The self-assembly and metal-mediated disassembly of a multi-topic [2]pseudorotaxane

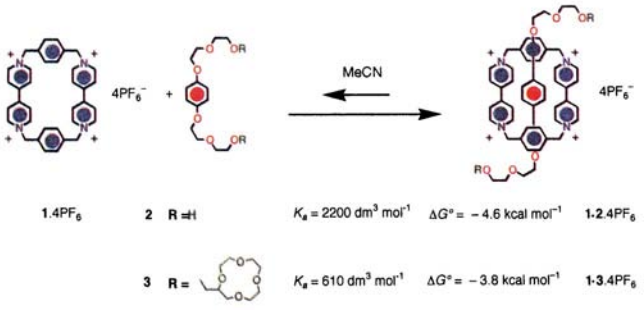
Peter R. Ashton,[a] Sayeedha Iqbal,[a] J. Fraser Stoddart[a] and Nigel D. Tinker[b]

[a] *School of Chemistry, University of Birmingham, Edgbaston, Birmingham, UK B15 2TT*
[b] *British Nuclear Fuels Plc, Springfields Works, Salwick, Preston, UK PR4 0JX*

A [2]pseudorotaxane, consisting of the cyclobis(paraquat-*p*-phenylene) tetracation complexing a polyether chain intercepted in its middle by a hydroquinone ring and terminated at each end by 12-crown-4 macrocycles, undergoes disassembly readily in acetonitrile solution on addition of alkali metal salts.

In recent years, there has been considerable interest[1] in constructing and controlling molecular assemblies and supramolecular arrays in solution. A combination of molecular recognition[2,3] and self-assembly[4,5] processes have been employed to generate a large number of these assemblies and arrays. One such superstructure—the [2]pseudorotaxane[6] **1·2**.4PF_6 shown in Scheme 1—consists of a tetracationic cyclophane $\mathbf{1}^{4+}$ containing π-electron deficient bipyridinium units encircling an acyclic polyether derivative containing a π-electron rich hydroquinone ring. The association constant (K_a = 2200 dm^3 mol^{-1}) for the complex **1·2**.4PF_6 is large in acetonitrile and so the [2]pseudorotaxane is the predominant species in solution. In a related [2]pseudorotaxane, in which a 1,5-dioxynaphthalene residue replaces the hydroquinone ring in **2**, a light-induced unthreading process has been demonstrated[7] in the presence of the 'sacrificial' reductant, triethanolamine.

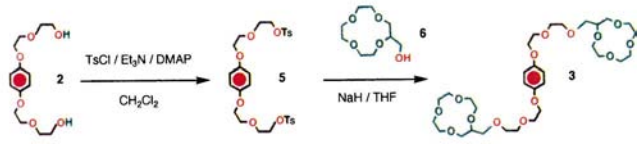
Here, we describe the synthesis (Scheme 2) of the bis-12-crown-4 derivative **3**,† which can act as both a host (towards alkali metal cations) and a guest (towards the tetracationic cyclophane $\mathbf{1}^{4+}$) in a supramolecular context. We go on to show how the binding of **3** by $\mathbf{1}^{4+}$ can be reduced by addition of metal cations, such as Li^+ and Na^+ ions, which are known to complex with 12-crown-4 derivatives. In this manner, we can achieve the unthreading of the [2]pseudorotaxane **1·3**.4PF_6 by chemical means.[8] The choice of **3** as a multi-topic cation binder was based on two observations: firstly, the fact that **2** forms[6] a stable [2]pseudorotaxane **1·2**.4PF_6 with **1**.4PF_6 in solution, and secondly, the fact that 12-crown-4 derivatives are known[9] to exhibit high affinities for binding alkali metal cations — particularly Li^+ and Na^+ ions — in solution. Inspection of CPK space-filling molecular models indicated that the 12-crown-4 rings at the termini of **3** should slip[10] through the cavity of the tetracationic cyclophane $\mathbf{1}^{4+}$. The basis for the chemically-controlled unthreading (Scheme 3) of the multi-topic [2]pseudorotaxane **1·3**.4PF_6 is thus established in principle. Now, we demonstrate that it happens in practice.



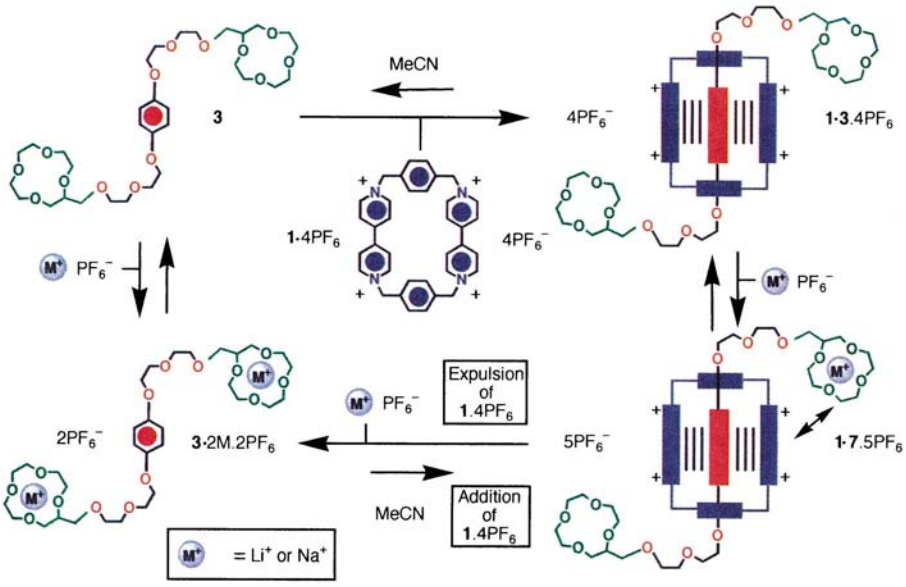
Scheme 1 The self-assembly of the [2]pseudorotaxanes **1·2**.4PF_6 and **1·3**.4PF_6

The bis-12-crown-4 derivative **3**‡ has been prepared (Scheme 2) from bis[2-(2-hydroxethoxy)ethoxy]benzene **2**.[5b] Tosylation ($TsCl$–Et_3N–DMAP–CH_2Cl_2) of **2** gave the ditosylated **5**[5b] in 80% yield. Reaction (NaH–THF) of two molar equivalents of 2-(hydroxymethyl)-12-crown-4§ **6** with **5** afforded **3**, as presumably a mixture of diastereoisomers,† in 70% yield. When equimolar acetonitrile solutions of **1**.4PF_6 and **3** are mixed, a red-orange colour appears immediately, indicating the formation of the (Scheme 3) [2]pseudorotaxane **1·3**.4PF_6¶ with its expected[11] charge transfer (CT) absorption band centred on λ = 466 nm. The 1 : 1 stoichiometry of the complex was established by performing a Job plot[12] on UV spectroscopic data obtained at this wavelength. A K_a value of 610 dm mol^{-1} was obtained‖ for **1·3**.4PF_6 in CD_3CN at 25 °C by ^1H NMR spectroscopy. This K_a value, which corresponds to a free energy of complexation of 3.8 kcal mol^{-1}, means that this 1 : 1 complex is slightly weaker than that represented by the [2]pseudorotaxane **1·2**.4PF_6 which has a $-\Delta G^\circ$ value of 4.6 kcal mol^{-1}. The subsequent addition of integer (1.0, 2.0, 3.0 *etc.*) molar proportions of either $LiPF_6$ or $NaPF_6$ to **1·3**.4PF_6 in MeCN led to the suppression progressively of the CT band in the UV spectrum of the [2]pseudorotaxane. The addition of a large excess (10 equiv.) of $NaPF_6$ to **1·3**.4PF_6 in MeCN brings about [Fig. 1(*A*)] the almost complete suppression of the CT absorption band, whereas the same experiment performed on **1·2**.4PF_6 results in only a very slight suppression [Fig. 1(*B*)] of the CT absorption band. These experiments indicate that disassociation of **1·3**.4PF_6 occcurs in MeCN when alkali metal cations, that can bind to the 12-crown-4 end groups, are added to the solution. This disassembly of the [2]pseudorotaxane **1·3**.4PF_6, can also be monitored by ^1H NMR spectroscopy in CD_3CN solution. Upon addition of an excess of $LiPF_6$ to a 6.43 × 10^{-3} mol dm^{-3} solution, signals corresponding to the free tetracationic cyclophane **1**.4PF_6 are enhanced significantly.** It would appear that, upon addition of an excess of alkali metal salt to the [2]pseudorotaxane **1·3**.4PF_6, an unstable metallated complex **1·7**.5PF_6 results which then rapidly unthreads to give the tetracationic cyclophane $\mathbf{1}^{4+}$ and ultimately the dimetallated dumbbell species **3**.2M.2PF_6. This unthreading process can be monitored by a reduction in the intensity of the CT band centred at 466 nm for **1·3**.4PF_6. Effectively, the electrostatic repulsion of the tightly bound metal cations within the 12-crown-4 **1·7**.5PF_6 results in its dissociation.

Analysis by liquid secondary ion mass spectrometry (LSIMS) of the complex **1·3**.4PF_6 [Fig. 2(*A*)] reveals peaks at *m/z* 1617, 1472 and 1327 corresponding to the loss of one, two,



Scheme 2 The self-assembly and metal-mediated disassembly of the [2]pseudorotaxane **1·3**.4PF_6



Scheme 3 The synthesis of the dumbbell-shaped compound **3** containing two 12-crown-4 macrocycles

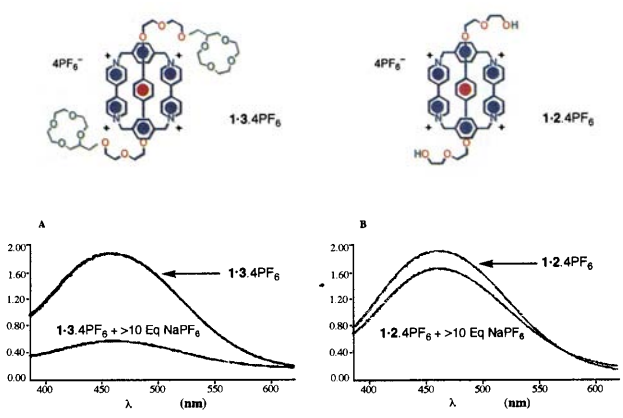


Fig. 1 The absorption UV spectra of (*A*) **1·2**.4PF$_6$ in CD_3CN (3.18 mmol dm^{-3}) at 298 K and of (*B*) **1·3**.4PF$_6$ in CD_3CN (3.18 mmol dm^{-3}) at 298 K

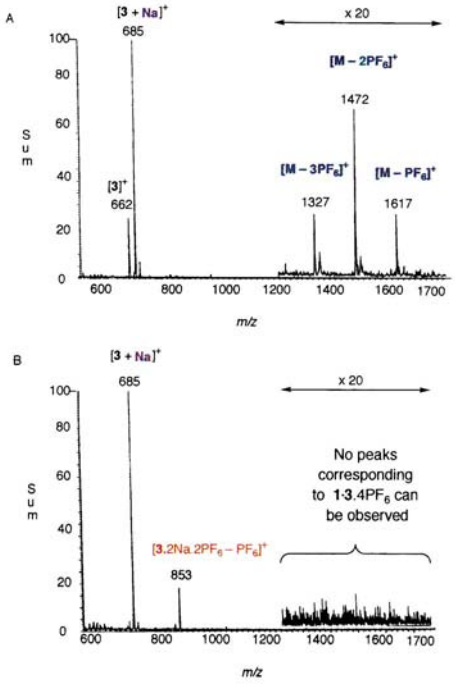


Fig. 2 The LSIMS of (*A*) **1·3**.4PF$_6$ and of (*B*) **1·3**.4PF$_6$ with the addition of NaPF$_6$

and three hexafluorophosphate counterions, respectively. The spectrum of the [2]pseudorotaxane, following the addition of a solution of LiPF$_6$ or NaPF$_6$ in MeCN to the probe, is shown in Fig. 2(*B*). Although no peaks corresponding to the [2]pseudorotaxane **1·3**.4PF$_6$ can be observed, the dimetallated dumbbell species **3**.2M.2PF$_6$ can now be detected at *m/z* 853 in a peak which corresponds to the loss of one hexafluorophosphate counterion.

The synthesis of a new multi-topic cation binder **3**, which is capable of selectively recognising and binding both metal and organic cations, has been achieved. A [2]pseudorotaxane **1·3**.4PF$_6$ has been self-assembled which can be disassembled chemically by the selective binding of alkali metal cations to the 12-crown-4 components of the multi-topic cation binder **3**. We have shown that it is possible to manipulate and control these systems at a molecular level in a manner which could lend them to molecular device development.

We thank the British Nuclear Fuels Plc in UK for financial support of this research.

Footnotes

† Compound **3** was obtained as a mixture of diastereoisomers.

‡ *Selected Data* for **3**: LSIMS 662 (M$^+$); ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.85 (4 H, s), 4.05 (4 H, m) and 3.80–3.50 (46 H, m); ^{13}C NMR (75 Mz, $CDCl_3$) δ 153.2, 115.6, 78.6, 71.7, 71.5, 70.9, 70.8, 70.7, 70.4, 70.2, 69.9 and 68.2.

§ Compound **6** was purchased from Aldrich as the racemic modification.

¶ *Selected data* for **1·3**.4PF$_6$: LSIMS 1617 [M$^+$ − PF$_6$]; the ^{1}H NMR spectrum of **1.3**.4PF$_6$ in CD_3CN at 298 K indicates that the [2]pseudorotaxane is equilibrating slowly with its components on the ^{1}H NMR time-scale. A set of resonances can be observed for the complexed tetracationic cyclophane **1**$^{4+}$ and the complexed dumbbell compound **3** along with another set for the free cyclophane **1**$^{4+}$ and the uncomplexed dumbbell compound **3**. The ratio of the complexed **1**$^{4+}$: free cyclophane **1**$^{4+}$ at 298 K is 50 : 50. Partial ^{1}H NMR (300 MHz, CD_3CN) δ 8.99–8.92 (8 H, m, α-bipyridinium–complexed **1**$^{4+}$), 8.91–8.89 (8 H, d, *J* 7 Hz, α-bipyridinium–free **1**$^{4+}$), 8.12–8.09 (8 H, d, *J* 7 Hz, β-bipyridinium–free **1**$^{4+}$), 7.89–7.82 (8 H, d, *J* 7 Hz, β-bipyridinium–complexed **1**$^{4+}$), 7.80 (8 H, s, *p*-phenylene-free **1**$^{4+}$), 7.60 (8 H, s, *p*-phenylene–complexed **1**$^{4+}$), 5.78–5.72 (16 H, m, NCH_2–complexed and free **1**$^{4+}$).

‖ The ratio of complexed to uncomplexed 1^{4+} varies with concentration and temperature. The β-bipyridinium and *p*-phenylene protons in 1^{4+} component were used as independent probes for obtaining data from which a K_a value was deduced.

** The ratio of complexed to free tetracationic cyclophane is 44 : 56 at 303 K in CD_3CN. Upon addition of a large excess of $LiPF_6$ to the [2]pseudorotaxane **1**·3.4PF_6, the ratio of complexed to free tetracationic cyclophane becomes 8 : 92.

References

1 (*a*) For controllable catenanes and rotaxanes, see: P. R. Ashton, R. A. Bissell, N. Spencer, J. F. Stoddart and M. S. Tolley, *Synlett*, 1992, 914; P. R. Ashton, R. Ballardini, V. Balzani, M. Blower, M. Ciano, M. T. Gandolfi, C. H. McLean, D. Philp, L. Prodi, N. Spencer, J. F. Stoddart and M. S. Tolley, *New J. Chem.*, 1993, **17**, 68; A. C. Benniston, A. Harriman and V. M. Lynch, *Tetrahedron Lett.*, 1994, **35**, 1473; R. Hoss and F. Vögtle, *Angew. Chem., Int. Ed. Engl.*, 1994, **33**, 375; P. R. Ashton, L. Pérez-García, J. F. Stoddart, A. J. P. White and D. J. Williams, *Angew. Chem., Int. Ed. Engl.*, 1995, **34**, 571; F. Diederich, C. Dietrich-Buchecker, J.-F. Nierengarten and J.-P. Sauvage, *J. Chem. Soc., Chem. Commun.*, 1995, 781; H. Sleiman, P. Baxter, J.-M. Lehn and K. Rissanen, *J. Chem. Soc., Chem. Commun.*, 1995, 715; (*b*) For a discussion on possible applications, see: R. A. Bissell and J. F. Stoddart, *Computations for the Nano-Scale*, Kluwer, Dordrecht, The Netherlands, 1993, p. 141; B. L. Feringa, W. F. Jager and B. Delange, *Tetrahedron*, 1993, **49**, 8267; K. E. Drexler, *Nanosystems, Molecular Machinery, Manufacturing and Computation*, Wiley, New York, 1992; (*c*) For systems with switch-like properties, see: S. Shinkai, M. Ishihara, K. Ueda and O. Manabe, *J. Chem. Soc., Perkin Trans. 1*, 1988, 1438; V. Goulle, A. Harriman and J.-M. Lehn, *J. Chem. Soc., Chem. Commun.*, 1993, 1034; P. D. Beer, J. P. Danks, D. Hesek and J. F. McAleer, *J. Chem. Soc., Chem. Commun.*, 1993, 1735; J.-C. Rodriguez-Ubis, O. Juanes and E. Brunet, *Tetrahedron. Lett.*, 1994, **35**, 1295; M. Shimomura, S. Aiba, S. Oguma, M. Oguchi, M. Matsute, H. Shimada, R. Kagimara, H. Emori, K. Yishiwara, K. Okuyana, T. Miyashita, A. Watanabe and M. Matsuda, *Supramolecular Science, 1*, 1994, **33**; M. Nakamura, A. Ikeda, N. Ise, T. Ikeda, H. Ikeda, F. Toda and A. Ueno, *J. Chem. Soc., Chem. Commun.*, 1995, 721.

2 C. J. Pedersen, *J. Incl. Phenom.*, 1988, **6**, 337; J.-M. Lehn, *J. Incl. Phenom.*, 1988, **6**, 6351; D. J. Cram, *J. Incl. Phenom.*, 1988, **6**, 397; J.-M. Lehn, *Science*, 1993, **260**, 1762.

3 G. W. Gokel, *Crown Ethers and Cryptands*, Monographs in Supramolecular Chemistry, ed. J. F. Stoddart, The Royal Society of Chemistry, Cambridge, 1991; D. J. Cram and J. M. Cram, *Containers and Their Guests*, Monographs in Supramolecular Chemistry, ed. J. F. Stoddart, The Royal Society of Chemistry, Cambridge, 1994.

4 J. S. Lindsey, *New J. Chem.*, 1991, **15**, 153.

5 (*a*) D. Philp and J. F. Stoddart, *Synlett.*, 1991, 445; (*b*) P. L. Anelli, P. R. Ashton, R. Ballardini, V. Balzani, M. Delgado, M. T. Gandolfi, T. T. Goodnow, A. E. Kaifer, D. Philp, M. Pietraszkiewicz, L. Prodi, M. V. Reddington, A. M. Z. Slawin, N. Spencer, J. F. Stoddart, C. Vicent and D. J. Williams, *J. Am. Chem. Soc.*, 1992, **114**, 193; (*c*) D. B. Amabilino, P. R. Ashton, C. L. Brown, E. Córdova, L. A. Godinez, T. T. Goodnow, A. E. Kaifer, S. P. Newton, M. Pietraszkiewicz, D. Philp, F. M. Raymo, A. S. Reder, M. T. Rutland, A. M. Z. Slawin, N. Spencer, J. F. Stoddart and D. J. Williams, *J. Am. Chem. Soc.*, 1995, **117**, 1271.

6 P. L. Anelli, P. R. Ashton, T. T. Goodnow, A. M. Z. Slawin, N. Spencer, J. F. Stoddart and D. J. Williams, *Angew, Chem., Int. Ed. Engl.*, 1991, **30**, 1036.

7 R. Ballardini, V. Balzani, M. T. Gandolfi, L. Prodi, M. Venturi, D. Philp, H. G. Ricketts and J. F. Stoddart, *Angew. Chem., Int. Ed. Engl.*, 1993, **32**, 1301.

8 R. A. Bissell, E. Córdova, A. E. Kaifer and J. F. Stoddart, *Nature*, 1994, **369**, 133.

9 R. B. Davidson, R. M. Izatt, J. J. Christensen, R. A. Shultz, D. M. Dishong and G. W. Gokel, *J. Org. Chem.*, 1984, **49**, 5080; *Cation Binding by Macrocycles*, ed. Y. Inoue and G. W. Gokel, Marcel Dekker, New York, 1990.

10 For references on slippage, see: P. R. Ashton, M. Bělohradský, D. Philip and J. F. Stoddart, *J. Chem. Soc., Chem. Commun.*, 1993, 1269; P. R. Ashton, M. Bělohradský, D. Philip and J. F. Stoddart, *J. Chem. Soc., Chem. Commun.*, 1993, 1274; D. B. Amabilino, P. R. Ashton, M. Bělohradský, F. M. Raymo and J. F. Stoddart, *J. Chem. Soc., Chem. Commun.*, 1995, 745; D. B. Amabilino, P. R. Ashton, M. Bělohradský, F. M. Raymo and J. F. Stoddart, *J. Chem. Soc., Chem. Commun.*, 1995, 751.

11 A. C. Benniston, A. Harriman, D. Philp and J. F. Stoddart, *J. Am. Chem. Soc.*, 1993, **115**, 5298.

12 Z. D. Hill and P. MacCarthy, *J. Chem. Ed.*, 1986, **64**, 162.

Received, 6th October 1995; Com. 5/06617D