Pseudorotaxanes and Rotaxanes Formed by Viologen Derivatives


Keywords: [2]Rotaxanes / Isothermal titration microcalorimetry / Noncovalent interactions / Host–guest system / Nanotechnology

Dibenzyl-4,4’-bipyridinium (BIPY2+) bis(hexafluorophosphate) and three of its derivatives – disubstituted at the para positions of the benzyl groups with CO2Me, F, and Me in turn – have been shown to form 1:1 complexes that are [2]pseudorotaxanes with dibenzo[24]crown-8 (DB24C8), benzometaphenylene[25]crown-8 (BMP25C8), and dipyridof[24]crown-8 (DP24C8) in CD3CN solution by 1H NMR spectroscopy and in one case in the solid state by X-ray crystallography. Binding constants (Ka) for all of these 1:1 complexes, which were determined both (1) by isothermal titration calorimetry in MeCN solution and (2) by the 1H NMR spectroscopic single-point method in CD3CN solution, were found to be, on the average, an order of magnitude less than the Ka values obtained for DB24C8 and DP24C8 with dibenzylammonium (DBA+) hexafluorophosphate and three of its derivatives, also disubstituted at the para positions of the benzyl groups with CO2Me, F and Me. In the case of BMP25C8, however, the Ka values with both categories (BIPY2+ and DBA+) of guests are much of a muchness, being both small and error prone. The equilibrium thermodynamics for these small libraries of [2]pseudorotaxanes indicate that the best bistable [2]rotaxanes incorporating both DBA+ and BIPY2+ recognition sites are going to involve ester functions in their dumbbell components and will employ DP24C8 or, failing that, DB24C8 as the ring component. The BIPY2+-threaded systems also directed the templated assembly of [2]rotaxanes incorporating the crown ethers (DB24C8, DP24C8, and BMP25C8) and triphenylphosphonium stoppers using the threading followed by stoppering approach. The rotaxanes were characterized in solution by 1H NMR spectroscopy, and in one case in the solid state by X-ray crystallography.

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Introduction

The ability to thread secondary dibenzylammonium ions (DBA+) through appropriately sized macrocyclic polyethers has resulted in the creation of numerous supramolecular assemblies,[1] as well as interlocked molecules,[2] some of which have been shown to function as nanoscale machines[3] and switches.[4] The bistability observed in some of these device-like systems is achieved by providing a secondary recognition site around which a crown ether may reside – a role that has been ably filled[3a,3b,4a] by viologen moieties – should the ammonium ion-recognition be “turned off” upon deprotonation. The rational design of such switching systems must exploit the relative binding affinities that these different (di)cationic “stations” exhibit toward different polyether macromolecules.[5] A closely related system has been studied by Loeb and co-workers,[6–8] in which bipyridinium ethane dications are shown to bind[6] crown ethers that have a [24]crown-8 constitution. This recognition pair has subsequently been utilized in the formation of both catenanes[7] and rotaxanes.[8] Although the binding properties of various substituted secondary dialkylammonium ions with crown ethers have been reported,[9] the experimental parameters often differ significantly from case to case – i.e., solvent, concentration, temperature, and method of sample interrogation (NMR spectroscopy, UV/Vis spectroscopy, calorimetry) – rendering comparisons difficult, if not circumspect. To compare legitimately the association of both dibenzylammonium (DBA+) and bipyridinium (BIPY2+) ions with a range of crown ethers, we describe in this full paper their binding characteristics, under a standard set of conditions, using two contrasting techniques, namely, the single-point method by 1H NMR spectroscopy[10] and isothermal titration calorimetry (ITC).[11] Stimulated by the binding ability of 24C8 and 25C8 constituted crowns with different thread-shaped components containing BIPY2+ units in MeCN, we report herein an easy one-step procedure to synthesize [2]rotaxanes incorporating the newly studied BIPY2+ dications as the sole template and

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Results and Discussion

Synthesis of Crowns and Threads

Dibenzylammonium salts 1-H·PF$_6$, 2-H·PF$_6$, 3-H·PF$_6$, and 4-H·PF$_6$ as well as the crown ethers DP24C$_8$ and BMP25C$_8$ were synthesized as previously reported. See Figure 1 for their structural formulas. The general synthetic pathway that leads to the formation of the viologen derivatives 5·2PF$_6$, 6·2PF$_6$, 7·2PF$_6$, 8·2PF$_6$, and 9·2PF$_6$ containing bipyridinium (BIPY$^{2+}$) units is depicted in Scheme 1. Each substitution reaction of the functionalized benzyl bromide with 4,4'-bipyridine in MeCN resulted in a yellow precipitate. The yellow solids, which are the bromide salts of the viologen derivatives, were collected by filtration and subjected to counterion exchange by dissolving them in hot water and precipitating with saturated aqueous NH$_4$PF$_6$ to afford the corresponding white hexafluorophosphate salts.

Pseudorotaxane Formation

Preliminary studies on the binding interactions between the viologen salts with the three crown ethers were conducted using mass spectrometric analysis. Solutions containing equimolar quantities of guest and crown ether were subjected to fast atom bombardment mass spectrometry (FABMS). In each case, the mass spectra had $m/z$ peaks corresponding to free crown ether, free guest, and the 1:1 complex.
complex formed between the host and guest. The presence of the peaks corresponding to the 1:1 complex between the macrocycle and the viologen derivative imply the presence of binding interactions between crown ethers and viologens in the gas phase; mass spectrometry, however, does not give any details regarding the geometry of the complexes formed.

Nonetheless, strong literature evidence supports a threaded complex in which the viologen guest resides within the cavity of the macrocycle, thus forming a [2]pseudorotaxane. X-ray quality single crystals of the DP24C8·6·2PF₆ complex were grown by layer diffusion of iPr₂.O into a 1:1 equimolar MeCN solution of the components. The solid-state superstructure (Figure 2) reveals that the small DP24C8 ring encircles the bulky 6·2PF₆ guest. The binding is mediated by a combination of [π···π], [C–H···O] and [C–H···π] bonding interactions. The DP24C8 ring in the complex adopts a very different conformation from that observed for the free crown ether. Because the free crown ether in the solid state is linked together to a neighboring ring by hydrogen bonding to form a centrosymmetrically related pair of DP24C8 molecules, the DP24C8 component of the [2]pseudorotaxane adopts a Z-like conformation, where the nitrogen atoms on the two pyridyl rings are facing each other. Moreover, the solid-state superstructure confirms that the 1:1 complex formed between the macrocycle and the viologen derivative is assembled in a threaded host-guest fashion.

Previously, the binding constants (Kₐ) for the 1:1 complexes, 1-H·PF₆·DB24C8,[9e] 1-H·PF₆·DP24C8,[9e] 1-H·PF₆·BMP25C8,[9e] 2-H·PF₆·DB24C8,[9e] 2-H·PF₆·DP24C8,[9e] 2-H·PF₆·BMP25C8,[9e] 3-H·PF₆·DB24C8,[9e] and 4-H·PF₆·DB24C8,[9e] had been determined using the single-point method, whereas in this study, all binding studies were carried out by ITC (Table 1) and compared, wherever possible, to literature values reported previously. In the case of complexes formed between the DBA⁺ cations and DB24C8, DP24C8, and BMP25C8 crowns, for which binding constants had already been obtained, the ITC results are in good agreement with the previously recorded Kₐ values obtained by the ¹H NMR spectroscopic single-point method (Table 1). Some general observations can be made from the Kₐ values determined by ITC. The poor binding affinities of BMP25C8 with the DBA⁺ guests is the result of disrupting the [O–C–O–C–O] geometry.[9b] The lower binding affinities of DB24C8 and DP24C8 for BIPY2⁺ guests than for DBA⁺ guests are both the result of steric and electronic interactions that are less favorable than the interactions in [2]pseudorotaxanes with the DBA⁺ guests. The complexes formed by the DB24C8 and the DBA⁺ guests are stabilized primarily by [N⁺–H···O] hydrogen bonds, aided by weaker [C–H···O] and [π···π] interactions between the ion center and the macrocyclic polyethers. The viologen guests are complexed in a fashion such that the crown ether encircles the guests, so that there is [C–H···O] hydrogen bonding as

**Figure 2.** The molecular superstructure of the dicationic C₇-symmetric 1:1 complex formed between DP24C8 and 6·2PF₆, showing the intra-[2]pseudorotaxane noncovalent bonding interactions. The hydrogen-bond geometries, [C–O], [H–O] [Å], [C–H–O] [°] are (a) 3.34, 2.48, 150; (b) 3.27, 2.58, 129. The [C–H–π] interaction (c) has an H···π separation of 3.01 Å, and a C–H···π angle of 128°. The π···π stacking interaction (d) has centroid–centroid and mean interplanar separations of 3.83 and 3.42 Å, respectively, the rings being inclined by ca. 16°.

**Table 1.** The stability constants (Kₐ) for the [2]pseudorotaxanes (1:1 complexes) formed in MeCN solutions at 298 K between DB24C8, BMP25C8 and DP24C8 and the dibenzylbipyridinium guests 5–8·2PF₆, and also by way of comparison, the dibenzyllammonium guests 1-H–4-H·PF₆, as determined by isothermal titration microcalorimetry (ITC).

<table>
<thead>
<tr>
<th>Guest</th>
<th>X</th>
<th>DB24C8 Kₐ [m⁻¹][a]</th>
<th>Crown DP24C8 Kₐ [m⁻¹][a]</th>
<th>BMP25C8 Kₐ [m⁻¹][a]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-H·PF₆</td>
<td>H</td>
<td>237 ± 112[b]</td>
<td>575 ± 163[b]</td>
<td>19 ± 7[b]</td>
</tr>
<tr>
<td>3-H·PF₆</td>
<td>F</td>
<td>495 ± 65[6]</td>
<td>1125 ± 92</td>
<td>34 ± 8</td>
</tr>
<tr>
<td>4-H·PF₆</td>
<td>Me</td>
<td>243 ± 90</td>
<td>362 ± 6</td>
<td>24 ± 5</td>
</tr>
<tr>
<td>5·PF₆</td>
<td>H</td>
<td>82 ± 16</td>
<td>95 ± 4</td>
<td>67 ± 10</td>
</tr>
<tr>
<td>6·PF₆</td>
<td>CO₂Me</td>
<td>71 ± 29</td>
<td>89 ± 19</td>
<td>69 ± 8</td>
</tr>
<tr>
<td>7·PF₆</td>
<td>F</td>
<td>72 ± 18</td>
<td>103 ± 28</td>
<td>64 ± 11</td>
</tr>
<tr>
<td>8·PF₆</td>
<td>Me</td>
<td>78 ± 2</td>
<td>77 ± 11</td>
<td>71 ± 2</td>
</tr>
</tbody>
</table>

[a] Fits were performed using software provided by Microlab LLC software, and the stoichiometry of all complexes was between 0.93 and 1.07, which indicates that a 1:1 complex was formed. [b] The binding constant has been previously reported as 320 m⁻¹, see ref.[9b]. [c] The binding constant for this system could not be measured accurately by the single-point method, see ref.[9b]. [d] The binding constant could not be attained by the single-point method, see ref.[9b]. [e] The binding constant has been previously reported as 1100 m⁻¹, see ref.[9b]. [f] The binding constant has been previously reported as 1700 m⁻¹, see ref.[9b]. [g] The binding constant for this system has been previously reported as < 100 m⁻¹, see ref.[9b]. [h] The binding constant for this system has been previously reported as 875 m⁻¹, see ref.[9]. [i] The binding constant for this system has been previously reported as 170 m⁻¹, see ref.[9].

well as optimal [π···π] stacking between the two, which together are weaker interactions than is the charge stabilization present in the DBA⁺-based [2]pseudorotaxanes with the crowns DB24C8 and DP24C8.[17] The data also suggest that BMP25C8 complexes BIPY²⁺ guests as strongly as it does DBA⁺ guests. This result is most likely because the larger cavity size of the BMP25C8 is more complementary to the bulkier BIPY²⁺ guests than the smaller DBA⁺ guests, whereas the smaller crown ethers, DB24C8 and DP24C8, stabilize the smaller DBA⁺ guests more than the larger BIPY²⁺ guests. For binding between DP24C8 and DB24C8 with DBA⁺ thread components, the binding increases with the increasing electron-withdrawing ability of the substituent,⁹b thus for both crowns binding is strongest with 2-H·PF₆ and weakest with 4-H·PF₆. As a result of weak binding between the three crowns with BIPY²⁺ thread components, the electronic effects are subdued and thus cause no large change in the binding due to the electron-withdrawing ability of the substituent on the thread. For DP24C8 and DB24C8 crowns, this data shows that, for molecular machines composed of DBA⁺ and BIPY²⁺ recognition sites, the crown will show a strong preference for the DBA⁺ recognition site as a result of the greater than an order of magnitude difference in $K_a$ that favors the DBA⁺ station over the BIPY²⁺ station.

We have obtained thermodynamic parameters by the ¹H NMR single-point method and ITC for the binding of the three crown ethers with 6·2PF₆ in order to compare the results from these two techniques for weakly binding systems. The general trend of the ¹H NMR spectra for all the 1:1 complexes formed between 6·2PF₆ and the crown ethers is that, at room temperature or higher, the species mostly exist as free guest and host, without any apparent association between the two that can be demonstrated by ¹H NMR spectroscopy. Upon cooling the solution to 235 K, the resonances for the complexed species appear as a result of the slow exchange of the species at low temperatures and also because the binding is stronger. Because of the faster equilibration between the complexed and the uncomplexed free crowns and viologen guests at room temperature, only line broadening was observed. Thus, the $K_a$ values were determined at lower temperature ranges (235–293 K), and the values were used to extrapolate to $K_a$ at room temperature using van’t Hoff plots.¹⁵ Figure 3 shows, as an example, the ¹H NMR spectra of a 1:1 equimolar solution of DB24C8 and 6·2PF₆, taken at 293 (trace a) and 235 K (trace b). As the solution is cooled, the peaks for the complex begin to grow on account of the weak interactions holding the [2]pseudorotaxane together that are less likely to break at lower temperatures as a result of a smaller disfa-
vorable entropic contribution to the binding. Because the peaks for the complexed and uncomplexed species do not shift with changes in temperature, and because the sharp peaks in the spectrum indicate that the complexed and uncomplexed species are slow to exchange as a consequence of the slow kinetics at low temperatures, this sample is a suitable one from which to obtain a single-point binding constant.

The thermodynamic values, \( \Delta H^o \), \( \Delta S^o \), \( \Delta G^o \), and \( K_a \) for the binding of 6-2PF\(_6\) with the three crown ethers DB24C8, BMP25C8, and DP24C8 were determined using both ITC and the \(^1\)H NMR single-point method (Table 2). The values for \( \Delta H^o \) and \( \Delta S^o \) overlap within the range of the errors, and with such small \( K_a \) values, the differences are insignificant, thus showing that thermodynamic parameters obtained by ITC are comparable\(^{[18]}\) to those obtained by the single-point method, which has been extensively used to determine the thermodynamic parameters for mono and dications with various crown ethers.\(^{[5-9]}\) This comparison established that ITC can yield \( K_a \) values that are in agreement with those obtained from the single-point method. The single-point method has limitations that ITC does not have. In the case of DP24C8C6·2PF\(_6\), line broadening begins to occur at 250 K because the rate of exchange increases between the complexed and uncomplexed states. Thus, only a few data points are available for the van’t Hoff plot, which leads to a poor fit when the data is extrapolated to 298 K.\(^{[16]}\) For reactions with low \( K_a \) values, a combination of both ITC and single-point measurements could be used to describe the system accurately. Both techniques have error limits that are high compared to the \( K_a \) values for the binding of 6-2PF\(_6\) with the crown ethers. We have shown that, on the average, the binding constants, \( K_a \) for these 1:1 complexes with BIPY\(^{2+}\) are one order of magnitude less than the \( K_a \) values obtained for DB24C8 and DP24C8 with DBA\(^+\) thread components. However, in the case of BMP25C8 for both recognition sites (DBA\(^+\) and BIPY\(^{2+}\)), the binding constants have very similar and small values because the electronic effects of the substituents on binding are subdued.

### Rotaxane Formation

Having shown that the viologens 5·8·2PF\(_6\) form threaded complexes with the crown ethers DB24C8, DP24C8, and BMP25C8, we used the viologen derivative, 9·2PF\(_6\), to template the synthesis of [2]rotaxanes with these crown. The viologen-based [2]rotaxanes, 11·4PF\(_6\), 12·4PF\(_6\), and 13·4PF\(_6\) were synthesized using a template-directed approach (Scheme 2) in 26, 21, and 7% yield, respectively. The [2]rotaxanes were first assembled between the dibromide 9·2PF\(_6\) (1 equiv.) and the selected crown ether (1.5–2.0 equiv.) in MeNO\(_2\). These [2] pseudorotaxanes were treated with triphenylphosphine (2.2 equiv.) overnight at room temperature. The resulting white precipitates, which were the dumbbell components (10·4PF\(_6\)), were collected by filtration. Et\(_2\)O was added to the filtrates and the resulting precipitates were collected, subjected to anion exchange with saturated NH\(_4\)PF\(_6\) aqueous solutions, and purified by column chromatography to yield the corresponding [2]rotaxane, which, along with the dumbbell component 10·4PF\(_6\), were characterized by mass spectrometry, \(^1\)H and \(^13\)C NMR spectroscopy and X-ray crystallography in the solid state in the case of 12·PF\(_6\).

The formation of the mechanically interlocked [2]rotaxanes was confirmed by high-resolution electrospray ionization (HR-ESI) mass spectrometry. In general, for all three interlocked molecules 11·13·4PF\(_6\), two significant \( m/z \) peaks were observed—one corresponding to [M – PF\(_6\)]\(^+\) and the other one to [M – 2PF\(_6\)]\(^+\) ions, with the isotopic distribution corresponding to the [M – 2PF\(_6\)]\(^+\) ion of 11·4PF\(_6\) shown in Figure 4.

In order to show that an interlocked structure has been formed, the \(^1\)H NMR spectra (in CD\(_3\)CN) of the [2]rotaxane 11·13·4PF\(_6\) can be compared with that of its components, the dumbbell-shaped component 10·4PF\(_6\) and the corresponding free crown ether. The general trend of the proton resonances in the crown ethers and 10·4PF\(_6\) on forming [2]rotaxanes is the upfield shift of the crown ether protons compared to those in the free crown ethers, and a significant shift in the bipyridinium protons. As an example, Figure 5 shows the \(^1\)H NMR spectrum of DB24C8-based [2]rotaxane 11·4PF\(_6\) along with the free DB24C8 and the free dumbbell component 10·4PF\(_6\).

Further confirmation of the interlocked structure was obtained from single-crystal X-ray analysis. Slow evaporation of a CH\(_2\)Cl\(_2\)/EtOH solution of the BMP25C8-based [2]rotaxane 12·4PF\(_6\) yielded single crystals suitable for X-ray structural analysis. The solid-state structure (Figure 6) reveals threading of the BIPY\(^{2+}\) unit through the center of the BMP25C8 macrocycle. The binding is stabilized mainly by [C–H···O] hydrogen bonding interactions (2.38 Å, 168.4°). The macrocycle adopts a Z-shaped conformation.
Scheme 2. Synthesis of [2]rotaxanes, 11·4PF₆, 12·4PF₆, 13·4PF₆ stoppered with triphenylphosphonium groups.

Figure 4. HR-ESI Mass spectrum of DB24C8-based [2]rotaxane 11·4PF₆. The peak at m/z = 1772.4851 corresponds to [M – PF₆]⁺ and the peak at 813.2583 corresponds to [M – 2PF₆]²⁺.

around the dumbbell, where the two benzene rings face each other. However, the rings of the macrocycle do not show appreciable [π···π] stacking interactions with the pyridyl rings of the BIPY²⁺ unit. Instead, we observe an appreciable [C–H···π] interaction between the proton at the 2-position of the resorcinol ring of the macrocycle and the pyridyl rings of the BIPY²⁺ unit. The solid state of 12·4PF₆ is also stabilized by intramolecular [C–H···π] stacking interactions between the phenyl rings of the triphenylphosphonium groups of the thread and the catechol (X1) and resorcinol (X2) rings of the crown with a distance of about 4.14 Å.
Conclusions

$^1$H NMR spectroscopy, isothermal titration calorimetry (ITC) and X-ray crystallography all support the conclusion that BIPY$^{2+}$ bis(hexafluorophosphate) salts, e.g., 5-8·2PF$_6$, as well as DBA$^+$ hexafluorophosphate salts, e.g., 1-4·PF$_6$, all form 1:1 complexes that are $^2$psedorotaxanes with the crown ethers DB24C8, DP24C8 and BMP25C8 in MeCN. The thermodynamic parameters ($K_a$, $\Delta G^\circ$, $\Delta H^\circ$, $\Delta S^\circ$), which were obtained by both ITC and the $^1$H NMR spectroscopic single-point method in CD$_3$CN for all these $^2$psedorotaxanes, were in good agreement for any particular 1:1 complex. When complexation is weak – as with all the complexes involving the BIPY$^{2+}$ salts, and with those complexes between the DBA$^+$ salts and BMP25C8 – ITC is capable of distinguishing the subtle effects involving electron-
accepting and donating substituents on the para positions of the terminal benzyl groups on both the BIPY²⁺ cations and DBA⁺ cations. The Kₐ values obtained for the complexation of DB24C8 and DP24C8 with the BIPY²⁺ bis(hexafluorophosphate) salts 5-8·2PF₆ are an order of magnitude less than the binding constants for the 1:1 complexes formed between these two crown ethers and the DBA⁺ hexafluorophosphate salts 1-4·PF₆. In the case of BMP25C8, however, the Kₐ values with both the BIPY-2PF₆ and DBA-2PF₆ salts are low, but, this time, the former are just slightly stronger than the latter. So what does all this information add up to when it comes to the template-directed synthesis of [2]rotaxanes where the dumbbell component contains a BIPY²⁺ unit as a template and ultimately a recognition site? The answer is that it becomes just as likely that any one of the three crown ethers – DB24C8, DP24C8 or BMP25C8 – could serve as the ring component, but that the yield of the rotaxane is not going to be all that high as a result of the weak interactions between the thread and the crown. And what about the design and construction of pH-controllable switches based on bistable [2]rotaxanes containing both dialkylammonium and bipyridinium recognition sites in their dumbbell components? The answer is that the best bistable [2]rotaxanes incorporating these recognition sites are going to involve ester functions in their dumbbell components and will employ DP24C8 or, failing that, DB24C8 as the ring component.

**Experimental Section**

**General Methods:** All reagents were purchased from commercial suppliers and used as received. Dibenzy-4,4′-bipyridinium bis(hexafluorophosphate) (5·2PF₆), bis(4′′-methylbenzyl)-4,4′-bipyridinium bis(hexafluorophosphate) (8·2PF₆), bis(4′′-bromomethylbenzyl)-4,4′-bipyridinium bis(hexafluorophosphate) (9·2PF₆) and benzomethaphenylene[25]crown-8 (BMP25C8)[9e] and dipyrido[24]crown-8 (DP24C8)[9e] were prepared according to published literature procedures and DB24C8 was purchased from a commercial supplier. Solvents were dried according to literature procedures. Thin-layer chromatography was carried out using aluminum sheets precoated with silica gel 60F (Merck 5554). Column chromatography was performed on silica gel 60 (Merck 40–60 µm, 230–400 mesh). Melting points are uncorrected. ¹H and ¹³C NMR spectroscopy and fast atom bombardment (FAB), high-resolution matrix-assisted laser-desorption ionization (HR-MALDI) and high-resolution electrospray ionization (HR-ESI) mass spectrometry (MS) were all obtained with commercially available instrumentation. NMR Spectra were recorded in CD₃CN solution with the residual solvent peaks used as internal standards. FAB-MS was obtained with a spectrometer equipped with a krypton primary atom beam using a 3-nitrobenzyl alcohol matrix.

6·2PF₆: Methyl 4-bromomethylbenzoate (1.5 g, 6.5 mmol) was added to a refluxing solution of 4,4′-bipyridine (500 mg, 3.2 mmol), dissolved in MeCN (100 mL). The reaction mixture turned yellow upon the addition of methyl 4-(bromomethyl)benzoate and a yellow precipitate started to form. The reaction mixture was heated under reflux for 3 h, after which time it was cooled down to room temperature. The precipitate was filtered, washed with MeCN and air-dried to give a yellow solid, which was subjected to anion exchange by dissolving it in hot H₂O and adding saturated aqueous NH₄PF₆ until no further precipitation was observed. The resulting solid was filtered, washed with H₂O and dried to yield 6·2PF₆ as a white solid (2.2 g, 93%); m.p. 230–233 °C (dec.). ¹H NMR (500 MHz, CD₃CN): δ = 8.37 (s, 6 H), 5.86 (s, 4 H), 7.57 (d, J = 8.3 Hz, 4 H), 8.08 (d, J = 8.3 Hz, 4 H), 8.36 (d, J = 6.9 Hz, 4 H), 8.94 (d, J = 6.9 Hz, 4 H) ppm. ¹³C NMR (125 MHz, CD₃CN): δ = 165.8, 150.3, 145.7, 137.0, 131.6, 130.5, 129.3, 127.5, 63.9, 51.9 ppm. HR-ESI-MS: m/z (%) = 599.1533 (100) (calculated [M – PF₆]⁺ requires 599.1529).

Slov evaporation of a solution of 6·2PF₆ in MeCN/Pr₂O yielded single crystals of the [2]pseudorotaxane suitable for X-ray crystallography (see Supporting Information).

7·2PF₆: 4-Fluorobenzyl bromide (1.27 g, 6.7 mmol) was added to a MeCN solution (100 mL) of 4,4′-bipyridine (500 mg, 3.2 mmol), heated under reflux. The reaction mixture turned yellow upon the addition of 4-fluorobenzyl bromide and a yellow precipitate started to form. The reaction mixture was heated under reflux for 3 h, after which time it was cooled down to room temperature. The precipitate was filtered, washed with MeCN and air-dried to give a yellow solid, which was subjected to anion exchange by dissolving it in hot H₂O and adding saturated aqueous NH₄PF₆ until no further precipitation was observed. The resulting solid was filtered, washed with H₂O and dried to yield 7·2PF₆ as a white solid (1.95 g, 92%); m.p. 230–233 °C (dec.). ¹H NMR (500 MHz, CD₃CN): δ = 8.95 (d, J = 7.6 Hz, 4 H), 8.37 (d, J = 7.6 Hz, 4 H), 7.57 (m, 4 H), 7.27 (m, 4 H), 5.81 (s, 4 H) ppm. ¹³C NMR (125 MHz, CD₃CN): δ = 150.22, 145.39, 131.85, 131.78, 127.35, 116.42, 116.24, 63.79 ppm. ¹⁹F NMR (400 MHz, CD₃CN): δ = –72.31 (d, J = 45 Hz), –113.08 ppm. HR-ESI-MS: m/z (%) = 519.1233 (100) (calculated [M – PF₆]⁺ requires 519.1216).

**Pseudorotaxane Self-Assembly:** Solutions of DB24C8, BMP25C8, DP24C8 and 6·2PF₆ (10 mM each), were prepared by dissolving each component separately in CD₃CN (0.600 mL) in individual NMR tubes. The [2]pseudorotaxanes are formed by mixing an equimolar amount of crown ether and a substrate in a new NMR tube. The tubes were inverted several times to ensure efficient mixing. ¹H NMR spectra were recorded 5 min after the mixing. Slow evaporation of a solution of the 1:1 complex between DB24C8 and 6·2PF₆ in MeCN/Pr₂O yielded single crystals suitable for X-ray crystallography.

10·4PF₆: Ph₂P (350 mg, 1.32 mmol) was added to a solution of 9·2PF₆ (500 mg, 0.60 mmol) dissolved in MeNO₂ (70 mL). The reaction was left to stir overnight at room temperature. The resulting white precipitate was filtered, washed with CH₂Cl₂ and collected. The air-dried precipitate was dissolved in H₂O and a MeCN solution of NH₄PF₆ was added until no further precipitation was observed. The resulting solid was filtered, washed with H₂O and dried to yield 10·4PF₆ (0.6 g, 76%); m.p. 196–198 °C (dec.). ¹H NMR (500 MHz, CD₃CN): δ = 4.66 (d, J = 14.8 Hz, 4 H), 5.74 (s, 4 H), 7.01 (d, J = 8.0 Hz, 4 H), 7.03 (d, J = 8.0 Hz, 4 H), 7.52–7.54 (m, 12 H), 7.64–7.83 (m, 12 H), 7.86–7.91 (m, 6 H), 8.37 (d, J = 6.9 Hz, 4 H), 8.88 (d, J = 6.9 Hz, 4 H) ppm. ¹³C NMR (125 MHz, CD₃CN): δ = 150.4, 145.6, 135.5, 134.1, 133.4, 133.2, 131.9, 131.8, 130.3, 130.1, 129.9, 129.8, 129.4, 129.1, 127.5, 63.9, 29.1 ppm. MS (FAB): m/z (%) = 1324.10 (25), 1178.34 (83), 1033.38 (100) ([M – PF₆]⁺, [M – 2PF₆]⁺, [M – 3PF₆]⁺ require 1324.22, 1178.23, 1033.23).

**General Procedure for the Synthesis of [2]Rotaxanes, 11·4PF₆, 12·4PF₆, 13·4PF₆:** Ph₂P (2.2 equiv.) was added to a solution of 9·2PF₆ (1 equiv.) and crown (1.5–2.0 equiv.) dissolved in MeNO₂. The reaction mixture was left to stir overnight at room temperature. The resulting white precipitate was filtered off, washed with
Reacting Ph3P (42.9 mg, 0.16 mmol) with the dibromide 9-2PF6 (60.2 mg, 0.074 mmol) in the presence of BMP25C8 (50.0 mg, 0.11 mmol) afforded, after work-up as described above, 12-2PF6 as a yellow solid (30 mg, 21%); m.p. 159 – 161 °C (dec.). 1H NMR (500 MHz, CD2CN): δ = 3.66 – 3.67 (m, 4 H), 3.69 – 3.71 (m, 4 H), 3.82 (s, 2 H), 3.86 – 3.87 (m, 4 H), 3.92 – 3.93 (m, 4 H), 4.01 (br. s, 1 H), 4.69 (d, J = 15 Hz, 4 H), 5.70 (s, 4 H), 5.90 – 5.92 (m, 2 H), 6.40 – 6.42 (m, 3 H), 6.56 – 6.58 (m, 2 H), 7.13 (d, J = 6.9 Hz, 4 H), 7.47 (d, J = 6.9 Hz, 4 H), 7.51 – 7.55 (m, 12 H), 7.61 – 7.64 (m, 12 H), 7.76 (d, J = 6.8 Hz, 4 H), 7.85 – 7.92 (m, 6 H), 8.98 (d, J = 6.8 Hz, 4 H) ppm. 13C NMR (125 MHz, CD2CN): δ = 159.0, 148.1, 147.1, 145.7, 135.4, 135.3, 134.2, 134.1, 132.1, 132.0, 130.6, 130.3, 130.1, 125.6, 121.0, 113.2, 104.3, 70.8, 70.3, 69.8, 67.5, 67.5, 63.8, 29.8 ppm. MS (HR-ESI): m/z (%) = 1772.4873 (50), 813.2542 (100) ([M – PF6]+, [M – 2PF6]+) require 1772.4873, 813.2566. Slow evaporation of a solution of 12-2PF6 in CH2Cl2/MeOH yielded single crystals suitable for X-ray crystallography.

13C­2PF6: The reaction of Ph3P (45.0 mg, 0.17 mmol) with the dibromide 9-2PF6 (64.6 mg, 0.080 mmol) in the presence of DP24C8 (50.0 mg, 0.12 mmol) afforded, after work-up as described above, 13C­2PF6 as a solid (39 mg, 26%); m.p. 179 – 181 °C (dec.). 1H NMR (500 MHz, CD2CN): δ = 3.60 – 3.62 (m, 3 H, 3.70 – 3.71 (m, 3 H, 3.88 (s, 8 H), 4.75 (d, J = 14.9 Hz, 4 H), 5.70 (s, 4 H), 6.73 – 6.80 (m, 6 H), 7.13 (d, J = 8.5 Hz, 4 H), 7.42 (d, J = 8.5 Hz, 4 H), 7.53 – 7.59 (m, 12 H), 7.63 – 7.68 (m, 12 H), 7.75 – 7.80 (m, 6 H), 8.19 (d, J = 6.9 Hz, 4 H), 8.78 (d, J = 6.9 Hz, 4 H) ppm. 13C NMR (125 MHz, CD2CN): δ = 155.6, 144.3, 135.4, 135.3, 134.1, 134.0, 132.0, 131.9, 130.2, 129.9, 129.8, 127.7, 74.1, 70.6, 70.2, 63.5, 29.4 ppm. MS (HR-ESI): m/z (%) = 1741.5815 (10), 798.2561 (100) ([M – PF6]+, [M – 2PF6]+) require 1741.5815, 798.2566.

X-ray Crystallography: The intensity data for the [2]pseudorotaxane DP24C8·6·2PF6 were collected with a Siemens P4 diffractometer, and those for the [2]rotaxane 12-2PF6 were collected with a Bruker Smart 1000 CCD-based X-ray diffractometer.[20a] The frames for the latter data collection were integrated with the Bruker SMART program using a narrow-frame integration algorithm.[20b] The structures were solved by direct methods and refined based on F2 using the SHELXTL software package.[20b] The Cambridge Crystallographic Data Centre provides the structure factor data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Crystal Data for DP24C8·6·2PF6: [C50H50N10PF6]2+, M = 1162.93, monoclinic, P21/c, a = 12.8321(14), b = 13.0828(12), c = 16.2059(13) Å, β = 97.211(8)°, V = 2699.14 Å3, Z = 2 (C2 symmetry), Dcalc = 1.431 g cm–3, μ(Mo-Kα) = 0.182 mm–1, T = 293 K, colorless prisms; 3978 independent measured reflections, F2 refinement, R1 = 0.076, wR2 = 0.191, 2525 independent observed reflections [F2 > 4σ(F2)], 2(Max = 47), 378 parameters. CCDC-264706.

Crystal Data for 12-4PF6: [C50H50N10PF6]2+, M = 1917.39, triclinic, P1, a = 9.9733(15), b = 10.7391(17), c = 20.8003(3) Å, α = 97.959(3), β = 91.794(3), γ = 96.608(3)°, V = 2189.16(16) Å3, Z = 1, Dcalc = 1.454 g cm–3, μ(Mo-Kα) = 2.30 cm–1, F(000) = 986, T = 120 K, 0.35 × 0.15 × 0.10 mm, refined based on F2 to give R1 = 0.0803, wR2 = 0.2190 for 8973 independent observed reflections [F2 > 4σ(F2)], 2(M = 50) and 652 parameters. CCDC-264433.

Isotothermal Titration Microcalorimetry: Microcalorimetry was carried out using a Microcal VP-ITC titration microcalorimeter. 3 – 7 μL aliquots of degassed solutions of the guest in MeCN were titrated into stirring solutions of the host at 298 K. The heat of dilution for each titration was measured by determining the heat released by the injection of guest into MeCN in the absence of crown, and the enthalpy of dilution was subtracted from the enthalpy of the titration to determine the enthalpy of complexation. Software provided by Microcal LLC was used to compute the thermodynamic parameters of the titration (ΔH, ΔS, K) based on the one-site binding model. The reported values in Table 1 are the mean results of multiple titration runs, and errors are reported as a standard deviation from the mean.

Supporting Information (see footnote on the first page of this article): Mass spectrometric data of pseudorotaxanes formed between the threads 1-4-HPF6 and 5-8-2PF6 with the crowns DB24C8, DP24C8 and BMP25C8; 1H NMR spectra of the threads 1-4-HPF6 and 5-8-2PF6 variable temperature 1H NMR complexation studies of the binding between thread 6-2PF6 with crowns DB24C8, DP24C8 and BMP25C8; sample ITC runs (uncorrected) between threads 1-4-HPF6 and 5-8-2PF6, with crowns DB24C8, DP24C8 and BMP25C8; solid-state structural data for DP24C8·6-2PF6; solid-state structural data for 6-2PF6.

Acknowledgments

The research was supported by the National Science Foundation (NSF) grant (CHE 0317170) and two NSF equipment grants (CHE 9974928 and CHE 0092036). We are grateful to the National Science Foundation for financial support through a GK-12 program grant DGE 02-31988 fellowship to A.B.B.


