Towards a Molecular Anchor Chain. Synthesis and Catenations of Spiro Crown Ethers

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Two new crown ethers (**1** and **2**) featuring a spiro linked assembly of two to three individual macrorings have been synthesised. The syntheses were achieved by means of high dilution techniques and blocking/deblocking procedures, beginning with pentaerythritol as the basic building block. The spiro and dispiro crown ethers **1** and **2** participate in template-directed self-assembly reactions with 1,1′-[1,4-phenylenebis(methylene)]bis-4,4′-bipyridinium bis(hexafluorophosphate) and 1,4-bis(bromomethyl)benzene at either one or both recognition sites. The resulting new [2]catenanes (**12** · $4PF_6$ and **14** · $4PF_6$) and bis[2]catenanes (**13** · $8PF_6$ and **15** · $8PF_6$), incorporating interlocked cyclobis(paraquat-*p*-phenylene) tetracations, were characterised by (dynamic) NMR spectroscopy and high resolution FAB mass spectrometry. The X-ray crystal structure of one of these spiro-linked bis[2]catenanes, namely **13** · $8PF_6$, is reported.

With the advent of supramolecular chemistry,[1] the formation of interlocked and intertwined molecular assemblies and supramolecular arrays,[2] such as catenanes, rotaxanes, knots, and pseudorotaxanes, has become an increasingly achievable goal through the borrowing of the concepts of self-assembly[3] and self-organisation[4] from nature. The formation of these intriguing molecular compounds and supramolecular complexes is impinging more and more on macromolecular chemistry as the science of the noncovalent bond is unravelled, allowing larger and larger structures and superstructures to be constructed. With this progression in mind, we have reported our strategies for the self-assembly of polyrotaxanes and polycatenanes[5] (structure I in Figure 1).[6] To date, we have achieved the template-directed synthesis[7] of many [2]catenanes,[8] some[3]catenanes[9] (structures II and III in Figure 1), two [4]catenanes,[10,11] and one [5]-catenane (Olympiadane).[11]

The molecular building blocks which we have employed for the self-assembly of the interlocked compounds are crown ethers and tetracationic cyclophanes, which exhibit π-π interactions[12] between their π-electron rich and deficient aromatic units, as well as hydrogen bonding interactions[13] between the polyether oxygen atoms of the crown ether and the α-bipyridinium hydrogen atoms of the tetracationic cyclophane. We are also exploring the possibility of forming poly[2]catenanes (structures IV and V in Figure 1) where the [2]catenane moieties are linked by covalent bonds along the backbone of the polymer. To achieve this kind of repeating unit, we have to link covalently two crown ethers and two tetracationic cyclophanes. Indeed, we have already reported the self-assembly of the model bis[2]catenanes VI and VII, where two tetracationic cyclophanes[14] or two crown ethers[15] are linked covalently by a spacer unit. The proposed polymer structural type V is a variant on the poly[2]catenane structure IV, where the spacer unit in the bis[2]catenanes is replaced by a spiro junction, resulting in what is analogous to an anchor chain in the macroscopic world. We have already reported[16] the self-assembly of a bis-[2]catenane with the model structure VIII in which the 'spiro junction' is a common durene unit linking two tetracationic cyclophanes. This paper details the synthesis and characterisation of two compounds where biscrown ether macrorings are linked by either one or two pentaerythritol spiro units.[17] These biscrown ethers (**1** and **2**, in Scheme 1 and 2, respectively) are able to serve as templates with the components of the tetracationic cyclophane to afford [2]catenanes and bis[2]catenanes, incorporating cyclobis(paraquat-*p*-phenylene) tetracations.

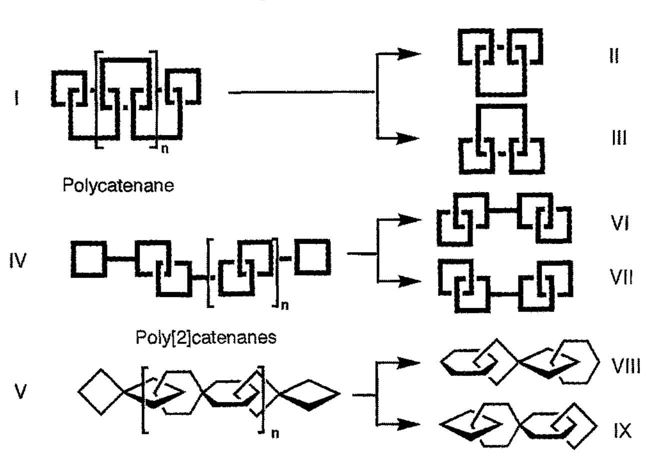
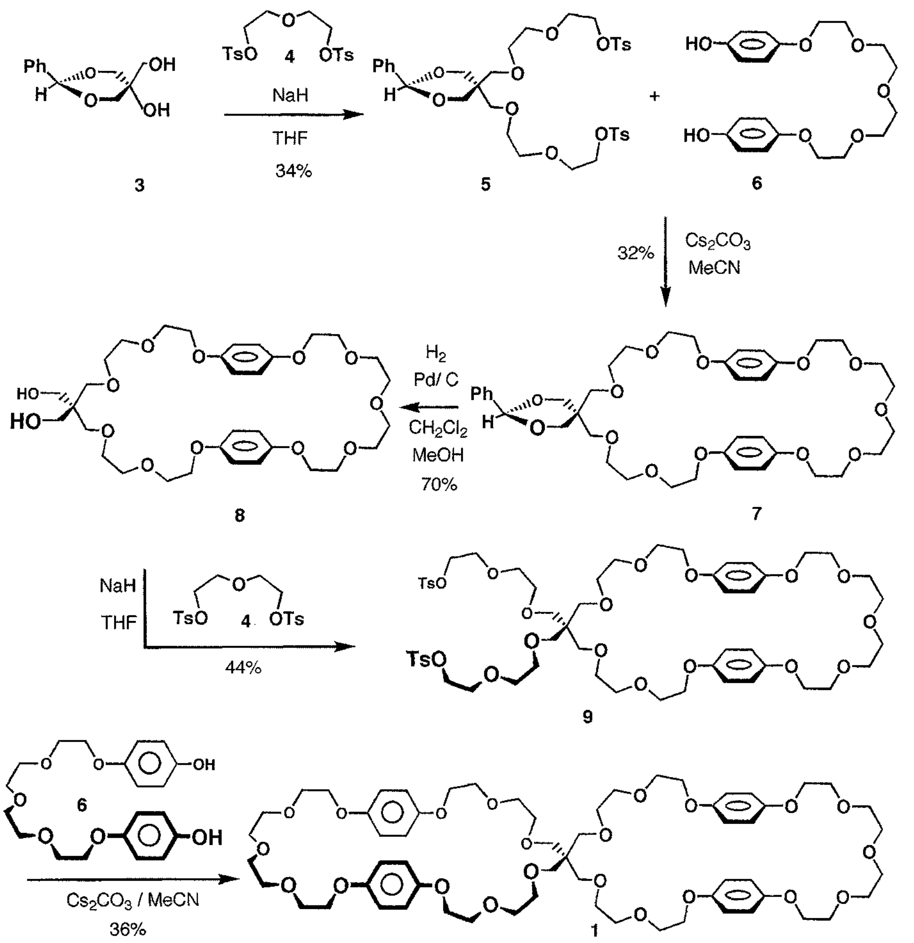


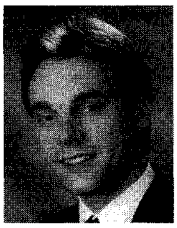
Figure 1. Cartoon illustrations of polymeric catenane structures, and model structures. Blue lines represent π-electon deficient cyclophanes and red lines represent π-electron rich crown ethers.

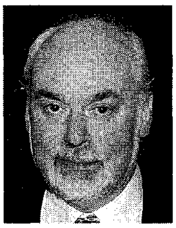
The biscrown ether **1**, in which two bis-*p*-phenylene-38-crown-11 macrocyles are linked via one central pentaerythritol spiro junction, was the initial synthetic target. The synthesis involved (Scheme 1) bisprotection of two of the hydroxyl functionalities of pentaerythritol with benzaldehyde under acidic conditions (HCl) to afford the cyclic acetal **3**.[18] The two remaining hydroxyl functionalities of **3** were then alkylated with diethylene glycol ditosylate[19] (**4**) under basic conditions (NaH) to afford **5** in 34%. The macrocyclisation step was performed under high dilution conditions via a reaction of the bisphenol **6** with the bistosylate **5** under basic conditions (Cs_2CO_3), affording the crown ether **7** in a yield of 32%. The masked diol functionality of **7** was then released by a catalytic hydrogenolysis using palladium on activated charcoal as the catalyst, affording the diol **8** in a yield of 70%. A two-step procedure, as described for the formation of the crown **7**, yielded, firstly, the bistosylate **9** (44%), and then the spiro crown ether **1** in a yield of 36%.



Scheme 1. Synthesis of the spiro crown ether **1**

Biographical Sketches





Peter R. Ashton was appointed Research Fellow in Mass Spectrometry at the University of Birmingham in October 1991. Previously, he was Senior Experimental Officer in Mass Spectrometry at the University of Sheffield. He gained a GRSC in Advanced Analytical Chemistry at Sheffield Hallam University in 1971 and was elected to Chartered Chemist status by the Royal Society of Chemistry in 1984. His research interests are concerned with the applications of modern mass spectrometry in supramolecular and biological sciences.

Thomas Horn received his Ph.D. with Prof. Dr. Klaus Mullen at the Max-Planck-Institut für Polymerforschung in Mainz, Germany 1994. After a postdoctoral period (1994–1995) with Prof. Fraser Stoddart at the University of Birmingham, he obtained a position at Procter & Gamble in Schwalbach Limes in Germany, working on raw material development for diapers.

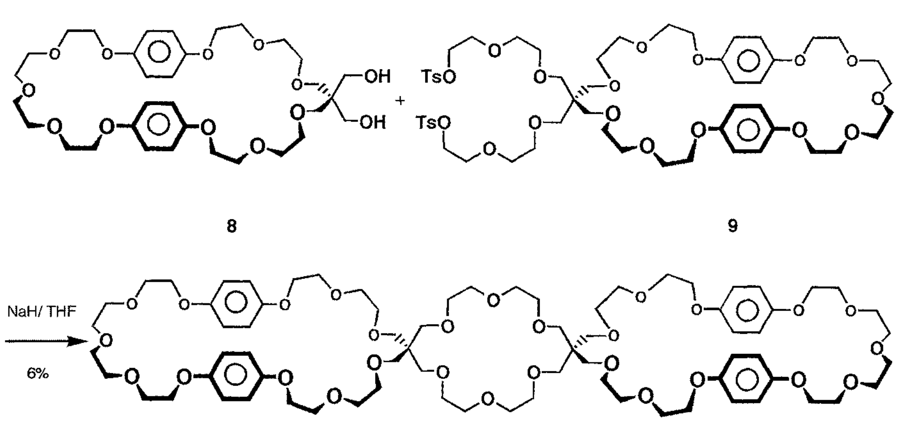
Stephan Menzer received his Ph.D. in Chemistry from the University of Dortmund in Germany. He currently works as a Postdoctoral Research Assistant with Prof. David Williams at Imperial College London on inorganic framework complexes, supramolecular chemistry and "crystallo-graphics".

Jon A. Preece obtained a First Class Honours B.Sc. Degree in Chemistry from Loughborough University of Technology in 1990, and a Ph.D. from the University of Birmingham in 1994 under the supervision of Prof. Fraser Stoddart. Following his Ph.D., he spent two years in the Research Group of Prof. Dr. Helmut Ringsdorf at the University of Mainz in Germany as a Royal Society European Science Exchange Research Fellow and latterly as a European Community Research Fellow. Recently, he has been appointed Research Fellow in Nanoscale Chemistry at the University of Birmingham. His research interests are in the fields of supramolecular chemistry, liquid crystals, and self-assembled monolayers.

Neil Spencer was born in Leeds in 1955. He received his B.Sc. and Ph.D. degrees from the University of Sheffield: the latter awarded in 1979 was under the supervision of Prof. Jon A. McCleverty. After occupying positions in industry, he returned to Sheffield in 1985 to join the Supramolecular Chemistry Research Group of Prof. Stoddart as a Postdoctoral Research Assistant carrying out synthetic chemistry and NMR spectroscopy. He moved with Prof. Stoddart to the University of Birmingham to run the Chemistry School's NMR facility. In 1995, he was appointed to a Research Fellowship in NMR spectroscopy at Birmingham to allow him to develop further his interests in the applications of NMR spectroscopy to research problems.

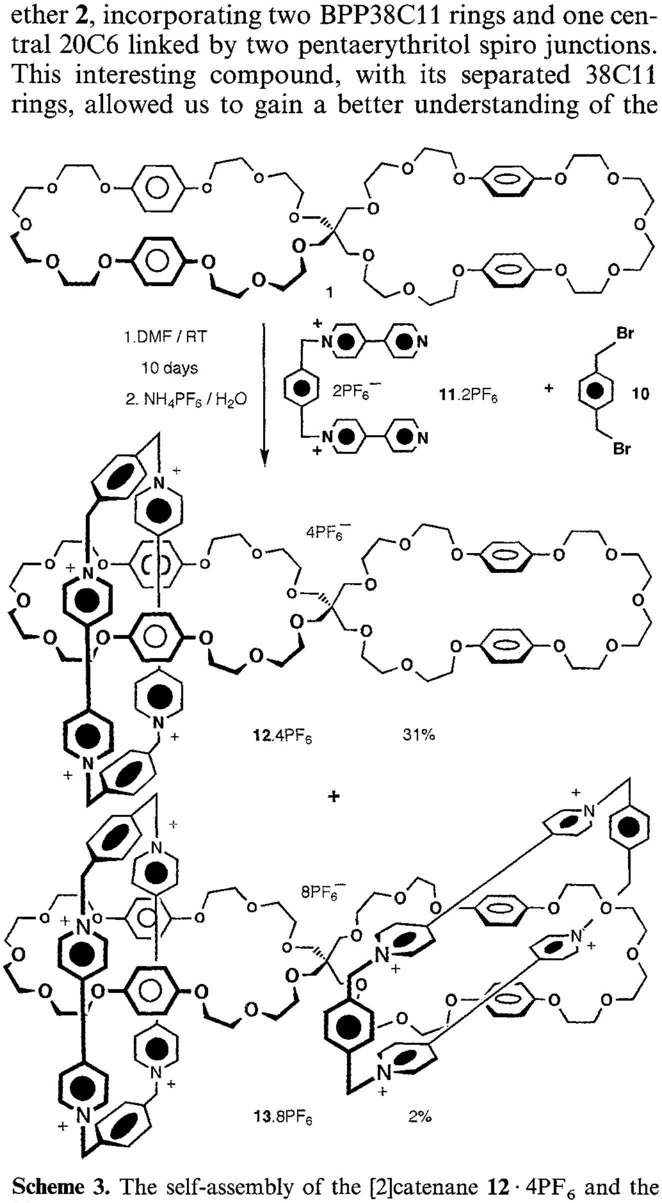
J. Fraser Stoddart has been Professor of Organic Chemistry since 1990 at the University of Birmingham. From 1970 he was a Lecturer and then Reader in Chemistry at the University of Sheffield. Between 1978–1981, he was seconded to the ICI Corporate Laboratory in Runcorn. He gained his B.Sc. in 1964, his Ph.D. in 1966, and his D.Sc. in 1980, all from the University of Edinburgh. He was elected to the Fellowship of the Royal Society of London in 1994. He has published more than 420 scientific papers, and has wide ranging interests in supramolecular science. At present, he is developing the transfer of concepts such as self-assembly between the life sciences and materials science.

David J. William's principal research interests are in the areas of supramolecular structural chemistry and the interpretation of the role of noncovalent interactions in determining short and long range molecular structure. He took his First Degree in Physics and obtained a Ph.D. in Crystallography at Imperial College London, where he is currently Professor of Structural Chemistry and Head of the Crystallography Section.



Scheme 2. Synthesis of the dispiro crown ether **2**

A fortuitous side reaction occurred in the synthesis of the bistosylate **9**. This side reaction is illustrated in Scheme 2. Accompanying the bistosylation was a [2+2] cyclisation, affording in a yield of 6 % the dispiro crown ether **2**, incorporating two BPP38C11 rings and one central 20C6 linked by two pentaerythritol spiro junctions. This interesting compound, with its separated 38C11 rings, allowed us to gain a better understanding of the self-assembly process when multiple catenations of one substrate are involved.

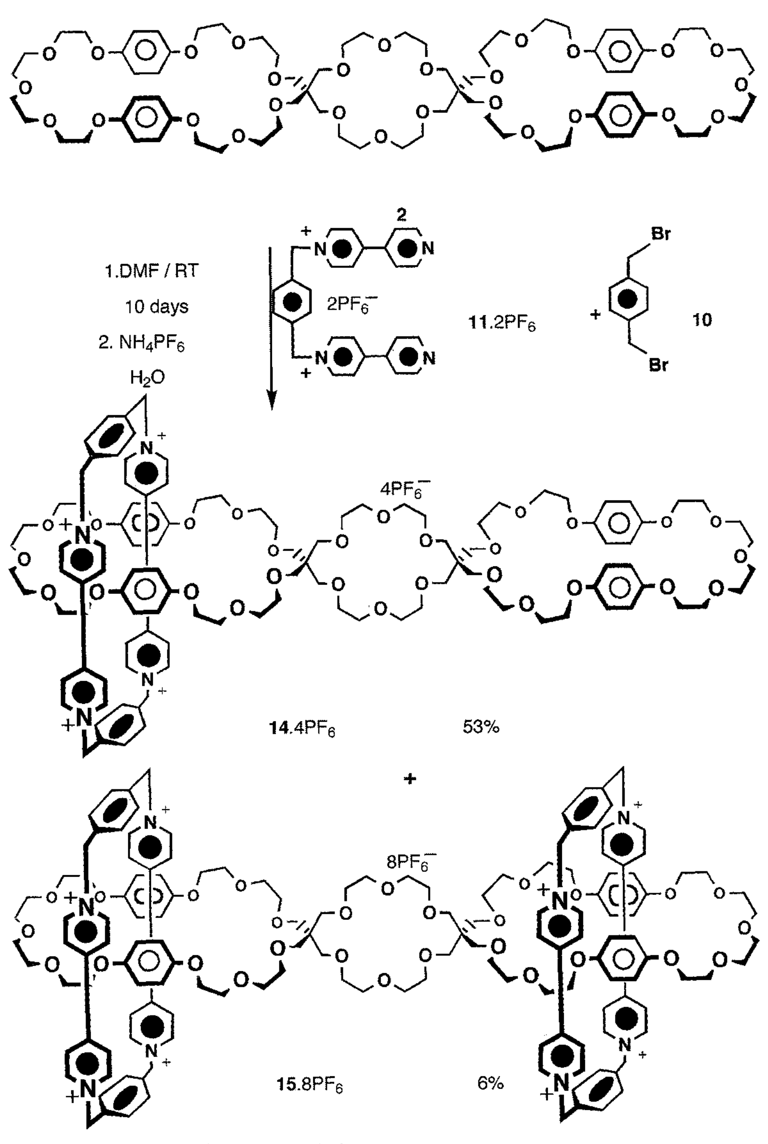


Scheme 3. The self-assembly of the [2]catenane **12** · 4PF$_6$ and the bis[2]catenane **13** · 8PF$_6$

In our previous papers[14–16] on the self-assembly of bis[2]catenanes, we have reported that only the bis[2]catenanes have been formed, i.e. no [2]catenanes with a free crown ether component remained uncatenated. However, upon reacting the spiro crown ether **1** with *p*-xylylene dibromide **(10)** and 1,1′-[1,4-phenylenebis(methylene)]bis-4,4′-bipyridinium bis(hexafluorophosphate)[19] (**11** · 2PF$_6$) in DMF at room temperature (Scheme 3), followed by column chromatography of the crude product and ion exchange to the hexafluorophosphate salts, two new catenated compounds were isolated. One of these compounds was the expected bis[2]catenane **13** · 8PF$_6$ (2 %) and the other was the intermediate [2]catenane **12** · 4PF$_6$ (31 %). The high yield of **12** · 4PF$_6$ was unexpected in view of our previous results,[14–16] where only bis[2]catenanes were formed.

However, the analogous catenation (Scheme 4) with the dispiro crown ether **2** helped to shed light on this anomalous behaviour. In this case, the yield of both the bis[2]catenane **15** · 8PF$_6$ and the intermediate [2]catenane **14** · 4PF$_6$ rose to 6 % and 53 %, respectively. Thus, it would appear that a negative allosteric effect is operating such that the second catenation is not favoured, perhaps as a result of the repulsive Coulombic interactions between the positive charges of the bipyridinium units of the already formed [2]catenane and the positive charges associated with the second catenation. By contrast, the introduction of the 20C6 ring into the middle of **2** separates the 38C11 macrocycles such that the Coulombic repulsion is greatly reduced, leading to a 3-fold increase in the yield of the bis[2]catenane **15** · 8PF$_6$, compared with **13** · 8PF$_6$. However, it should be noted that the spacer distance is still sufficiently short to favour the intermediate [2]catenane formation **14** · 4PF$_6$.

The X-ray crystal structure analysis[20] of **13** · 8PF$_6$ reveals (Figure 2) the expected bis[2]catenane[21] constitution and topology wherein one hydroquinone ring in each macrocyclic polyether is threaded through the centre of the tetracation in a geometry very similar to that observed in a range of analogous threaded systems. The other 'outside' hydroquinone rings are positioned adjacent to one of the bipyridinium units so as to form a 'con-



Scheme 4. The self-assembly of the [2]catenane $\mathbf{14}\cdot4PF_6$ and the bis[2]catenane $\mathbf{15}\cdot8PF_6$

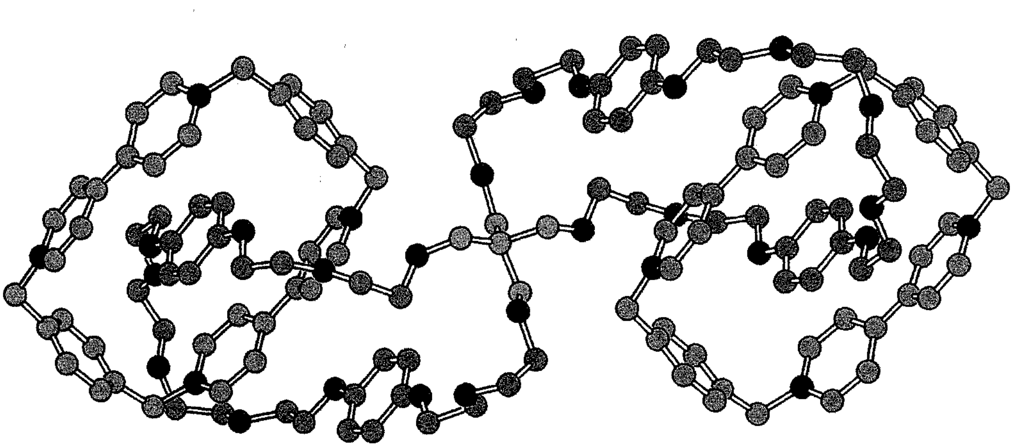


Figure 2. A ball-and-stick representation of the solid state structure of the bis[2]catenane $\mathbf{13}^{8+}$ with the oxygen atoms shaded red and the nitrogen atoms blue

ventional' acceptor-donor arrangement within each component of the bis[2]catenane $\mathbf{13}^{8+}$. Stabilisation is achieved by a combination of the usual π-π, C–H...π, and C–H ...O interactions. The π-π interactions between the 'inside' bipyridinium units and the 'outside' hydroquinone ring are clearly weakened on account of the 'outside' hydroquinone ring being noticeably offset with respect to the 'axis' that passes through the centre of the included hydroquinone ring and the centres of the bonds linking each pair of pyridine rings in the bipyridinium units. This offset is almost certainly a consequence of the geometrical constraints imposed upon each polyether ring as a result of the accommodation of a spiro centre at the junction of the two rings. Despite this offset, a fairly uniform pattern of interplanar separations between the bipyridinium units and the hydroquinone rings of between 3.4 and 3.5 Å is maintained. An investigation of the packing of the bis[2]catenane molecules reveals (Figure 3) that the pattern of intramolecular π-donor/π-acceptor stacking extends in rather an elegant fashion throughout the crystal to include lattice-translated molecules.

A qualitative ^{1}H NMR saturation transfer experiment at 12 °C (400 MHz, CD_3COCD_3) on **13** · $8PF_6$ revealed the anisochronous nature of the hydroquinone protons. Upon irradiation of the 'outside' hydroquinone protons ($\delta = 6.34$), that is the protons which are not in the cavity of the tetracationic cyclophane, it was apparent that they were in slow exchange with the 'inside' hydroquinone protons ($\delta = 3.79$), that is the hydroquinone protons inside the cavity of the tetracationic cyclophane. On warming up this solution to 54 °C, these two resonances coalesced and the activation energy barrier ($-\Delta G^{\ddagger}$) for the site exchange was calculated[22] to be 14.1 kcal mol^{-1}. This $\Delta G^{\ddagger}$ value is consistent with those values observed[16,19,23] for other catenated system. It is associated with the circumrotation of the crown ether component through the cavity of the tetracationic cyclophane. It should be noted, however, that, in this bis[2]catenane system, we are observing only partial circumrotation of the crown through the cavity of the tetracationic cyclophane, as a result of the spiro junction not allowing complete circumrotation. The kinetic and thermodynamic data for this process are summarised in Table 1.

The room temperature ^{1}H NMR spectra (400 MHz, CD_3COCD_3) of **13** · $8PF_6$ revealed that, in contrast to the observation of two sets of resonances for an 'inside' and 'outside' set of hydroquinone protons on the crown ether, the α- and β-bipyridinium protons resonate as only one doublet in each case, indicating that both bipyridinium units are isochronous – i.e. the tetracationic cyclophane is circumrotating rapidly, with respect to the ^{1}H NMR timescale, through the cavity of the crown ether. However, a low temperature ^{1}H NMR spectroscopic study revealed that the doublet associated with the α-bipyridinium protons and the doublet associated with the β-bipyridinium protons both separate into two

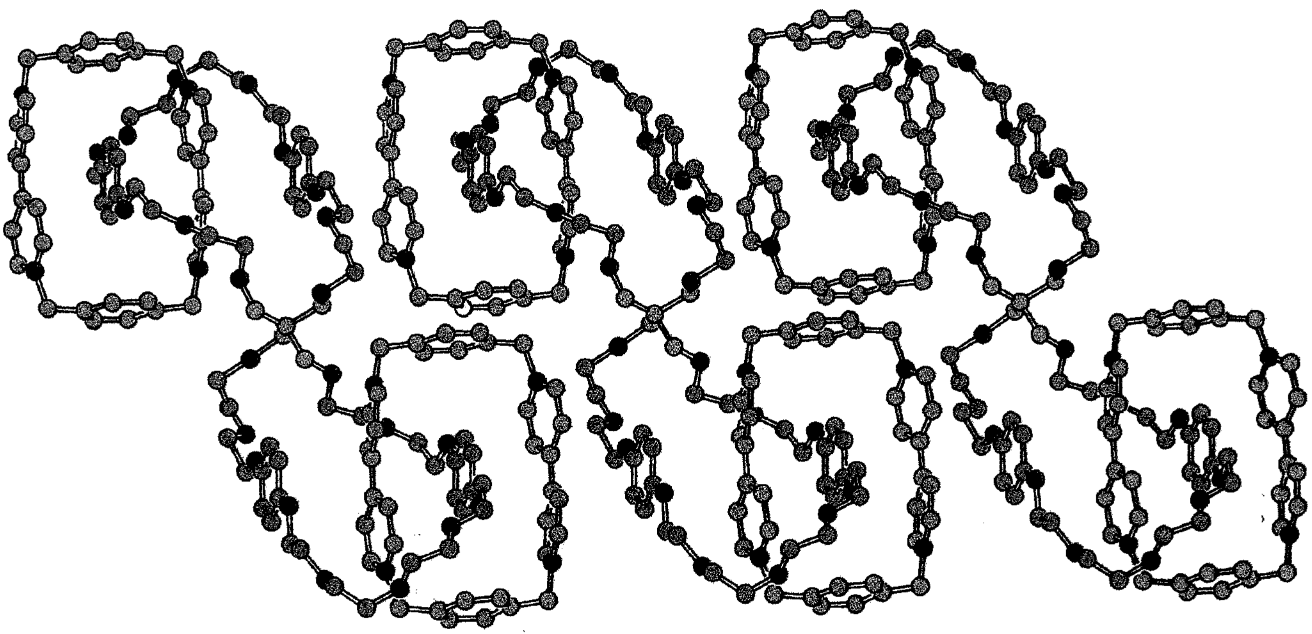


Figure 3. Part of the continuous stacked array of the bis[2]catenane molecules in the crystal of **13** · $8PF_6$, showing the extended π-donor/π-acceptor sequence

Table 1. Kinetic and thermodynamic data for the circumrotations of the crown ether rings through the cavities of the tetracationic cyclophanes in the bis[2]catenane **13** · $8PF_6$ (400 MHz, ^{1}H NMR signals, CD_3COCD_3 solution)

Probe Protons	Line Broadening Temperature T_{ex}/°C	Half-Line Width $\Delta\nu$/Hz	Rate Constant k_{ex}/s^{-1}	$\Delta G^{\ddagger}_{ex}$ kcal mol^{-1}
Outside Hydroquinone	54	1030	2280	14.1

Table 2. Kinetic and thermodynamic data for the circumrotations of the tetracationic cyclophanes components through the cavities of the crown ether rings **13** · 8PF$_6$ (400 MHz, ^{1}H NMR signals, CD$_3$COCD$_3$ solution)

Probe Protons	Coalescence Temperature T_c/°C	Limiting Chemical Shifts $\Delta\nu$/Hz	Rate Constant k_c/s^{-1}	$\Delta G^{\ddagger}_{ex}$ kcal mol^{-1}
α-Bipyridinium[a]	−2.5	37	82	13.4
β-Bipyridinium[b]	−8	40	89	13.0

[a] Exchanging set of doublets at δ = 9.36 and 9.26.

[b] Exchanging set of doublets at δ = 8.23 and 8.13.

doublets. This behaviour is consistent with the circumrotation of the tetracationic cyclophane slowing down until at least, on the ^{1}H NMR timescale, the two bipyridinium units are anisochronous – reflecting them being 'inside' and 'outside' the cavity of the crown. The coalescence of the two sets of α- and β-bipyridinium doublets has been used to calculate the kinetic and thermodynamic data associated with this dynamic process.[21] This data is listed in Table 2.

The present investigations demonstrate that spiro-linked crown ethers such as **1** and **2** are capable of exhibiting self-assembly at both recognition sites. However, we have established that the recognition sites in the crown ether components should be sufficiently separated such that repulsive Coulombic interactions between the cationic charges, which develop upon catenation, do not hinder the self-assembly processes. Our recently published work[16] reveals that, if the crown ether units are separated by a biphenyl spacer, then this spacer is sufficient to allow us to neglect these Coulombic interactions. The fact that, in both of the catenations, sizable quantities of mono catenated products were isolated is an important observation. It appears that these mono catenated products are intermediates which attain significant concentrations in the reaction mixtures during the molecular self-assembly processes. However, we know that these self-assembly steps are proceeding under kinetic control,[24] and so cannot be applied to make high molecular weight polymers in high yields at the present time. Thus, one of our future research objectives is to hone up the mutual recognition between the molecular components in order to enable the self-assembly steps to proceed in quantitative yields. To date we have achieved the self-assembly of a [2]catenane with a yield of 88%.[16] We are getting there!

Solvents were purified and dried using literature methods. Regents were employed as purchased from Aldrich. Tetrahydrofuran (THF) was purified by fresh distillation from K under N$_2$. NaH was used as 60% suspension in mineral oil. Thin layer chromatography (TLC) was carried out using aluminium sheets, precoated with silica gel 60 F (Merck 5554) or aluminium oxide 60 F neutral (Merck 5550). The plates were inspected by UV-light prior to development with iodine vapour or by treatment with ceric ammonium molybdate reagent and subsequent heating. Column chromatography was performed using silica gel 60 (Merck 7734, 0.063–0.200 mm). Elemental analyses were performed by the Microanalytical Laboratory at the University of Sheffield. Mass spectra were recorded on a Kratos Profile spectrometer (EIMS and CIMS) or on a Kratos MS80 spectrometer, equipped with a saddle-field source (Ion Tech Limited) operating at 8 keV using a Krypton primary atom beam (FABMS). High resolution mass spectra were obtained from a VG Zabspec triple-focussing mass spectrometer operating at a resolution of 5000 and using voltage scanning with CsI as a reference. ^{1}H NMR spectra were recorded on a Bruker AC 300 (300 MHz spectra) or a Bruker AMX 400 (400 MHz spectra). ^{13}C NMR spectra were recorded on a Bruker AC 300 (75.5 MHz spectra). All chemical shifts are quoted in ppm on the δ scale using TMS or the solvent as an internal standard.

5,5-Bis[7-(*p*-toluenesulfonyloxy)-2,5-dioxyheptyl]-2-phenyl-1,3-dioxane (5):

A solution of diethylene glycol ditosylate[18] (**4**) (30 g, 72 mmol) in THF (100 mL) and NaH (1.2 g, 30 mmol) was heated under reflux in an N$_2$ atmosphere. After 5 min, a solution of monobenzalpentaerythritol[17] (**3**) (2.0 g, 0.8 mmol) in THF (50 mL) was added dropwise over a period of 2 h. Heating was continued for a further 2 days. The mixture was cooled to r.t. and slowly quenched with H$_2$O (10 mL). The THF was removed in vacuo and the resulting solid was dissolved in CH$_2$Cl$_2$ (400 mL) and washed with H$_2$O (2 x 100 mL). The organic layer was dried (MgSO$_4$), filtered and the solvent removed in vacuo. The resulting solid was recrystallised twice from hexane/EtOAc (1 : 1) to yield unreacted ditosylate **4**. The mother liquors, containing the desired product, were combined and concentrated. The residue was subjected to silica gel column chromatography using hexane/EtOAc (1 : 1) as the eluent. The first fraction contained unreacted monobenzalpentaerythritol (**3**), the second – ditosylate **4**, and the third – the desired product **5**. The eluent was removed in vacuo, affording **5** (2.2 g, 34%) as a colourless oil.

MS: $C_{34}H_{44}O_{12}S_2$ requires [M]$^+$ 708. Found [M]$^+$ 706.

^{1}H NMR (300 MHz, CDCl$_3$, 25 °C): δ = 7.75–7.86 (3 H, m), 7.42–7.52 (2 H, m), 7.28–7.42 (8 H, m), 5.40 (1 H, s), 3.45–4.20 (24 H), m), 2.42 (6 H, 2s).

^{13}C NMR (75.5 MHz, CDCl$_3$, 25 °C): δ = 144.9, 144.8, 138.5, 133.1, 129.9, 129.8, 128.9, 128.3, 127.9, 126.1, 101.9, 101.7, 71.2, 71.0, 70.9, 70.7, 70.6, 70.5, 70.4, 70.0, 69.6, 69.4, 69.3, 68.7, 68.6, 38.9, 21.6, 20.7.

Anal. Calcd. C, 57.59; H, 6.26. Found C, 57.64; H, 6.46.

27′-Spiro-5′-(2′-phenyl-1′,3′-dioxane)-1,4,7,12,15,18,21,24,29,32,35-undecaoxa[27]-1,4-bisbenzophane (7):

A suspension of Cs$_2$CO$_3$ (2.14 g, 6.5 mmol) and caesium tosylate (0.7 g, 2.3 mmol) in anhyd MeCN (200 mL) was heated under reflux in N$_2$ atmosphere. A solution of bis(hydroxy-*p*-phenoxy)trioxaundecane[18] (**6**) (2.0 g, 2.8 mmol) and **5** (1.06 g, 2.8 mmol) in anhyd MeCN (400 mL) was slowly added during a period of 4 h. The mixture was heated under reflux for an additional 2 days, cooled and filtered. The solvent was removed in vacuo and the remaining residue was subjected to silica gel column chromatography using CH$_2$Cl$_2$/EtOAc (1 : 1) as the eluent. The fractions containing the product were then combined and the eluent was removed in vacuo to afford **7** (0.66 g, 32%) as a colourless oil, which crystallised on standing overnight.

MS: $C_{40}H_{54}O_{13}$ requires [M]$^+$ 742. Found [M]$^+$ 742.

^{1}H NMR (300 MHz, CDCl$_3$, 25 °C): δ = 7.42–7.52 (2 H, m), 7.30–7.40 (3 H, m), 6.25 (8 H, 2s), 5.38 (1 H, s), 3.50–4.20 (40 H, m).

^{13}C NMR (75 MHz, CDCl$_3$, 25 °C): δ = 153.2, 153.1, 153.0, 138.4, 128.8, 128.2, 126.1, 117.3, 116.6, 115.7, 115.6, 115.5, 101.7, 101.6, 101.5, 71.6, 71.1, 70.8, 70.7, 70.6, 70.5, 70.2, 70.0, 69.7, 69.5, 69.3, 69.1, 68.6, 68.3, 68.2, 68.1, 38.9.

Anal. Calcd. C, 64.65; H, 7.33. Found C, 64.37; H, 7.15.

37,37-Bis(hydroxymethyl)-1,4,7,12,15,18,21,24,29,32,35-undecaoxa-[27]-1,4-bisbenzophane (8):

A solution of **7** (0.6 g, 0.81 mmol) in CH_2Cl_2/MeOH (1 : 1) (300 mL), to which Pd on activated charcoal (0.6 g, 10 %) had been added, was stirred overnight under 2 atmospheres of H_2. The mixture was filtered over Celite and the filtrate removed in vacuo. The residue was subjected to silica gel column chromatography using CH_2Cl_2/MeOH (5:1) as the eluent. The fractions containing the product were combined and evaporated to yield **8** (0.37 g, 70 %) as a colourless oil.

MS: $C_{33}H_{50}O_{13}$ requires $[M]^+$ 654. Found: $[M+Na]^+$ 677, $[M]^+$ 654.

^{1}H NMR (300 MHz, CD_3COCD_3, 25 °C): $\delta = 6.84$ (8 H, s), 3.48–4.10 (36 H, m), 2.40 (4 H, s).

^{13}C NMR (75.5 MHz, CD_3COCD_3, 25 °C): δ = 154.0, 116.3, 71.6, 71.4, 71.0, 70.6, 70.3, 68.9, 68.8, 68.2, 67.9, 63.7, 46.3.

Anal. Calcd. C, 60.51; H 7.70. Found C, 60.41; H 7.65.

37,37-Bis[7-(*p*-toluenesulfonyloxy)-2,5-dioxaheptyl]-1,4,7,12,15,18,21,24,29,32,35-undecaoxa[27]-1,4-bisbenzophane (9) and 1,4,7,12,15,18,21,24,29,32,35-Undecaoxa[27]-1,4-bisbenzophane-37-spiro-6′-[2′,5′,8′,38′,41′,44′]hexaoxy[9.9]cyclododecane-43′-spiro-37″-[1″,4″,7″,12″,15″,18″,21″,24″,29″,32″,35″-undecaoxa]-1,4-bisbenzophane (Dispiro Crown) (2):

A solution of diethylene glycol ditosylate[17] (**4**) (15 g, 36 mmol) in anhyd THF (300 mL) and NaH (0.4 g, 10 mmol) was heated under reflux in N_2 atmosphere. After 2 min, a solution of **8** (1.085 g, 0.16 mmol) in anhyd THF (100 mL) was added dropwise over a period of 3 h. Heating was continued for a further 2 days. The mixture was cooled to r.t. and carefully quenched with H_2O (10 mL). The THF was removed in vacuo and the resulting solid was dissolved in $CHCl_3$ (400 mL) and washed with H_2O (2 × 50 mL). The organic layer was dried ($MgSO_4$) and filtered. The filtrate was concentrated in vacuo and the remaining solid was subjected to silica gel column chromatography [gradient elution CH_2Cl_2/MeOH (100:5) to CH_2Cl_2/MeOH (100:20)]. The first fraction contained unreacted ditosylate **4**, the second, compound **9** (0.827 g, 44 %) and the third, the dispiro crown **2** (0.194 g, 8 %).

9: MS: $C_{55}H_{78}O_{21}S_2$ requires $[M]^+$ 1139. Found $[M]^+$ 1139, [M-tosyl]$^+$ 985.

^{1}H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 7.30–7.75 (8 H, AB), 6.72 (8 H, s), 3.30–4.15 (56 H, m), 2.39 (6 H, s).

^{13}C NMR (75 MHz, $CDCl_3$. 25 °C): δ = 153.1, 148.3, 144.8, 142.9, 133.1, 129.8, 127.9, 115.6, 115.5, 71.1, 71.0, 70.8, 70.7, 70.6, 70.5, 69.9, 69.8, 69.7, 69.4, 68.6, 68.2, 68.1, 45.6, 21.6.

Anal. Calcd. C, 57.69; H, 6.90. Found C, 57.42; H, 7.09.

2: MS: $C_{74}H_{112}O_{28}$ requires $[M]^+$ 1471.8. Found $[M+Na]^+$ 1472.

^{1}H NMR (300 MHz, $CDCl_3$ 25 °C): δ = 6.75 (16 H, s), 3.50–4.00 (80 H, m), 3.45 (16 H, s).

^{13}C NMR (75.5 MHz, $CDCl_3$, 25 °C): δ = 153.1, 115.7, 115.5, 71.2, 71.1, 70.9, 70.8, 70.6, 70.4, 69.8, 69.7, 68.2, 68.1, 45.6.

Anal. Calcd. C, 61.28; H, 7.80. Found C, 60.87; H, 8.08.

37,37′-Spirobis[1,4,7,12,15,18,21,24,29,32,35-undecaoxa[27]-1,4-bisbenzophane] (Spiro Crown) (1):

A suspension of Cs_2CO_3 (0.9 g, 0.28 mmol) and caesium tosylate (0.3 g, 0.9 mmol) in anhyd MeCN (250 mL) was heated under reflux in N_2 atmosphere. After 2 min, a solution of **9** (0.9 g, 0.79 mmol) and bis(hydroxy-*p*-phenoxy)trioxaundecane (**6**)[11] (0.299 g, 0.79 mmol) in anhyd MeCN (250 mL) was added dropwise over 4 h. The mixture was heated under reflux for 2 days. The mixture was cooled, filtered and the filtrate concentrated in vacuo. The remaining residue was subjected to silica gel column chromatography [gradient elution EtOAc to $CHCl_3$/MeOH (10:1)]. The fractions containing the product were combined and the eluent removed in vacuo to afford **1** (0.333 g, 36 %) as a white solid.

MS: $C_{61}H_{88}O_{22}$ required $[M]^+$ 1173. Found $[M+Na]^+$ 1195, $[M]^+$ 1173.

^{1}H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 6.74 (16 H, s), 3.50–4.05 (64 H, m), 3.45 (8 H, s).

^{13}C NMR (75.5 MHz, $CDCl_3$, 25 °C): δ = 153.1, 115.6, 115.5, 71.1, 70.9, 70.8, 70.6, 70.0, 69.8, 69.7, 69.6, 68.2, 68.1, 45.6.

Anal. Calcd. C, 62.43; H, 7.56. Found C, 62.31; H, 7.47.

[2]Catenane 12 · 4PF$_6$ and Bis[2]catenane 13 · 8PF$_6$:

A solution of 1,1′-[1,4-phenylenebis(methylene)]bis-4,4′-bipyridinium bis(hexafluorophosphate) (**11** · $2PF_6$) (0.900 g, 1.27 mmol), 1.4-bis(bromomethyl)benzene (**10**) (0.337 g, 1.27 mmol) and the spiro crown **1** (0.374 g, 0.32 mmol) in anhyd DMF 810 mL) was stirred at r.t. for 14 days. The solution developed a red colour. The mixture was evaporated under reduced pressure and the residue was purified by silica gel column chromatography using MeOH/2M aq. NH_4Cl/$MeNO_2$ (7:2:1) as the eluent to obtain two red-coloured fractions. These two fractions were concentrated to dryness and the residue was redissolved in water. Precipitation with sat. aq NH_4PF_6 yielded two red-coloured solids. Further purification was achieved by vapour diffusion of *i*-Pr_2O into MeCN solutions of the two catenanes to afford the [2]catenane **12** · $4PF_6$ (0.244 g, 31 %) as a red oil and the bis[2]catenane **13** · $8PF_6$ (0.021 g, 2 %) as red crystals, which were suitable for X-ray structural analysis.

12 · $4PF_6$: MS: $C_{97}H_{120}N_4O_{22}F_{24}P_4$ requires 2274. Found 2274 $[M]^+$, 2129 $[M\text{-}PF_6]^+$, 1984 $[M\text{-}2PF_6]^+$, 1838 $[M\text{-}3PF_6]^+$.

^{1}H NMR (300 MHz, CD_3COCD_3, 25 °C): δ = 9.28 (8 H, d), 8.13 (8 H, d), 8.02 (8 H, s), 6.82 (8 H, s), 6.03 (8 H, s), 6.10–6.60 (4 H, b), 3.30–4.10 (76 H, m).

^{13}C NMR (75.5 MHz, CD_3COCD_3, 25 °C): δ = 154.0, 147.1, 145.6, 137.7, 131.8, 126.6, 116.4, 116.2, 71.7, 71.3, 70.8, 70.3, 69.9, 69.0, 68.9, 65.8, 47.0.

HRMS (LSIMS): $C_{97}H_{120}N_4O_{22}F_{24}P_3$ requires 2127.7320 $[M\text{-}PF_6]^+$. Found $[M\text{-}PF_6]^+$ 2127.7269.

13 · $8PF_6$: MS: $C_{133}H_{152}N_8O_{22}F_{48}P_8$ requires $[M]^+$ 3374. Found $[M\text{-}PF_6]^+$ 3229, $[M\text{-}2PF_6]^+$ 3084, $[M\text{-}3PF_6]^+$ 2939.

^{1}H NMR (300 MHz, CD_3COCD_3, 25 °C): δ = 9.30 (16 H, br m), 8.15 (16 H, br m), 8.08 (16 H, s), 6.18–6.50 (8 H, br m), 5.90–6.18 (16 H, br m), 3.30–4.10 (66 H, m).

^{13}C NMR (100 MHz, CD_3COCD_3, −25 °C): δ = 152.8, 150.8, 150.7, 146.6, 145.7, 145.5, 144.9, 137.7, 131.6, 125.2, 115.5, 115.2, 113.5, 73.0, 72.0, 71.5, 71.2, 70.6, 70.5, 70.4, 70.3, 69.5, 69.3, 68.9, 67.9, 67.0, 66.9, 65.2, 60.4, 47.0.

HRMS (LSIMS): $C_{133}H_{152}N_8O_{22}F_{48}P_8$ requires $[M\text{-}PF_6]^+$ 3227.8514. Found $[M\text{-}PF_6]^+$ 3227.8373.

[2]Catenane 14 · 4 PF$_6$ and Bis[2]catenane 15 · 8PF$_6$:

A solution of 1,1′-[1,4-phenylenebis(methylene)]bis-4,4′bipyridinium bis(hexafluorophosphate) (**11** · $2PF_6$) (0.307 g, 0.43 mmol), 1,4-bis(bromomethyl)benzene (**10**) (0.115 g, 0.43 mmol) and the dispiro crown **2** (0.154 g, 0.11 mmol) in anhyd DMF (10 mL) was stirred at r.t. for 14 days. The solution turned red. The mixture was evaporated under reduced pressure and the residue was purified by silica gel column chromatography using MeOH/1M aq NH_4Cl/$MeNO_2$ (7:2:1) as the eluent to obtain two red-coloured fractions. These two fractions were concentrated to dryness and the residue was redissolved in H_2O. Precipitation with sat. aq NH_4PF_6 yielded two red-coloured solids after filtration. These two solids were purified further by vapour diffusion of *i*-Pr_2O into MeCN solutions of the red compounds. This purification procedure afforded the [2]catenane **14** · $4PF_6$ (0.145 g, 53 %) as a red oil and the bis[2]catenane **15** · $8PF_6$ (0.025 g, 6 %) as a red solid.

14 · $4PF_6$: MS: $C_{110}H_{144}N_4O_{28}F_{24}P_4$ requires $[M]^+$ 2550. Found 2550 $[M]^+$, 2405 $[M\text{-}PF_6]^+$, 2260 $[M\text{-}2PF_6]^+$, 2115 $[M\text{-}3PF_6]^+$.

^{1}H NMR (300 MHz, CD_3COCD_3, 25 °C): δ = 9.30 (8 H, d), 8.15 (8 H, d), 8.06 (8 H, s), 6.70 (8 H, s), 6.07 (8 H, s), 6.20–6.50 (4 H, b), 3.30–4.10 (100 H).

^{13}C NMR (75.5 MHz, CD_3COCD_3, 25 °C): δ = 154.0, 147.1, 145.6, 137.7, 131.8, 128.6, 126.6, 116.3, 116.2, 72.3, 72.0, 71.8, 71.3, 71.1, 70.0, 69.1, 68.9, 65.7, 57.0, 56.5.

HRMS (LSIMS): $C_{110}H_{144}N_4O_{28}F_{24}P_4$ requires $[M\text{-}PF_6]^+$ 2403.8893. Found $[M\text{-}PF_6]^+$ 2403.8915.

15 · $8PF_6$: MS: $C_{146}H_{176}N_8O_{28}F_{48}P_8$ requires $[M]^+$ 3650. Found $[M\text{-}PF_6]^+$ 3505, $[M\text{-}2PF_6]^+$ 3360, $[M\text{-}3PF_6]^+$ 3215.

^{1}H NMR (300 MHz, CD_3COCD_3, 25 °C): δ = 9.30 (16 H, d), 8.15 (16 H, d), 8.06 (16 H, s), 6.10–6.50 (8 H, b), 6.05 (16 H, s), 3.30–4.12 (106 H, m).

^{13}C NMR (75.5 MHz, CD_3COCD_3, 25 °C): δ = 147.2, 145.6, 137.8, 131.0, 126.6, 71.9, 71.4, 71.0, 70.8, 70.4, 69.8, 69.2, 65.8, 47.2.

HRMS (LSIMS): $C_{146}H_{176}N_8O_{28}F_{48}P_8$ requires $[M\text{-}PF_6]^+$ 3359.0445. Found $[M\text{-}PF_6]^+$ 3359.0374.

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(20) Crystal data for **13** · $8PF_6$: $C_{133}H_{152}N_8O_{22}F_{48}P_8 \cdot 8MeCN$, M = 3702.82, monoclinic, $a = 23.451(3)$, $b = 14.024(1)$, $c = 27.590(1)$ Å, $\beta = 110.16(1)°$, $V = 8518.0(1)$ Å^3, space group $P2_1/n$, $Z = 2$ (molecule has crystallographic C_1 symmetry), $D_c = 1.444\ g\ cm^{-3}$, μ (Cu-K_α) = 1.83 mm^{-1}, $\lambda = 1.54178$ Å, F(000) = 3820. Data for a crystal of the dimensions 0.43 × 0.43 × 0.07 mm were measured on a Siemens P4/RA diffractometer with Cu-K_α radiation (graphite monochromated) using ω scans. Of the 8575 independent reflections measured ($\theta \leq 60°$), 3837 had $I_0 > 2\ \sigma\ (I_0)$ and were considered to be observed. The structure was solved by direct methods. Disorder is observed around the spiro-centre thus simulating a centrosymmetric structure, also in one of the MeCN molecules. In both cases, this disorder was resolved by refinement of different partial occupancy orientations. Due to a shortage of observed data, the PF_6^- anions, aromatic rings and MeCN solvent molecules were refined as rigid bodies. Anisotropic refinement of the anions, the full-weight atoms of the spiro-crown and the solvent, the remainder held isotropic, gave $R_1 = 0.1536$ and $wR_2 = 0.4234$ based on F^2. Atomic coordinates, bond lengths and angles have been deposited at the Cambridge Crystallographic Data Centre (CCDC).

(21) As the bis[2]catenane **13** · $8PF_6$ crystallises in the uniquely determinable space group $P2_1/n$ with two molecules in the unit cell, the averaged structure throughout the crystal is required to have an inversion centre. Since it is not possible for the spiro structure to contain a centre of symmetry, the molecule of **13**$^{8+}$ has to be disordered. As the central quaternary carbon atom lies on a crystallographic symmetry centre, two centrosymmetrically-related superimposed tetrahedral carbon centres and associated emanating polyether chains had to be modelled. Because of this disorder and the presence of disordered PF_6^- anions and MeCN solvent molecules, the final value of R is somewhat high. However, the bis[2]catenated nature of the structure is unambiguous.

(22) The kinetic data were obtained by either the exchange method, where values of the rate constant (k_{ex}) were obtained (Sand-

ström, J.; Dynamic NMR Spectroscopy; Academic Press: London, 1982, Chapter 6) from the approximate expression $k_{ex} = \pi (\Delta v)$, where Δv is the difference (in Hertz), at the exchange temperature (T_{ex}), or by the coalescence method, where values of the rate constant (k_c) at the coalescence temperature (T_c) were obtained (Sutherland, I.O. *Annu. Rep. NMR Spectrosc.* **1971**, *4*, 71) from the approximate expression $k_c = \pi\Delta v/(2)^{1/2}$, where Δv is the limiting chemical shift difference (in Hertz) between the exchanging proton resonances measured below T_c. The Eyring equation was used to calculate $\Delta G^{\ddagger}_{ex}$ and $\Delta G^{\ddagger}_{c}$ values at T_{ex} and T_c, respectively.

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