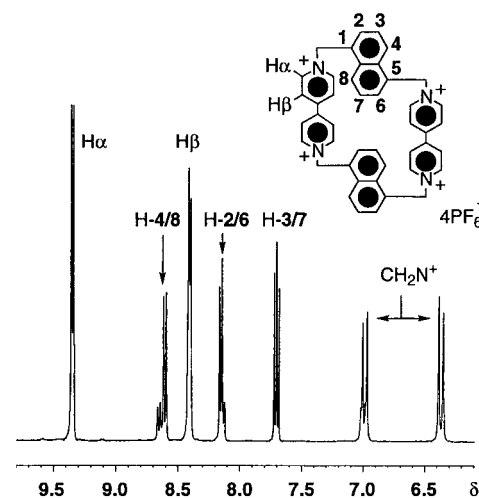


Figure 6. The ^1H NMR spectrum of $4 \cdot 4\text{PF}_6$ recorded at 30°C (400 MHz) in CD_3COCD_3 .

the case of the H-4/8 protons on the naphthalene spacers of the tetracationic cyclophane. They seem to be the most sensitive to the geometrical differences that characterize the achiral and chiral forms.^[8] The ratio between the two separate sets of signals remains virtually unchanged over a wide range (210 K to 333 K) of temperatures suggesting that the interconversion between the isomers (i.e., the rotation of one or both naphthalene spacers around an axis defined by their ring-junction carbon atoms in positions 4a and 8a) does not occur on the ^1H NMR timescale below 333 K . By contrast, since only one set of signals is observed for the α -CH and β -CH bipyridinium protons, the rotation of the bipyridinium units about their N \cdots N axis is, presumably, fast on the ^1H NMR timescale.

The ^1H NMR spectrum (400 MHz) of $5 \cdot 4\text{PF}_6$ showed temperature-dependent behavior in CD_3COCD_3 . At 298 K (Figure 7a), two sets of resonances are present in a 4:1 ratio corresponding to the chiral and achiral forms of the [2]catenane, which incorporate the (*RR/SS*) and the (*RS*) forms of the tetracationic cyclophane component, respectively. The exchange of the inside and alongside hydroquinone rings of the π -electron-rich macrocycle (Process 1) can occur as a result of the circumrotation of the crown ether through the

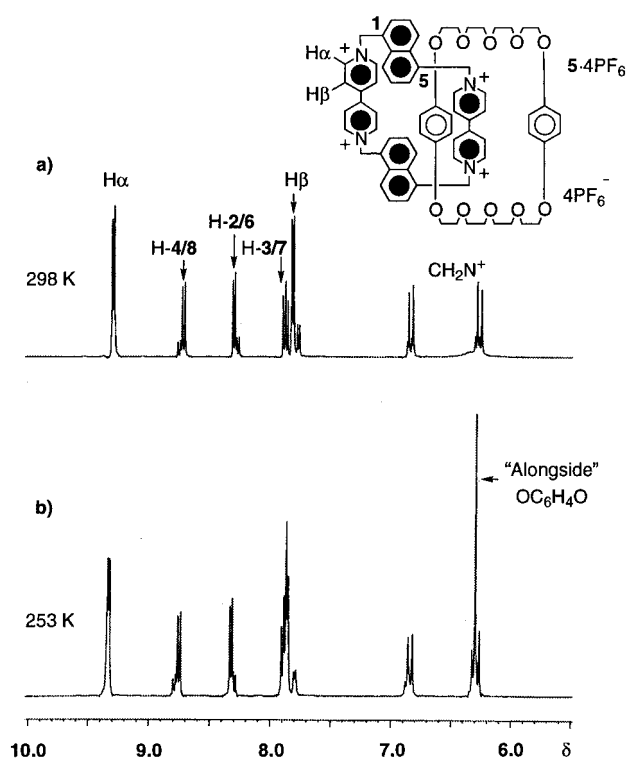


Figure 7. Comparison of the ^1H NMR spectra recorded at a) 298 K and b) 253 K for a solution of the [2]catenane $5 \cdot 4\text{PF}_6$ (400 MHz) in CD_3COCD_3 .

cavity of the tetracationic cyclophane. Similarly, the exchange of the inside and alongside bipyridinium units of the π -electron-deficient macrocycle (Process 2) can occur as a result of the circumrotation of the tetracationic cyclophane through the cavity of the crown ether. At 253 K (Figure 7b), distinct alongside and inside resonances for the hydroquinone ring protons of the crown ether BPP34C10 could be identified^[9] in the spectrum of the [2]catenane at $\delta = 6.30$ and 3.15, respectively. A value for the energy barrier ($\Delta G_c^\ddagger = 14.3 \text{ kcal mol}^{-1}$) associated with Process 1 could be obtained by means of the approximate coalescence treatment.^[10,11] When a sample of the [2]catenane in CD_3COCD_3 was cooled to 240 K, two sets of resonances arising from the α -CH bipyridinium protons, as well as two sets of resonances attributed to the β -CH bipyridinium protons, could be observed. This indicates that either the rotation of the bipyridinium units about their N...N axis or Process 2 has been slowed down on the ^1H NMR timescale at this temperature. The associated en-

ergy barrier could be calculated ($\Delta G_c^\ddagger = 9.6 \text{ kcal mol}^{-1}$) by means of the approximate coalescence treatment.^[11]

The [2]catenane $6 \cdot 4\text{PF}_6$ incorporates two 1,5-dioxynaphthalene rings within the macrocyclic polyether component and two 1,5-disubstituted naphthalene spacers within the tetracationic cyclophane component; thus it possesses a total of four elements of planar chirality (Figure 8). Each element of planar chirality can adopt (*R*) or (*S*) forms, and as a result the sixteen combinations listed in the matrix shown in Figure 8 are possible. However, the elements of planar chirality **A** and **B** are related by local reflection symmetry when they exhibit different chiralities, that is, when one is (*R*) and the other is (*S*) or vice versa. Thus, the diastereoisomers δ and ζ , as well as their enantiomers δ' and ζ' , can each be described by two different lines of the matrix. In summary, $6 \cdot 4\text{PF}_6$ can exist as a mixture of six diastereoisomeric pairs of enantiomers, a total of twelve stereoisomers. Interconversion of these isomers can occur, in principle, after the reversal of the local chiralities associated with the four elements of planar chirality **A–D**, that is, after the rotation of the naphthalene rings around an axis defined by their ring-junction carbon atoms in positions 4a and 8a. As an example, interconversion of α into its enantiomer α' can be achieved, at least in principle, by flipping all naphthalene rings from the (*R*) to the (*S*) chirality. Alternatively, interconversion between two diastereoisomers (but not between two enantiomers) can be effected after the circumrotation of the macrocyclic polyether through the cavity of the tetracationic cyclophane (Process 1). Indeed, Process 1 exchanges the elements of planar chirality **C** and **D** and when these possess different chiralities—one is (*R*) while the other is (*S*)—the interconversion between two diastereoisomers possessing the same form of the tetracationic cyclophane and the (*RS*) or (*SR*) forms of the macrocyclic polyether can be achieved. Similarly, Process 2 exchanges the elements of planar chirality **A** and **B**. However, since these are related by symmetry when possessing different chiralities (i.e., when one is (*R*) the other (*S*)) in all cases, the

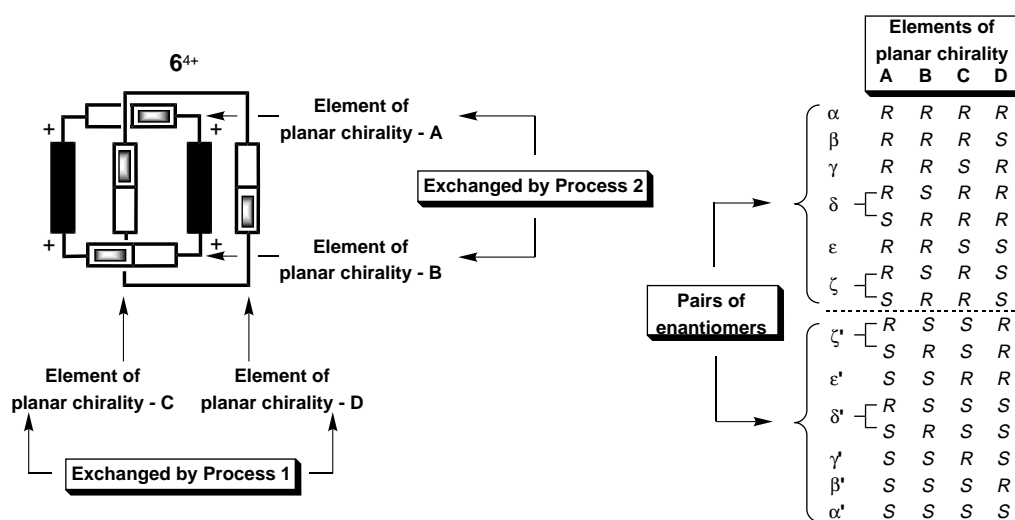


Figure 8. Spelling out the elements of planar chirality in the [2]catenane $6 \cdot 4\text{PF}_6$. Although certain diastereoisomers can interconvert with relative ease, inversion of enantiomers would be a process associated with a very high activation barrier.

rotation of the tetracationic cyclophane through the cavity of the macrocyclic polyether is a degenerate process, affording the original isomer (compare, for example, the two matrix lines describing the same enantiomer **I** before and after exchanging the elements of planar chirality **A** and **B**). In summary, interconversion of two enantiomers can be achieved only after the reversal of the local chiralities associated with the four elements of planar chirality **A–D**, while interconversion of two diastereoisomers can occur by the reversal of the local chiralities and/or the circumrotation of the macrocyclic polyether through the cavity of the tetracationic cyclophane component.

At 300 K in CD_3COCD_3 , Process 1 is slow on the ^1H NMR timescale and one of the 1,5-dioxynaphthalene residues of the neutral macrocyclic polyether may be considered to reside inside the cavity of the tetracationic cyclophane. However, there is no differentiation between the inside and alongside environments for the tetracationic cyclophane because Process 2 remains fast on the ^1H NMR timescale. Furthermore, at this temperature reversal of the local chiralities associated with the elements of planar chirality **A–C** does not occur on the ^1H NMR timescale, as suggested by the variable-temperature ^1H NMR spectroscopic investigations of $4\cdot 4\text{PF}_6$ (vide supra) and of the [2]catenane $3\cdot 4\text{PF}_6$.^[4b] By contrast, the flipping of the alongside 1,5-dioxynaphthalene ring (the reversal of the local chirality associated with the element of planar chirality **D**) is fast on the ^1H NMR timescale. As a result, the fourth column of the matrix shown in Figure 8 can be neglected reducing the number of isomers to six, namely the three pairs of enantiomers **I–III** shown in Figure 9.

The partial ^1H NMR spectrum (400 MHz) of $6\cdot 4\text{PF}_6$, recorded in CD_3COCD_3 at 300 K, is shown in Figure 10. The resonances arising from all of the local symmetry-related

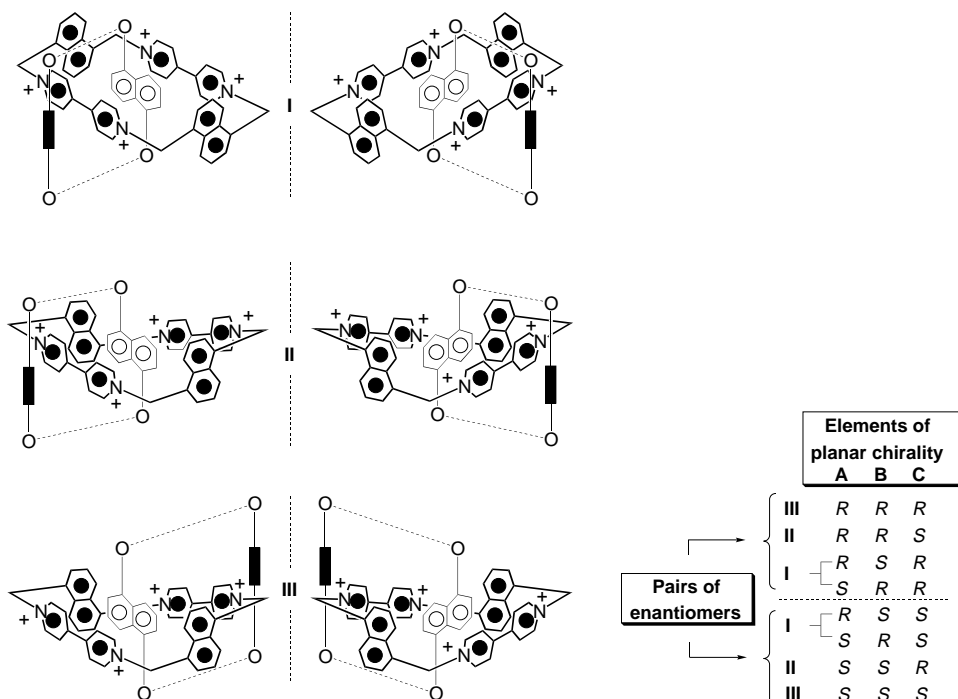


Figure 9. The three pairs of enantiomers associated with the [2]catenane $6\cdot 4\text{PF}_6$ at low temperatures.

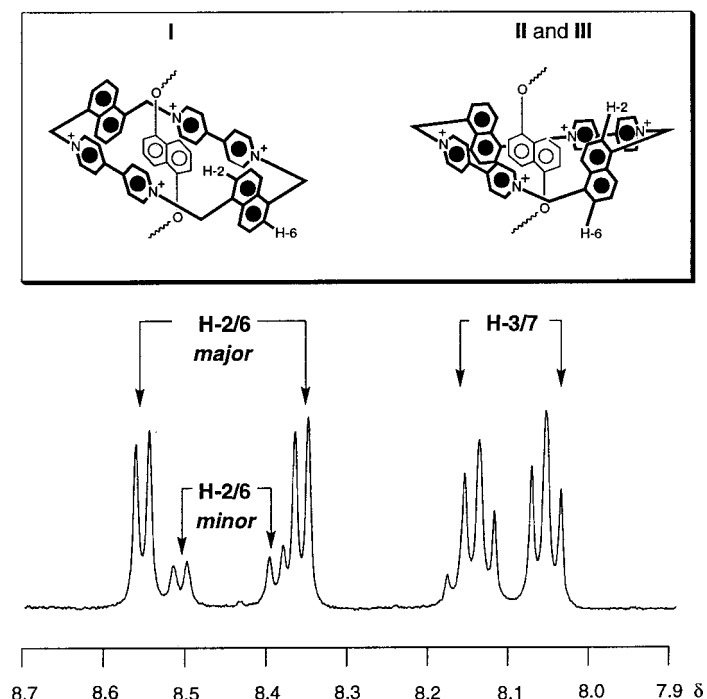


Figure 10. Partial representation of the ^1H NMR spectrum of the [2]catenane $6\cdot 4\text{PF}_6$ in CD_3COCD_3 at 300 K, showing the resonances associated with protons attached to the 1,5-disubstituted naphthalene spacers in the tetracationic cyclophane.

H-2/6, H-3/7 and H-4/8 protons on the naphthalene spacers of the tetracationic cyclophane component appear as different sets of doublets as a result of their intrinsic positions away from the oxygen and close to the oxygen of the inside 1,5-dioxynaphthalene residue of the 1/5DN38C10 component.

The ^1H NMR spectrum (Figure 10) depicts only two sets of signals in a 3:1 ratio,^[12] presumably, because **II** and **III** give rise to isochronous resonances. Similarly, two sets of resonances, again in a 3:1 ratio, are observed for the H-2/6 protons of the inside dioxynaphthalene residue at 300 K (Figure 11). However, on cooling the solution down to 220 K, Process 2 becomes slow on the ^1H NMR timescale and the less intense set of resonances separates into two equally intense signals. Indeed, while the H-2/6 protons of the inside dioxynaphthalene residue in **II** and **III** are homotopic, in **I** they become diastereotopic once the circumrotation of the tetracationic cyclophane through the cavity of the macrocyclic polyether becomes slow on the ^1H NMR timescale. Thus, at 220 K the H-2/6 proton resonances for the inside 1,5-dioxynaphthalene residue appear as one doublet centered on $\delta = 5.82$ for **II** and **III**—the major species in

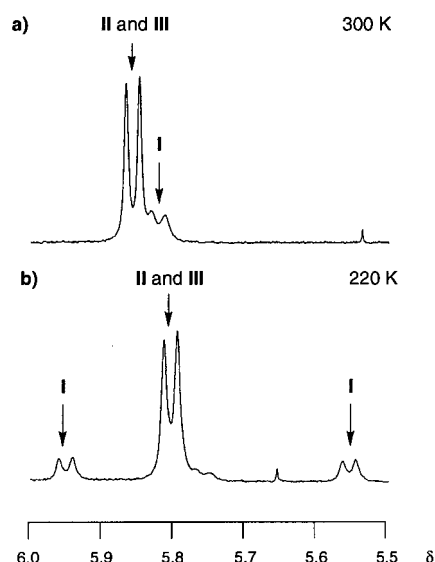


Figure 11. Partial representation of the ^1H NMR spectrum of the [2]catenane $6 \cdot 4\text{PF}_6$ in CD_3COCD_3 showing the resonances associated with the H-2/6 protons of the inside 1,5-dioxynaphthalene units at a) 300 and b) 220 K.

solution—while they are separated into two doublets centered on $\delta = 5.56$ and 5.97 in **I** (Figure 11). A (^1H – ^1H)NOESY experiment at 220 K in CD_3COCD_3 showed exchange between the two minor peaks, but not between them and the major one. Furthermore, they integrate correctly in a 1:6:1 ratio. The same pattern emerges for the symmetry-related H-3/7 and H-4/8 protons associated with the inside dioxynaphthalene residues.^[13]

Whereas recrystallizations by vapor diffusion of $i\text{Pr}_2\text{O}$ in MeCN solutions of $4 \cdot 4\text{PF}_6$ and of $5 \cdot 4\text{PF}_6$ did not improve their diastereoisomeric ratios, ^1H NMR spectroscopy revealed that three recrystallizations of $6 \cdot 4\text{PF}_6$ by the same method afforded a diastereoisomeric mixture in which the pair of enantiomers **I** was present only in trace amounts (7%). A fourth recrystallization, with the same procedure, produced single crystals suitable for X-ray structural analysis.

Solid-state structures of the two [2]catenanes: Single crystals of $5 \cdot 4\text{PF}_6$ were grown by vapor diffusion of PhH into a MeNO_2 solution containing a 4:1 mixture of the diastereoisomeric forms of the [2]catenane. X-ray structural analysis shows that $5 \cdot 4\text{PF}_6$ (Figure 12) crystallizes in the centrosymmetric space group $P2_1/c$. Thus, the crystals contain equal numbers of molecules of opposite chiralities. The tetracationic cyclophane possesses an open conformation with local non-crystallographic D_2 symmetry. The length and breadth of the tetracationic cyclophane are 7.3 and 10.4 Å,^[14] respectively, and the 1,5-disubstituted naphthalene spacers are essentially planar. The BPP34C10 macrocycle is threaded through the center of the tetracationic cyclophane so that the π -electron-rich hydroquinone ring is sandwiched between the two π -electron-deficient bipyridinium units with its $-\text{OC}_6\text{H}_4\text{O}-$ axis inclined by 38° to the mean plane of the tetracation defined by the four methylene carbon atoms, which are coplanar to within 0.34 Å.^[15] The separation between the inside hydro-

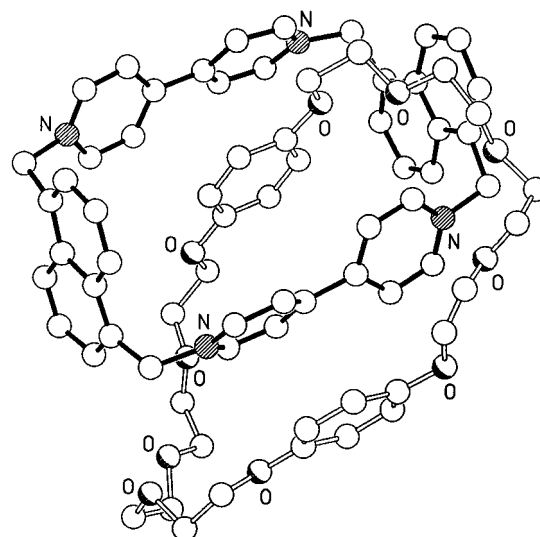


Figure 12. The structure of the [2]catenane $5 \cdot 4\text{PF}_6$ in the solid state.

quinone ring and the inside bipyridinium unit is 3.71 Å, while its corresponding distance from the alongside bipyridinium unit is 3.61 Å. The inside hydroquinone ring is located approximately at the center of the tetracationic cyclophane with its phenoxymethylene bonds adopting an *anti* geometry. The alongside hydroquinone ring (which is located at 3.95 Å from the inside bipyridinium unit) is markedly offset from the vector defined by the centers of the bonds linking the pyridinium rings of each bipyridinium unit,^[16] with its phenoxymethylene bonds adopting a *syn* geometry. In addition to the π – π stacking interactions between the bipyridinium components of the cyclophane and the π -electron-rich units of the BPP34C10 macrocycle, the [2]catenane is stabilized by both C–H $\cdots\pi$ and C–H $\cdots\text{O}$ interactions. The former is associated with T-type edge-to-face interactions between the inside hydroquinone ring and the two 1,5-disubstituted naphthalene spacers with C–H $\cdots\pi$ distances of 2.74 and 2.85 Å. The latter is associated with diametrically-opposite α -CH groups of the inside bipyridinium unit and oxygen atoms on the polyether chains (C $\cdots\text{O}$, O $\cdots\text{H}$ distances and C–H $\cdots\text{O}$ angles 3.19 Å, 2.35 Å, 145° and 3.23 Å, 2.36 Å, 150° , respectively). There is also a strong C–H $\cdots\text{O}$ hydrogen bond between one of the hydrogen atoms on one of the methylene carbon atoms attached to the inside bipyridinium unit and one of the oxygen atoms of the polyether linkage (C $\cdots\text{O}$, O $\cdots\text{H}$ distances and C–H $\cdots\text{O}$ angle 3.19 Å, 2.25 Å, and 167° , respectively).

Inspection of the packing of the [2]catenane (Figure 13) reveals that C_1 -related molecules form π -stacked dimer pairs involving the overlap of just one of the 1,5-disubstituted naphthalene spacers of the tetracationic cyclophane (centroid–centroid distance of 3.38 Å and mean interplanar separation of 3.59 Å). These dimer pairs then form weakly associated polar stacks; the alongside hydroquinone ring of one molecule overlays one of the alongside pyridinium rings of the next with a centroid–centroid separation of 4.12 Å. There are no significant approaches to the other 1,5-disubstituted naphthalene spacers of the tetracationic cyclophane.

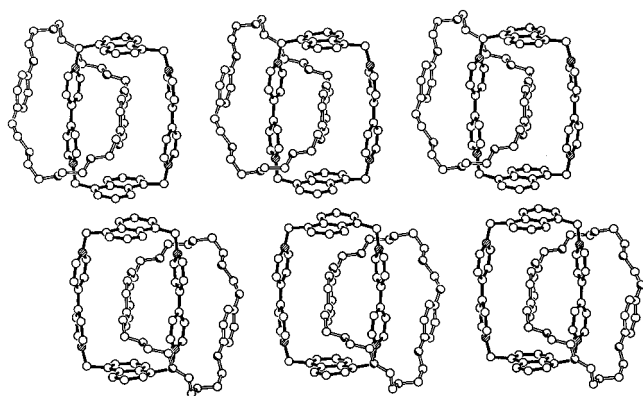


Figure 13. Packing of the [2]catenane $5 \cdot 4\text{PF}_6$.

The X-ray structural analysis of $6 \cdot 4\text{PF}_6$ shows that the [2]catenane crystallizes in the noncentrosymmetric space group $P1$ with only one molecule in the unit cell (Figure 14).

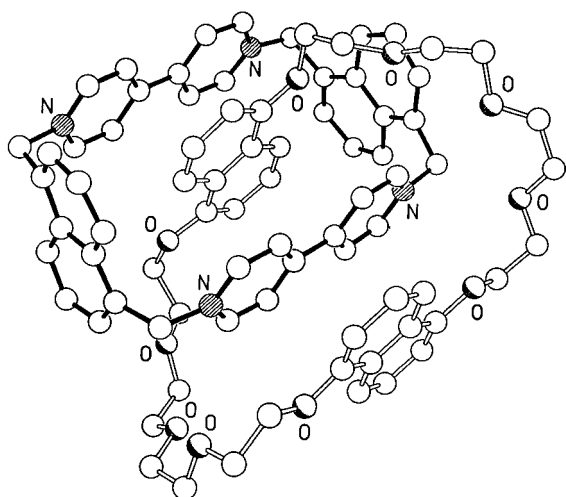


Figure 14. The structure of the [2]catenane $6 \cdot 4\text{PF}_6$ in the solid state.

Thus the crystal contains molecules of one chirality only, spontaneous resolution having occurred upon crystallization.^[17] The tetracationic cyclophane adopts an open conformation^[18] with local noncrystallographic D_2 symmetry. The planar chirality associated with both 1,5-disubstituted naphthalene rings is (*S*). A noticeable feature of the geometry of the tetracationic cyclophane [cf. that of cyclobis(paraquat-*p*-phenylene)]^[19] is a marked reduction in both the twisting and bowing of the bipyridinium spacers.^[20] The largest deformations are in the 1,5-disubstituted naphthalene spacers where the $\text{CH}_2-\text{C}_{10}\text{H}_6$ bonds within each of the spacers form angles of ca. 20° . The introduction of these 1,5-disubstituted naphthalene spacers produces only a very small skewing distortion of the cyclophane; the $\text{N}\cdots\text{N}$ axes of each bipyridinium unit is inclined by only ca. 7° . The 1/5DN38C10 macrocycle is threaded through the center of the tetracationic cyclophane such that the π -electron-rich 1,5-dioxynaphthalene residue is sandwiched between the two π -electron-deficient bipyridinium units with its $\text{OC}_{10}\text{H}_6\text{O}$ axis inclined by 53° to the mean

plane of the tetracation as defined by the four methylene carbon atoms, which are coplanar to within 0.33 \AA . The separation between the inside 1,5-dioxynaphthalene residue and the inside bipyridinium unit is 3.46 \AA , while the corresponding distance to the alongside bipyridinium unit is 3.42 \AA . The alongside 1,5-dioxynaphthalene residue is positioned alongside the inside bipyridinium unit at a distance of 3.44 \AA . The $\text{OC}_{10}\text{H}_6\text{O}$ axis of the alongside 1,5-dioxynaphthalene residue is inclined by only 6° to the $\text{N}\cdots\text{N}$ axis of the inside bipyridinium unit. The 1/5DN38C10 macrocycle also has molecular D_2 symmetry and one of its C_2 axes (that linking the center of the two naphthalene rings) is coincident with one of the C_2 axes of the tetracationic cyclophane (that passing through the centers of the bonds linking the pyridinium rings of each bipyridinium unit) resulting in C_2 symmetry for the [2]catenane as a whole. Again, the planar chirality associated with both 1,5-dioxynaphthalene rings is (*S*). In addition to the $\pi-\pi$ interactions described above, the [2]catenane is stabilized by both $\text{C}-\text{H}\cdots\pi$ interactions and $\text{C}-\text{H}\cdots\text{O}$ hydrogen bonds. The former are associated with the T-type edge-to-face interactions between the inside 1,5-dioxynaphthalene residue of 1/5DN38C10 and the two 1,5-disubstituted naphthalene spacers of the tetracation with $\text{C}-\text{H}\cdots\pi$ distances of 2.68 and 2.70 \AA . The latter occur between diametrically opposite α -CH groups on the inside bipyridinium unit and the central oxygen atom of the polyether linkages ($\text{C}\cdots\text{O}$, $\text{O}\cdots\text{H}$ distances, and $\text{C}-\text{H}\cdots\text{O}$ angles 3.29 \AA , 2.38 \AA , 159° and 3.37 \AA , 2.45 \AA , 159° , respectively). There are also $\text{C}-\text{H}\cdots\text{O}$ hydrogen bonds between one of the hydrogen atoms at each corner methylene carbon atom attached to the inside bipyridinium unit and the oxygen atoms in the polyether linkages ($\text{C}\cdots\text{O}$, $\text{O}\cdots\text{H}$ distances and $\text{C}-\text{H}\cdots\text{O}$ angles 3.20 \AA , 2.44 \AA , 136° and 3.13 \AA , 2.27 \AA , 150° , respectively).

Inspection of the packing of the [2]catenanes (Figure 15) reveals the formation of bidirectional polar stacks. In one direction (up the page) the molecules are arranged to produce $\cdots\text{DADADA}\cdots$ stacks (where D and A represent π -donors and π -acceptors, respectively) with the alongside bipyridin-

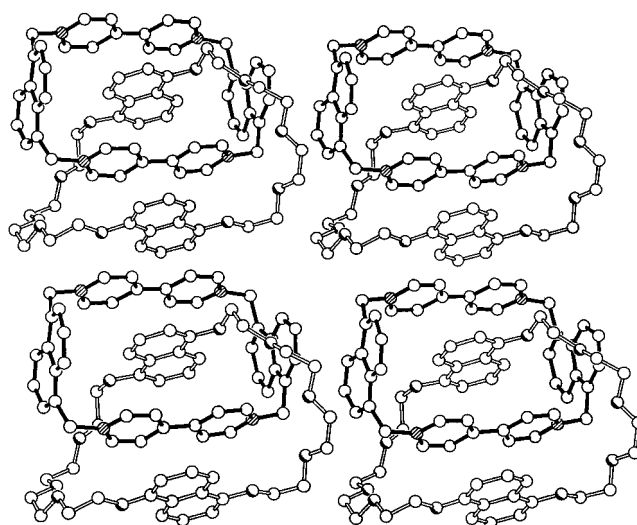


Figure 15. Part of the continuous two-dimensional mosaic formed by the [2]catenane $6 \cdot 4\text{PF}_6$ in the crystal.

ium unit in one molecule aligned with the alongside 1,5-dioxynaphthalene residue of the next (ring–ring separation 3.39 Å). In the other direction (across the page) the 1,5-disubstituted naphthalene spacers of one molecule are stacked adjacent to those in the next with a mean interplanar separation of 3.44 Å. The combination of these two types of stacking interactions produces mosaic-like sheets of molecules as illustrated in Figure 15.

Molecular modeling: The tetracationic cyclophane **4**·4PF₆ exists in solution as a mixture of two diastereoisomeric forms (Figure 2) in a ratio of 3:1, as revealed by ¹H NMR spectroscopy. In order to assess the relative stabilities of the two diastereoisomeric forms, a conformational search was performed employing the Monte Carlo method.^[21] The molecular mechanics calculations revealed an energy difference of 1.3 kcal mol⁻¹ in favor of the chiral (*RR*) and (*SS*) forms with respect to the achiral (*RS*) form. In addition, the energy of the tetracationic cyclophane **4**·4PF₆ was calculated as a function of the dihedral angle around the bond linking one of the methylene groups and the adjacent naphthalene spacer.^[22] Energy barriers of 21.7 and 23.0 kcal mol⁻¹ for the interconversion of the achiral into the chiral form and vice versa were derived from these calculations.

In order to compare the relative stabilities of the diastereoisomers α – ζ (Figure 8) of **6**·4PF₆, each diastereoisomer was subjected to a Monte Carlo conformational search. Comparison of the calculated energies ($-E$, kcal mol⁻¹), associated with the lowest energy state for each diastereoisomer, shows that the stabilities of the diastereoisomers decreases as follows: (*RR,SS*)- ϵ (108.6) > (*RR,RR*)- α (107.2) > (*RS,RR*)- δ (107.1) > (*RR,RS*)- β (105.9) > (*RR,SR*)- γ (104.5) > (*RS,RS*)- ζ (102.3). Thus, the diastereoisomers that incorporate the (*RS*) or (*SR*) forms of the macrocyclic polyether are less stable than those with the (*SS*) or (*RR*) forms. Similarly, the diastereoisomers that incorporate the (*RS*) or (*SR*) forms of the tetracationic cyclophane are less stable than those with the (*RR*) or (*SS*) forms. These observations are consistent with the ¹H NMR spectroscopic investigation (vide supra) which revealed (Figures 9–11) that the pairs of enantiomers **II** are **III** are more abundant than the pair of enantiomers **I** in solution.

Conclusions

It has been established that planar chirality can be introduced into [2]catenanes and that the self-assembly of the resulting diastereoisomers can occur with diastereoselectivities in excess of at least 50%. In the case of **6**·4PF₆, spontaneous resolution occurs on crystallization, affording the (*SS,SS*) form. Considering that the 1,5-dioxynaphthalene rings present in the crown ether 1/5DN38C10 are also capable of supporting planes of chirality, there are twelve possible stereoisomeric forms (six diastereoisomeric pairs of enantiomers) of **6**·4PF₆. However, only one stereoisomer was present in the single crystal examined by X-ray diffraction. The chiral [2]catenane molecules form a two-dimensional supramolecular array in

which the molecules are orientated simultaneously in a polar manner in two different directions that are approximately orthogonal to each other.

Experimental Section

General methods: Chemicals were purchased from Aldrich and used as received. Solvents were dried according to procedures described in the literature (DMF over CaH₂, MeCN over P₂O₅).^[23] The compounds 1,5-bis(bromomethyl)naphthalene (**7**),^[6] BHEEB,^[4a] BHEEN,^[7] BPP34C10,^[4a] and 1/5DN38C10^[4b] were prepared according to literature procedures. Thin-layer chromatography (TLC) was carried out with aluminum sheets precoated with silica gel 60 F (Merck 5554). The plates were inspected by UV light and developed with iodine vapor. Column chromatography was carried out with silica gel 60 F (Merck 9385, 230–400 mesh). Melting points were determined on an Electrothermal 9200 apparatus and are not corrected. UV/Vis spectra were recorded on a Perkin–Elmer Lambda 2 with HPLC quality solvents. ¹H Nuclear magnetic resonance spectra were recorded either on a Bruker AC300 (300 MHz) or on a Bruker AMX400 (400 MHz) spectrometer with either the solvent or TMS as internal standards. ¹³C NMR spectra were recorded on either a Bruker AC300 (75.5 MHz) or a Bruker AMX400 (100.6 MHz) spectrometer, with either the solvent or TMS as internal standards. All chemical shifts are quoted on the δ scale. Low-resolution mass spectra were performed with a Kratos Profile spectrometer, operating in electron impact (EIMS) mode. Fast atom bombardment mass spectra (FABMS) were recorded on a Kratos MS 80 spectrometer operating at 8 keV with a xenon primary atom beam. The matrix used was 3-nitrobenzyl alcohol (NBA). High-resolution mass spectra (HRMS) were obtained on a VG ZabSpec instrument with a liquid secondary ion (LSIMS) technique at a resolution of 7500 with NBA as the matrix and a poly(ethylene glycol) reference. Microanalyses were performed by the University of North London Microanalytical Service.

1,1'-[1,5-Naphthalenebis(methylene)]-bis(4,4'-bipyridinium)-bis(hexafluorophosphate) (8·2PF₆): A solution of 1,5-bis(bromomethyl)naphthalene **7** (100 mg, 0.31 mmol) in dry MeCN (20 mL) was added dropwise to a refluxing solution of 4,4'-bipyridine (247 mg, 1.58 mmol) in MeCN (30 mL) over a 6 h period. Heating under reflux was continued for another 18 h. The solvent was then removed in vacuo, and the residue purified by column chromatography (SiO₂: eluent MeOH(2M aq.)/NH₄Cl/MeNO₂, 7:2:1). The solvent from product-containing fractions was removed in vacuo, the residue was dissolved in H₂O, and a saturated solution of NH₄PF₆ in H₂O was added until no further precipitation occurred. The precipitate was filtered off and air-dried to yield **8**·2PF₆ as a white solid (70 mg, 30%). ¹H NMR (300 MHz, CD₃COCD₃, 25 °C): δ = 9.39 (d, J = 7 Hz, 4H, α -CH pyridinium), 8.90 (d, J = 7 Hz, 4H, α -CH pyridyl), 8.72 (d, J = 7 Hz, 4H, β -CH pyridinium), 8.45 (d, J = 8 Hz, 2H, naphthalene-*H*-4/8), 8.03 (d, J = 7 Hz, 4H, β -CH pyridyl), 7.93 (d, J = 8 Hz, 2H, naphthalene-*H*-2/6), 7.78 (t, J = 8 Hz, 2H, naphthalene-*H*-3/7), 6.74 (s, 4H, -CH₂N⁺); ¹³C NMR (75 MHz, CD₃COCD₃, 25 °C): δ = 155.9, 152.2, 145.9, 142.1, 132.6, 131.2, 130.3, 128.5, 127.3, 126.5, 122.9, 62.8; MS (FAB): m/z = 611 [M - PF₆]⁺; HRMS (LSIMS) C₃₂H₂₆F₆N₄P₁: [M - PF₆]⁺ calcd 611.1799, found 611.1795.

Cyclobis(paraquat-1,5-naphthalene) (4·4PF₆): Compounds **7** (49 mg, 0.16 mmol) and **8**·2PF₆ (100 mg, 0.13 mmol), and the template BHEEN (500 mg, 1.48 mmol) were dissolved in dry MeCN (30 mL), and the reaction mixture was stirred for 14 d at room temperature. The solvent was then removed in vacuo, and the residue dissolved in a mixture of MeOH and H₂O, before being purified by column chromatography (SiO₂: eluent MeOH(2M aq.)/NH₄Cl/MeNO₂, 7:2:1). The solvent from the product-containing fractions was removed in vacuo, the residue was dissolved in H₂O, and a saturated solution of NH₄PF₆ in H₂O was added until no further precipitation occurred. The precipitate was filtered off and air-dried to yield **4**·4PF₆ as a yellow solid (102 mg, 64%). M.p.: > 250 °C; ¹H NMR (400 MHz, CD₃COCD₃, 31 °C): δ [(*RR/SS*) form only] = 9.35 (d, J = 7 Hz, 8H, α -CH bipyridinium), 8.61 (d, J = 8 Hz, 4H, naphthalene-*H*-4/8), 8.42 (d, J = 7 Hz, 8H, β -CH bipyridinium), 8.16 (d, J = 8 Hz, 2H, naphthalene-*H*-2/6), 7.71 (t, J = 7 Hz, 2H, naphthalene-*H*-3/7), 6.98 (d, J = 13 Hz, 4H, -CH₂N⁺), 6.36 (d, J = 13 Hz, 4H, -CH₂N⁺); ¹³C NMR (400 MHz, CD₃COCD₃, 31 °C): δ [(*RR/SS*) form only] = 154.4, 150.7, 136.6, 136.5, 136.2, 133.1, 132.3, 130.8, 67.5; MS (FAB): m/z = 1055 [M - PF₆]⁺, 910 [M -

2PF_6^+ , 765 $[M - 3\text{PF}_6]^+$; HRMS (LSIMS) $\text{C}_{44}\text{H}_{36}\text{F}_{12}\text{N}_4\text{P}_2$: $[M - 2\text{PF}_6]^+$ calcd 910.2224, found 910.2192.

[2]Catenane 5·4PF₆: Compounds **7** (16 mg, 0.05 mmol) and **8**·2PF₆ (31 mg, 0.04 mmol), and the crown ether BPP34C10 (56 mg, 0.10 mmol) were dissolved in dry MeCN (30 mL), and the reaction mixture was stirred for 14 d at room temperature. The solvent was then removed in vacuo, and the residue dissolved in a mixture of MeOH and H₂O, before being purified by column chromatography (SiO₂; eluent MeOH(2M aq.)/NH₄Cl/MeNO₂, 7:2:1). The solvent from the product-containing fractions was removed in vacuo, the residue was dissolved in H₂O and a saturated solution of NH₄PF₆ in H₂O was added until no further precipitation occurred. The precipitate was filtered off and air-dried to yield **5**·4PF₆ as a purple solid (13 mg, 17%). M.p.: > 250 °C; ¹H NMR (300 MHz, CD₃COCD₃, 25 °C): δ[(RR/SS) form only] = 9.35 (d, *J* = 7 Hz, 8H, α-CH bipyridinium), 8.75 (d, *J* = 8 Hz, 4H, naphthalene-*H*-4/8), 8.34 (d, *J* = 8 Hz, 4H, naphthalene-*H*-2/6), 7.91 (t, *J* = 8 Hz, 4H, naphthalene-*H*-3/7), 7.86 (d, *J* = 7 Hz, 8H, β-CH bipyridinium), 6.90 (d, *J* = 14 Hz, 4H, -CH₂N⁺), 6.32 (d, *J* = 14 Hz, 4H, -CH₂N⁺), 6.25 (brs, 4H, alongside hydroquinone), 4.1–3.4 (m, 32H, -CH₂O), 3.2 (brs, 4H, inside hydroquinone); ¹³C NMR (300 MHz, CD₃COCD₃, 31 °C): δ[(RR/SS) form only] = 147.7, 146.2, 132.9, 132.0, 131.6, 128.7, 126.6, 126.5, 126.4, 126.2, 71.8, 71.7, 70.5, 70.4, 63.0; MS (FAB): *m/z* = 1591 $[M - \text{PF}_6]^+$, 1446 $[M - 2\text{PF}_6]^+$, 1301 $[M - 3\text{PF}_6]^+$; HRMS (LSIMS) $\text{C}_{72}\text{H}_{76}\text{F}_{18}\text{N}_4\text{P}_3\text{O}_{10}$: $[M - \text{PF}_6]^+$ calcd 1591.4487, found 1591.4543.

[2]Catenane 6·4PF₆: Compounds **7** (25 mg, 0.08 mmol) and **8**·2PF₆ (50 mg, 0.07 mmol), and the crown ether 1/5-DN38C10 (126 mg, 0.20 mmol) were dissolved in dry MeCN (30 mL), and the reaction mixture was stirred for 14 d at room temperature. The solvent was then removed in vacuo, and the residue dissolved in a mixture of MeOH and H₂O, before being purified by column chromatography (SiO₂; eluent MeOH(2M aq.)/NH₄Cl/MeNO₂, 7:2:1). The solvent from the product-containing fractions was removed in vacuo, the residue was dissolved in H₂O, and a saturated solution of NH₄PF₆ in H₂O was added until no further precipitation occurred. The precipitate was filtered off and air-dried to yield **6**·4PF₆ as a purple solid (80 mg, 66%). M.p.: > 250 °C; ¹H NMR (400 MHz, CD₃COCD₃, 25 °C): δ[(RR/SS) form only] = 9.20–8.95 (m, 10H, α-CH

bipyridinium and naphthalene-*H*-4/8), 8.90 (d, *J* = 8 Hz, 2H, naphthalene-*H*-4/8), 8.62 (d, *J* = 8 Hz, 2H, naphthalene-*H*-2/6), 8.40 (d, *J* = 8 Hz, 2H, naphthalene-*H*-2/6), 8.18 (t, *J* = 8 Hz, 2H, naphthalene-*H*-3/7), 8.10 (t, *J* = 8 Hz, 2H, naphthalene-*H*-3/7), 7.33 (brs, 2H, alongside 1,5-dioxynaphthalene-*H*-2/6), 7.18 (m, 2H, alongside 1,5-dioxynaphthalene-*H*-3/7), 6.98–6.85 (m, 8H, β-CH bipyridinium), 6.55–6.30 (m, 10H, -CH₂N⁺ and alongside 1,5-dioxynaphthalene-*H*-4/8), 5.92 (d, 2H, inside 1,5-dioxynaphthalene-*H*-2/6), 4.30–3.85 (m, 32H, -CH₂O), 3.75 (t, 2H, inside 1,5-dioxynaphthalene-*H*-3/7), 2.60 (d, 2H, inside 1,5-dioxynaphthalene-*H*-4/8). At room temperature, the exchange of the 1,5-dioxynaphthalene residues of the crown ether between the inside and alongside environments of the tetracationic cyclophane is already slow on the NMR timescale. Additionally, the twofold symmetry imposed upon the cyclophane by the inside 1,5-dioxynaphthalene residue results in a separation of the resonances of the naphthalene spacers in the cyclophane into inwards and outwards environments. See text for details. These proton assignments were made by a combination of double irradiation techniques including NOE and saturation transfer experiments carried out at 25 °C. ¹³C NMR (400 MHz, CD₃CN, 31 °C): δ[(RR/SS) form only] = 145.8, 145.2, 132.5, 131.5, 129.7, 128.9, 127.1, 126.7, 126.5, 125.0, 124.5, 119.2, 114.7, 109.6, 106.5, 104.4, 72.4, 72.3, 72.1, 71.4, 70.6, 70.4, 68.6, 63.7, 62.8; MS (FAB): *m/z* = 1691 $[M - \text{PF}_6]^+$, 1546 $[M - 2\text{PF}_6]^+$, 1401 $[M - 3\text{PF}_6]^+$; $\text{C}_{80}\text{H}_{80}\text{F}_{24}\text{N}_4\text{P}_2\text{O}_{10}$ (1837.4): calcd C 52.29, H 4.36, N 3.05; found C 52.26, H 4.40, N 2.96.

Method for the determination of the association constants by UV/Vis spectroscopy with the titration methodology:^[24] A series of solutions with a fixed concentration (3×10^{-4} M) of cyclobis(paraquat-*p*-phenylene) and containing different amounts of BHEEB and BHEEN (10^{-4} – 10^{-1} M) in MeCN were prepared. The absorbance at the wavelength (λ_{max}) corresponding to the maximum of the charge-transfer band for the 1:1 complex was measured for all the solutions at 25 °C. The correlation between the absorbance and the guest concentration was used to evaluate the association constant (K_a) in a non-linear curve-fitting program (Ultrafit, Biosoft, Cambridge, 1992), run on an Apple Macintosh personal computer.

X-Ray crystallography: Table 1 provides a summary of the crystal data, data collection, and refinement parameters for the [2]catenanes **5**·4PF₆ and **6**·4PF₆ as well as for the complexes **4**·4PF₆·BHEEB and **4**·4PF₆·

Table 1. Crystal data, data collection, and refinement parameters for **4**·4PF₆·BHEEB, **4**·4PF₆·2BHEEN, **5**·4PF₆, and **6**·4PF₆.^[a]

	4 ·4PF ₆ ·BHEEB	4 ·4PF ₆ ·2BHEEN	5 ·4PF ₆	6 ·4PF ₆
formula	$\text{C}_{58}\text{H}_{58}\text{N}_4\text{O}_6 \cdot 4\text{PF}_6$	$\text{C}_{62}\text{H}_{60}\text{N}_4\text{O}_6 \cdot \text{C}_{18}\text{H}_{24}\text{O}_6 \cdot 4\text{PF}_6$	$\text{C}_{72}\text{H}_{76}\text{N}_4\text{O}_{10} \cdot 4\text{PF}_6$	$\text{C}_{80}\text{H}_{80}\text{N}_4\text{O}_{10} \cdot 4\text{PF}_6$
solvent	6 MeCN	7 MeCN	1.5 Me ₂ CO · 2 H ₂ O · PhH	7 MeCN
<i>M_r</i>	1733.3	2160.8	1938.5	2124.7
color, habit	orange/red prisms	red blocks	red blocks	red prisms
crystal size (mm)	0.83 × 0.30 × 0.15	0.47 × 0.30 × 0.23	0.47 × 0.27 × 0.23	0.30 × 0.30 × 0.17
lattice type	monoclinic	triclinic	monoclinic	triclinic
space group, number	<i>P</i> 2 ₁ / <i>c</i> , 14	<i>P</i> 1̄, 2	<i>P</i> 2 ₁ / <i>c</i> , 14	<i>P</i> 1, 1
<i>T</i> (K)	203	203	203	193
<i>a</i> (Å)	14.261(1)	14.127(1)	14.850(2)	13.891(1)
<i>b</i> (Å)	14.105(1)	14.337(1)	21.726(4)	14.289(3)
<i>c</i> (Å)	20.101(1)	14.482(1)	28.167(4)	14.452(1)
α (°)	–	67.41(1)	–	66.11(1)
β (°)	102.06(1)	84.16(1)	93.95(1)	72.75(1)
γ (°)	–	72.40(1)	–	88.42(1)
<i>V</i> (Å ³)	3954.3(5)	2581.1(2)	9066(3)	2490.8(5)
<i>Z</i>	2 ^[b]	1 ^[b]	4	1
<i>D_c</i> (g cm ⁻³)	1.456	1.390	1.420	1.416
<i>F</i> (000)	1780	1118	4008	1098
μ (mm ⁻¹)	1.89	1.61	1.75	1.64
θ range (°)	3.2–64.0	3.3–60.0	2.6–56.0	3.4–62.6
no. of unique reflections				
measured	6562	7385	11692	7756
observed, <i>F_o</i> > 4σ(<i>F_o</i>)	4180	6418	6574	6396
no. of variables	647	832	1202	1297
<i>R</i> ₁ ^[c]	0.070	0.088	0.116	0.086
<i>wR</i> ₂ ^[d]	0.158	0.250	0.312	0.231
weighting factors <i>a</i> , <i>b</i> ^[e]	0.070, 3.313	0.159, 3.596	0.260, 3.540	0.181, 1.856
largest difference peak, hole (eÅ ⁻³)	0.29, –0.36	0.60, –0.50	0.98, –0.54	0.65, –0.38

[a] Details in common: graphite-monochromated radiation, ω-scans, Siemens P4 rotating anode diffractometer, Cu_{Kα} radiation, refinement based on *F*².

[b] The molecule has crystallographic *C*₁ symmetry. [c] $R_1 = \sum ||F_o| - |F_c|| / \sum |F_o|$. [d] $wR_2 = \sqrt{[\sum w(F_o^2 - F_c^2)^2] / [\sum w(F_o^2)^2]}$. [e] $w^{-1} = \sigma^2(F_o^2) + (aP)^2 + bP$.

2BHEEN. All four structures were solved by direct methods and were refined by full-matrix least-squares based on F^2 . In each case, the major occupancy non-hydrogen atoms and the hexafluorophosphate counterions were refined anisotropically. In both $4 \cdot 4\text{PF}_6 \cdot \text{BHEEB}$ and $4 \cdot 4\text{PF}_6 \cdot 2\text{BHEEN}$, 50:50 disorder was found in the orientations of the unique 1,5-disubstituted naphthalene spacers of the centrosymmetric pseudorotaxanes. In all cases, one of the PF_6 anions was found to be disordered over two partial occupancy sites (50:50, 65:35, 65:35, and 50:50 for $5 \cdot 4\text{PF}_6$, $6 \cdot 4\text{PF}_6$, $4 \cdot 4\text{PF}_6 \cdot \text{BHEEB}$, $4 \cdot 4\text{PF}_6 \cdot 2\text{BHEEN}$, respectively). In $4 \cdot 4\text{PF}_6 \cdot 2\text{BHEEN}$, 50:50 disorder was found in the position of the terminal hydroxyl oxygen atom of the adjacent thread molecule; both orientations were treated anisotropically. The seven MeCN solvent molecules in the crystals of $6 \cdot 4\text{PF}_6$ were found to be disordered over six full and two half-occupancy sites, and all of the non-hydrogen atoms of these eight sites were refined anisotropically. In $5 \cdot 4\text{PF}_6$, the Me_2CO molecules were found in two sites, one of full occupancy and one of 50% occupancy; only the non-hydrogen atoms of the full occupancy site were treated anisotropically. The two H_2O molecules were distributed over six partial occupancy sites, all of which were refined isotropically. The full-occupancy, ordered PhH molecule was refined anisotropically. The seven MeCN molecules in the centrosymmetric pseudorotaxane $4 \cdot 4\text{PF}_6 \cdot 2\text{BHEEN}$ were located over three full and one half-occupancy sites, all of which were treated anisotropically. In $4 \cdot 4\text{PF}_6 \cdot \text{BHEEB}$, the three unique MeCN molecules were located at three full occupancy sites and were refined anisotropically. The CH hydrogen atoms in all four structures were placed in calculated positions, assigned isotropic thermal parameters $U(\text{H}) = 1.2U_{\text{eq}}(\text{C})$ [$U(\text{H}) = 1.5U_{\text{eq}}(\text{C}-\text{Me})$], and allowed to ride on their parent atoms. The hydroxyl hydrogen atoms in $4 \cdot 4\text{PF}_6 \cdot 2\text{BHEEN}$ were located from ΔF maps, optimised, assigned isotropic thermal parameters $U(\text{H}) = 1.5U_{\text{eq}}(\text{O})$, and allowed to ride on their parent atoms. The hydrogen atoms of the H_2O molecules in $5 \cdot 4\text{PF}_6$ and of the unique hydroxyl group in $4 \cdot 4\text{PF}_6 \cdot \text{BHEEB}$ could not be located. Computations were carried out with the SHELXTL PC program system.^[25] Crystallographic data (excluding structure factors) for the structures reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-101016. Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (Fax: Int. code + (44) 1223 336-033; e-mail: deposit@ccdc.cam.ac.uk).

Molecular modeling: The tetracationic cyclophane $4 \cdot 4\text{PF}_6$ was constructed within the input mode of Macromodel 5.0.^[21] The geometry was optimized by an energy minimization performed employing the Polak–Ribiere conjugate gradient (PRCG) method^[26], and the resulting structure was subjected to a Monte Carlo conformational search^[27] for which the default settings of Macromodel 5.0 were employed. In both calculations, the AMBER* forcefield^[28] and the generalized-Born surface-accessible (GB/SA) solvation model^[29] for H_2O were employed as implemented in Macromodel 5.0. The change of the energy of $4 \cdot 4\text{PF}_6$ was monitored by variation the dihedral angle around the bond linking one of the methylene groups and the adjacent naphthalene spacer by means of the monodimensional angle-drive routine of Macromodel 5.0 in conjunction with the AMBER* forcefield, the PRCG method, and the GB/SA solvation model for H_2O .

The six diastereoisomers α – ζ (Figure 8) of the [2]catenane $6 \cdot 4\text{PF}_6$ were constructed within the input mode of Macromodel 5.0. Each diastereoisomer was subjected individually to PRCG energy minimization and then to a Monte Carlo conformational search for which the default settings of Macromodel 5.0 were employed. In both calculations, the AMBER* forcefield and the GB/SA solvation model for H_2O were employed as implemented in Macromodel 5.0.

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- [5] For a similar example of cyclophanes possessing planar chirality and existing in chiral and achiral forms ([2.2](1,5)naphthalenophane, in which two 1,5-disubstituted naphthalene units are bridged by bis-methylene spacers) see: M. V. Haenel, *Chem. Ber.* **1978**, *111*, 1789–1797.
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- [8] The H-2/6 proton resonances of the tetracationic cyclophane were located by means of an inverse heteronuclear multiple bond correlation experiment. The delay which allows the evolution of the long-range coupling was optimized for a coupling constant of 5 Hz. The ^1H doublet at $\delta = 8.15$ has a cross-peak to the methylene carbon atom ^{13}C resonance at $\delta = 67.5$. This cross-peak must be attributed to a 3J coupling constant (a 2J is clearly impossible and a 4J is very small and will not correlate), therefore this doublet was assigned to the H-2/6 proton resonances. Accordingly, the doublet at $\delta = 8.74$ must be attributed to the H-4/8 proton resonances.
- [9] The position of the inside hydroquinone ring proton resonance was located by means of a saturation transfer experiment by irradiating the alongside hydroquinone ring proton resonance at $\delta = 6.30$.
- [10] The kinetic and thermodynamic data were calculated by means of the coalescence method, in which values for the rate constant k_c at the coalescence temperature (T_c) were calculated (I. O. Sutherland, *Annu. Rep. NMR Spectrosc.* **1971**, *4*, 71–235) from the approximate expression $k_c = \pi(\Delta\nu)/(2)^{1/2}$, where $\Delta\nu$ is the limiting chemical shift difference (Hz) between the coalescing signals in the absence of exchange. The Eyring equation was employed subsequently to calculate ΔG_c^\ddagger values at T_c from the k_c values.
- [11] The kinetic and thermodynamic parameters for Process 1 are as follows: probe protons, $\text{C}_6\text{H}_4\text{O}$; $T_c = 323$ K; $\Delta\nu = 1260$ Hz; $k_c = 2798$ Hz; $\Delta G_c^\ddagger = 14.3 \pm 0.2$ kcal mol $^{-1}$. The kinetic and thermodynamic parameters for either the rotation of the bipyridinium units about their N...N axis or Process 2 in the [2]catenane $5 \cdot 4\text{PF}_6$ are as follows: probe protons, CH_2N ; $T_c = 200$ K; $\Delta\nu = 56$ Hz; $k_c = 124$ Hz; $\Delta G_c^\ddagger = 9.6 \pm 0.2$ kcal mol $^{-1}$.
- [12] Although the diastereoisomers could not be separated by column chromatography or HPLC, no change in the diastereoisomeric ratio was observed on heating a solution of the 3:1 mixture of $6 \cdot 4\text{PF}_6$ in CD_3SOCD_3 at 90°C for 18 h.
- [13] The resonances associated with the H-2/6 protons of the inside 1,5-dioxynaphthalene residue should appear, at low temperature, as two doublets associated with the pair of enantiomers **I** and two doublets associated with the pairs of enantiomers **II** and **III**. The failure to observe such a pattern could be attributed to the presence at low temperature of only two of these three pairs of enantiomers, or to the fact that in two of them the probe protons are, accidentally, isochronous. This latter situation is not an unreasonable one when we consider that **II** and **III**, for example, differ only in that the alongside 1,5-dioxynaphthalene residues are located alongside different bipyridinium units. The ^1H NMR environment experienced by the probe protons attached to the inside 1,5-dioxynaphthalene residue and shielded by the surrounding tetracationic cyclophane should be

- very similar. The complexity of the spectrum of the [2]catenane $6 \cdot 4 \text{PF}_6$ in the region 7–9 δ at low temperatures did not allow us to follow the behavior of other probe protons (for example, the protons attached to the naphthalene spacers of the cyclophane), which could be more sensitive to the changes in the NMR environment within the pairs of enantiomers **II** and **III**.
- [14] The twist angles between the pyridinium rings of the inside and alongside bipyridinium units are 35° and 26° , respectively, and the corresponding bow angles, that is, the angles formed by the NCH_2 bonds within each bipyridinium unit, are 16° for the inside and 26° for the alongside unit.
- [15] The $\text{N} \cdots \text{N}$ axes of each bipyridinium unit are inclined by ca. 11° with respect to each other.
- [16] The vector linking the centroid of the alongside hydroquinone ring with the centroid of the bond linking the pyridinium rings of the inside bipyridinium unit forms an angle of 73° with the vector defined by the centroids of the bonds linking the pyridinium rings of the inside and alongside bipyridinium unit. Furthermore, the two hydroquinone rings are not coplanar and their mean planes form an angle of ca. 14° .
- [17] The term spontaneous resolution indicates that only one of the two possible enantiomers of a racemic form is present in the crystal. In principle, the crown ether can also exist in different stereochemical forms that are in fast equilibrium at room temperature, the conditions under which the crystals were grown.
- [18] The length and breadth of the tetracationic cyclophane, as defined by the distances between the centroids of the two naphthalene rings and between the centers of the bonds linking the pyridyl rings within each bipyridinium unit, are 10.7 Å and 6.9 Å, respectively.
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- [20] The twist angles between the pyridinium rings of the inside and alongside bipyridinium units are 3° and 1° , respectively, and the corresponding bow angles, that is, the angles formed by the NCH_2 bonds within each bipyridinium unit, are 14° for the inside and 13° for the alongside unit.
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