DOI: 10.1002/ejoc.201001277

Synthesis and Complexation Studies between Trifluoromethylammonium Threads and Dibenzo[24]Crown-8

Carsten Johnsen,[a] Paul C. Stein,[a] Kent A. Nielsen,[a] Andrew D. Bond,[a] and Jan O. Jeppesen*[a]

Keywords: Crown compounds / Ammonium salts / Rotaxanes / Self-assembly / Supramolecular chemistry

Two new ammonium threads were synthesized and characterized. They are composed of either one or two bis-alkylammonium sites that can act as recognition elements for dibenzo[24]crown-8 (DB24C8) and are both appended with two electron-withdrawing trifluoromethyl (CF_3) groups. The pseudorotaxanes formed between the trifluoromethyl ammonium threads and DB24C8 were characterized by single-crystal X-ray diffraction analyses and studied by NMR spectroscopy. The NMR spectroscopic data reveal that attachment of two electron-withdrawing trifluoromethyl groups to the single-site ammonium thread enhances the binding strength between the DB24C8 ring and the ammonium thread. Investigations carried out between the double-site ammonium thread and DB24C8 reveal that the relative amount between the [2]pseudorotaxane and the [3]pseudorotaxane can be controlled by changing the ratio between the double-site ammonium thread and DB24C8. Quantitative studies carried out by NMR titrations indicate at weak (K_2/K_1 = 0.24) anticooperative effect in the formation of the [3]pseudorotaxane.

Introduction

Crown ethers have, since their discovery in 1967 by Pedersen,[1] been an important constituent of supramolecular chemistry, and they have been widely used as the ring component in catenanes[2] and rotaxanes[2a,2d,3] or as the recognition element in cation sensors.[4] In particular, the complexation between crown ethers and ammonium threads has been intensively studied during the last decades. Pedersen demonstrated that 18-crown-6 (18C6) was capable of forming complexes with different alkyl ammonium salts, and it was found that primary alkyl ammonium salts can penetrate sufficiently deep into the crown ether cavity allowing complexation to take place. On the other hand, secondary and tertiary alkyl ammonium salts are sterically hindered, which prevents them in forming complexes with 18C6. However, Kolchinski et al. and Ashton et al. later showed[5] that secondary alkyl ammonium salts can penetrate into the cavity of crown ethers when the crown ether ring consists of 24 atoms or more, leading to the formation of pseudorotaxanes. Further investigations carried out by Ashton et al. revealed[6] that the presence of electron-withdrawing and electron-donating groups (EWGs and EDGs) on the ammonium thread impact the binding strength between the crown ether and the alkyl ammonium threads. In particular, investigations conducted by Loeb et al.[7] indicated that attachment of a trifluoromethyl (CF_3) group to the ammonium thread increases the binding strength of the complex formed between the crown ether and the ammonium thread.

In this paper, we present the synthesis of the novel ammonium threads **3**-H·PF_6 and **4**-H_2·2PF_6 (Figure 1) appended with two CF_3 groups. Two different synthetic approaches were applied for the preparation of **4**-H_2·2PF_6. Thereafter, we describe and discuss some complexation studies carried out between the bis-alkyl ammonium threads and dibenzo[24]crown-8 (DB24C8).

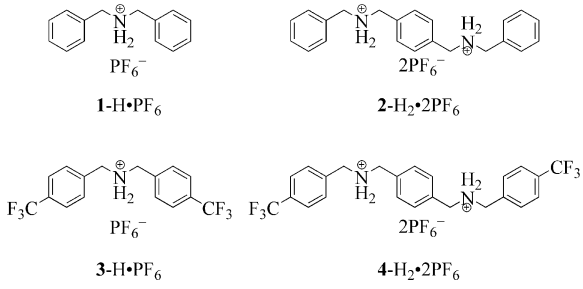


Figure 1. Molecular formulas of ammonium threads **1**-H·PF_6, **2**-H_2·2PF_6, **3**-H·PF_6, and **4**-H_2·2PF_6.

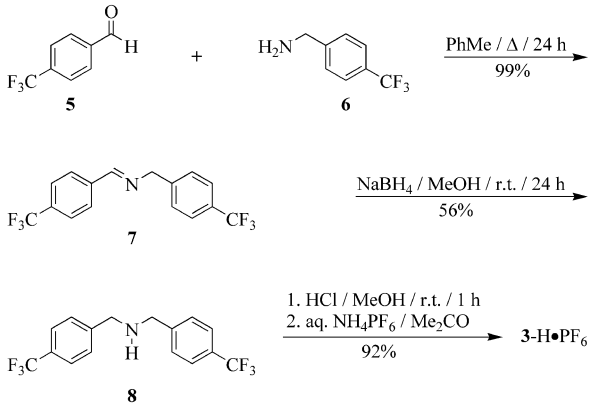
Results and Discussion

Synthesis

The syntheses of ammonium threads **1**-H·PF_6 and **2**-H_2·2PF_6 shown in Figure 1 and their complexation with DB24C8 have already been reported.[5] For comparison

[a] Department of Physics and Chemistry, University of Southern Denmark,
Campusvej 55, 5230 Odense M, Denmark
Fax: +45-6615-8780
E-mail: joj@ifk.sdu.dk

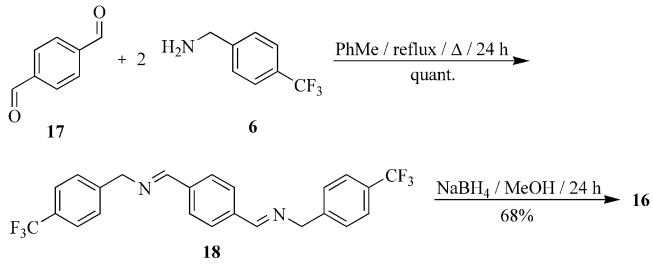
reasons, **1**-H·PF_6 and **2**-H_2·2PF_6 were synthesized according to literature procedures,[8] whereas **3**-H·PF_6 was synthesized as shown in Scheme 1. Here, 4-trifluoromethylbenzaldehyde (**5**) and 4-trifluoromethylbenzylamine (**6**) were condensed to imine **7** (99%), followed by reduction with $NaBH_4$ to afford amine **8** in 56% yield. Finally, after protonation and anion change with NH_4PF_6, **3**-H·PF_6 was obtained in 92% yield.



Scheme 1. Synthesis of compound **3**-H·PF_6.

Ammonium thread **4**-H_2·2PF_6 was synthesized by two different synthetic routes. Route 1 is shown in Scheme 2 and was inspired by earlier work carried out by Ashton and Loeb.[7,9] First, 4-trifluoromethylbenzylamine (**6**) and methyl-4-formylbenzoate (**9**) were condensed to afford imine **10** in quantitative yield, which subsequently was reduced (74%) to amine **11** by using $NaBH_4$. To prevent any unwanted alkylation of the amino functionality in the following syntheses, the amine functionality of **11** was protected by using di-*tert*-butyl dicarbonate (Boc_2O) to afford Boc-protected amine **12** in 97% yield. Reduction of methyl ester **12** with $LiAlH_4$ in THF gave primary alcohol **13** in good yield (84%). Thereafter, the hydroxy group in **13** was converted into bromide **14** through the use of CBr_4 and Ph_3P in excellent yield (96%). Treatment of **14** with 4-trifluoromethylbenzylamine (**6**, 2 equiv.) afforded compound **15** in 54% yield. Subsequently, the Boc protecting group in **15** was removed by using trifluoroacetic acid (TFA), providing bisamine **16** in 64% yield. After protonation and anion exchange with NH_4PF_6, desired bis-ammonium thread **4**-H_2·2PF_6 was obtained in quantitative yield.

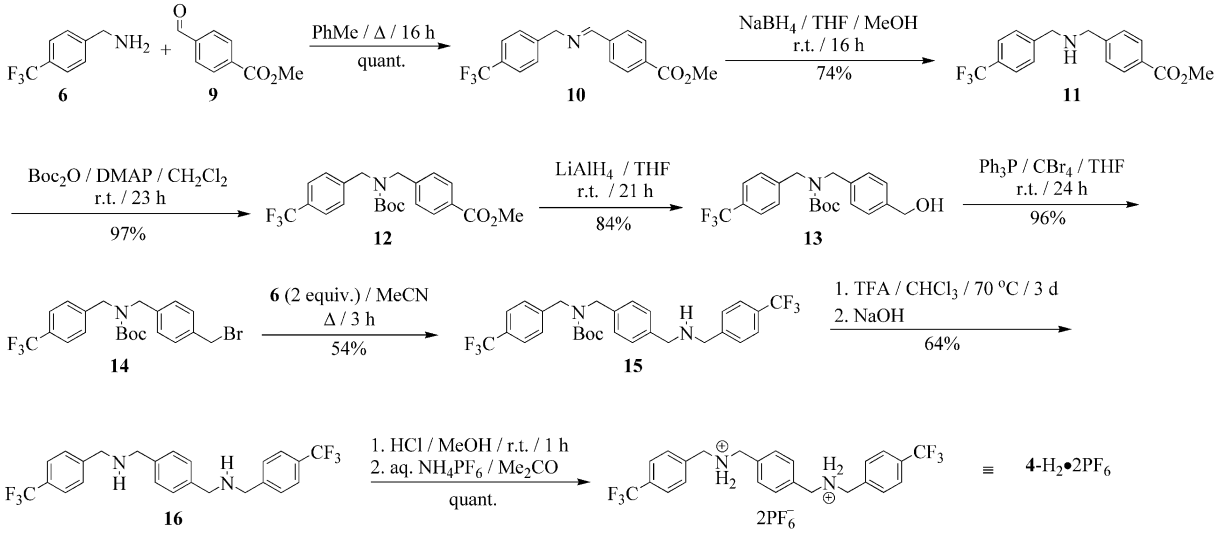
Although most of the yields in route 1 were rather high, the overall yield (20%) of this route is not very impressive. Consequently, an alternative route was devised for the preparation of compound **16**, as illustrated in Scheme 3. Route 2 uses a similar strategy to that used for the synthesis of **2**-H_2·2PF_6.[8] Terephthal dicarboxaldehyde (**17**) was treated with 4-trifluoromethylbenzylamine (**6**, 2 equiv.) to provide diimine **18** in quantitative yield, which subsequently was reduced with $NaBH_4$ to give amine **16** in 68% yield. Finally, protonation and anion exchange with NH_4PF_6 gave **4**-H_2·2PF_6 in quantitative yield. The overall yield of this alternative route is 68%, which is an obvious improvement to the overall yield obtained from route 1.



Scheme 3. Synthesis of compound **16** (route 2).

Characterization

All new compounds described in this paper were characterized by NMR spectroscopy, mass spectrometry, and elemental analysis. The ^{1}H NMR spectrum (200 MHz, 298 K)



Scheme 2. Synthesis of compound **16** (route 1) and its corresponding bis-ammonium thread **4**-H_2·2PF_6.

recorded (Figure 2) in CD_3CN of bis-ammonium thread **4**-H_2·$2PF_6$ revealed two singlets at δ = 4.29 and 4.34 ppm, which can be assigned to the resonances associated with the benzylic CH_2N^+ protons H^5 and H^4, respectively. In the aromatic region, the inner *p*-xylyl protons (i.e., H^6) appear as a singlet at δ = 7.55 ppm, whereas the outer *p*-xylyl protons (i.e., H^2 and H^3) are observed as an AB system at δ = 7.67 and 7.79 ppm. Matrix-assisted laser-desorption/ionization time-of-flight (MALDI-TOF) mass spectrometry of **4**-H_2·$2PF_6$ gave peaks at *m*/*z* = 599.09, 453.12, and 227.09 corresponding to the $[M - PF_6]^+$, $[M - HPF_6]^+$, and $[M - 2PF_6]^{2+}$ ion, respectively.

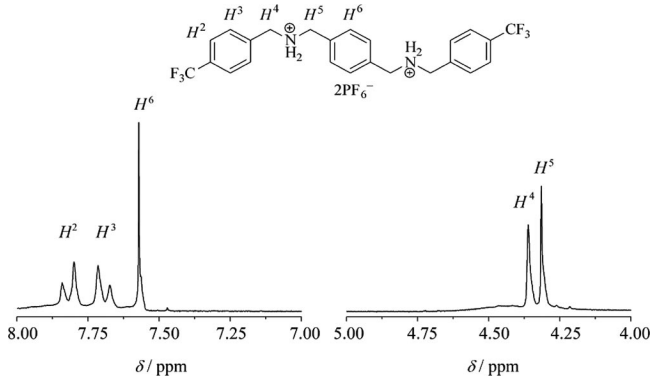


Figure 2. Partial ^{1}H NMR spectrum (200 MHz, CD_3CN, 298 K) of **4**-H_2·$2PF_6$. The applied numbering of protons on the bis-ammonium thread will be used throughout the article.

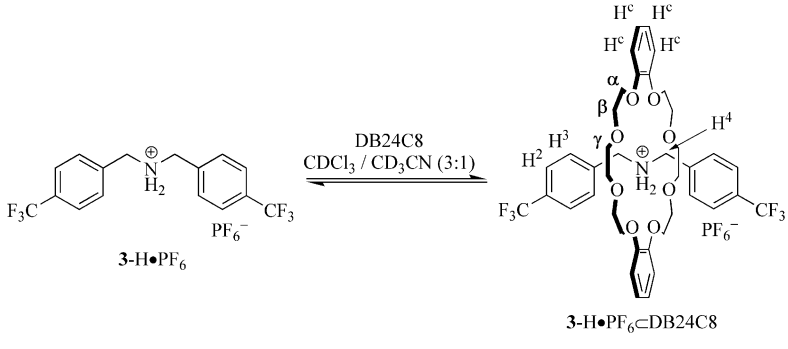
Complexation Studies

The inclusion of ammonium threads inside the cavity of DB24C8 is well documented[5–7] and leads to the formation of pseudorotaxanes under thermodynamic control upon mixing of their cyclic and acyclic components in solution. In the present study, the complexation between DB24C8 and ammonium threads **1**-H·PF_6, **2**-H·PF_6, **3**-H·PF_6, and **4**-H_2·$2PF_6$ was investigated by using ^{1}H NMR spectroscopy.

Single-Site Ammonium Threads

Addition of ammonium thread **3**-H·PF_6 (1 equiv.) to a $CDCl_3$/CD_3CN (3:1) solution of DB24C8 leads (Scheme 4) to the formation of [2]pseudorotaxane **3**-H·PF_6⊂DB24C8, as evidenced by the appearance of several new signals in the ^{1}H NMR spectrum (300 MHz, 298 K), a situation which is characteristic of superstructures containing an ammonium thread located inside DB24C8. The exchange between the complexed and uncomplexed species in the 1:1 complex formed between thread **3**-H·PF_6 and DB24C8 occurs slowly on the ^{1}H NMR timescale, allowing the association constant K_a to be determined (vide infra) by using the single-point method.[10,11]

A comparison of the ^{1}H NMR spectra (Figure 3) of DB24C8 and ammonium thread **3**-H·PF_6 with that recorded of a 1:1 mixture of DB24C8 and **3**-H·PF_6 reveals, as expected, that the formation of [2]pseudorotaxane **3**-H·PF_6⊂DB24C8 induces a significant shift in the resonances associated with the protons in both the thread and the crown ether component.[5] In the aromatic region, all signals of [2]pseudorotaxane **3**-H·PF_6⊂DB24C8 are shifted upfield relative to its free constituents. The signals associated with the aromatic protons H^2 and H^3 of **3**-H·PF_6 shift from 7.67/7.79 ppm (AB system) to 7.43 ppm (singlet) upon complexation, whereas the signal associated with the aromatic protons H^c of DB24C8 shift from 6.89 ppm (singlet) to 6.73/6.85 ppm (two multiplets). These observations can most likely be accounted for by the presence of π–π stacking interactions between the aromatic rings in thread **3**-H·PF_6 and the DB24C8 ring. In the aliphatic region of the ^{1}H NMR spectrum, the complexation event results in a downfield shift of the benzylic H^4 protons from 4.34 to 4.78 ppm, whereas the signals associated with the glycolic protons (α, β, and γ) of DB24C8 all shift upfield from 4.13, 3.88, and 3.78 ppm to 4.06, 3.80, and 3.55 ppm, respectively, a situation which can be explained by the formation of hydrogen-bonding interactions between the ammonium protons in **3**-H·PF_6 and the oxygen atoms in the glycol chains of DB24C8. Formation of hydrogen bonds deshield the benzylic CH_2N^+ protons (i.e., H^4) of **3**-H·PF_6, while shielding the glycolic OCH_2 protons (i.e., α, β, and γ) of DB24C8 at the same time. All relevant chemical shifts are summarized in Table 1. [2]Pseudorotaxane **3**-H·PF_6⊂DB24C8 was observed to be in slow exchange with its free constituents on the ^{1}H NMR timescale (300 MHz, 298 K), as both complexed and uncomplexed resonances are present in the ^{1}H NMR spectrum (Figure 3d). As noted above, several of the protons in both the thread and the



Scheme 4. Formation of [2]pseudorotaxane **3**-H·PF_6⊂DB24C8.

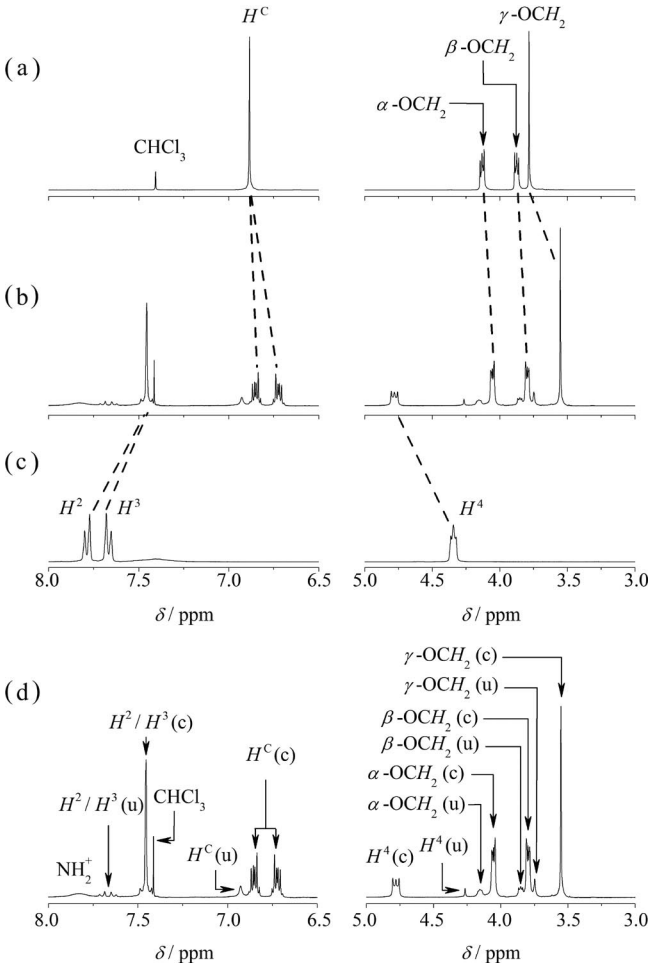


Figure 3. Partial ^{1}H NMR spectra recorded at 298 K of (a) DB24C8 (300 MHz, $CDCl_3/CD_3CN$, 3:1), (b) a 1:1 mixture of DB24C8 and **3**-H·PF_6 (300 MHz, $CDCl_3/CD_3CN$, 3:1), and (c) **3**-H·PF_6. (200 MHz, CD_3CN). (d) Complete assignment of all signals in the ^{1}H NMR spectrum recorded of a 1:1 mixture of DB24C8 and **3**-H·PF_6 [300 MHz, $CDCl_3/CD_3CN$ (3:1), 298 K]. The descriptions c and u refer to *complexed* and *uncomplexed* components, respectively.

ring component show significant shifts (Table 1) in their resonances upon complexation, which makes it possible to determine the association constants (K_a) by employing the ^{1}H NMR single-point method.[12] The signal associated with the benzylic CH_2N^+ protons (i.e., H^4) of **3**-H·PF_6 was found to be the most useful probe and a K_a value[13] of 3700 M^{-1} for the complexation of **3**-H·PF_6 by DB24C8 in $CDCl_3/CD_3CN$ (1:1) at 298 K was obtained. By employing a similar approach and for comparison reasons, we also determined the K_a value[13] for the complexation of **1**-H·PF_6 by DB24C8 in $CDCl_3/CD_3CN$ (1:1) to be 2000 M^{-1} at 298 K. These results indicate that attachment of two CF_3 groups to the single-site ammonium thread enhances the binding strength between the DB24C8 ring and the ammonium thread.

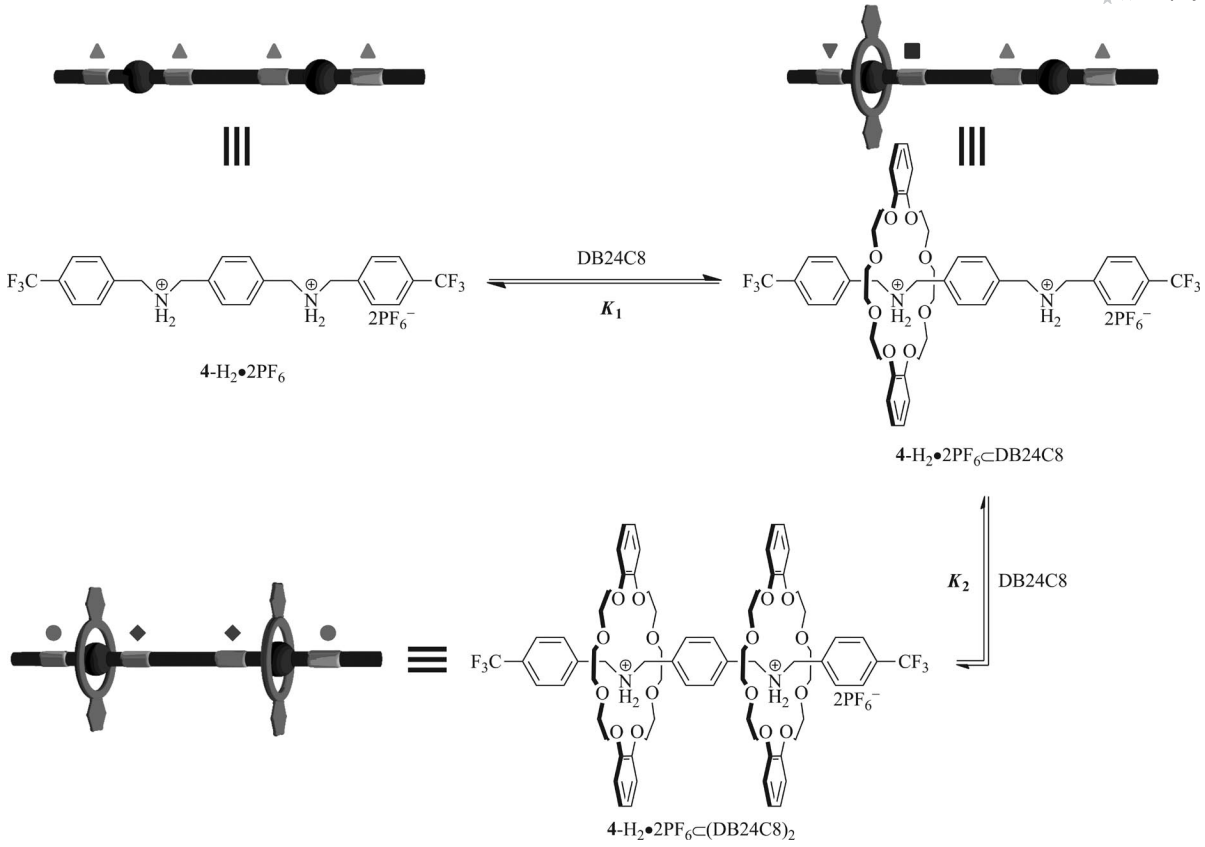
Double-Site Ammonium Threads

Double-site ammonium thread **4**-H_2·2PF_6 contains two ammonium recognition sites for the DB24C8 ring. Consequently, addition of DB24C8 to **4**-H_2·2PF_6 can lead to the formation (Scheme 5) of both [2]pseudorotaxane **4**-H_2·2PF_6⊂DB24C8 and [3]pseudorotaxane **4**-H_2·2PF_6⊂$(DB24C8)_2$. In common with the single-site ammonium threads, the exchange between the complexed and uncomplexed species formed between **4**-H_2·2PF_6 and DB24C8 occurs slowly on the ^{1}H NMR timescale [$CDCl_3/CD_3CN$ (1:1), 300 MHz][14] at 298 K. Thus, both the resonances for the complexed and uncomplexed species can be observed in the ^{1}H NMR spectrum (Figure 4) recorded on a mixture of **4**-H_2·2PF_6 and DB24C8 (2 equiv.) in $CDCl_3/CD_3CN$ (1:1). The ^{1}H NMR spectrum reveals that new signals appear as a result of complexation. The resonances associated with aromatic protons H^2, H^3, and H^6 in thread component **4**-H_2·2PF_6 shift from 7.80, 7.67, and 7.55 ppm to 7.49, 7.41, and 7.05 ppm, respectively, upon complexation with DB24C8. In the aliphatic region, two multiplets at δ = 4.54 and 4.75 ppm are observed, which can be assigned to the complexed benzylic CH_2N^+ protons (i.e., H^4 and H^5). Al-

Table 1. Selected ^{1}H NMR spectroscopic data (δ values) for [2]pseudorotaxanes **1**-H·PF_6⊂DB24C8 and **3**-H·PF_6⊂DB24C8 and [3]pseudorotaxanes **2**-H_2·2PF_6⊂$(DB24C8)_2$ and **4**-H_2·2PF_6⊂$(DB24C8)_2$, together with their corresponding free constituents at 298 K. s = singlet, d = doublet, t = triplet, m = multiplet, AB = AB system.

Compound/complex	Crown ether				Ammonium thread	
	o-$O_2C_6H_4$	α-OCH_2	β-OCH_2	γ-OCH_2	CH_2N^+	C_6H_4
DB24C8[a]	6.89 (s)	4.13 (m)	3.88 (m)	3.78 (s)	–	–
1-H·PF_6[b]	–	–	–	–	4.23 (s)	7.46(s)
1-H·PF_6⊂DB24C8[a]	6.78–6.83 (m), 6.87–6.93 (m)	4.10 (m)	3.76 (m)	3.44 (s)	4.62 (m)	7.17–7.36 (m)
3-H·PF_6[b]	–	–	–	–	4.34 (m)	7.67 and 7.79 (AB)
3-H·PF_6⊂DB24C8[c]	6.70–6.76 (m), 6.82–6.89 (m)	4.06 (m)	3.80 (m)	3.55 (s)	4.78 (m)	7.43 (s)
2-H_2·2PF_6[b]	–	–	–	–	4.23 (m)	7.53 (s), 7.46 (s)
2-H_2·2PF_6⊂$(DB24C8)_2$[a]	6.68–6.76 (m), 6.78–6.86 (m)	3.98 (m)	3.68–3.72 (m)	3.40–3.65 (m)	4.63 (m), 4.45 (m)	6.92 (s), 7.20–7.40 (m)
4-H_2·2PF_6[b]	–	–	–	–	4.29 (s), 4.34 (s)	7.55 (s), 7.67 and 7.80 (AB)
4-H_2·2PF_6⊂$(DB24C8)_2$[c]	6.66–6.76 (m), 6.78–6.87 (m)	3.98 (m)	3.63–3.82 (m)	3.56 (s)	4.50–4.60 (m), 4.70–4.80 (m)	7.07 (s), 7.41 and 7.49 (AB)

[a] ^{1}H NMR spectra were recorded in $CDCl_3/CD_3CN$ (3:1) at 300 MHz. [b] ^{1}H NMR spectra were recorded in CD_3CN at 200 MHz. [c] ^{1}H NMR spectra were recorded in $CDCl_3/CD_3CN$ (1:1) at 300 MHz.



Scheme 5. Formation of [2]pseudorotaxane **4**-H_2·2PF_6⊂DB24C8 and [3]pseudorotaxane **4**-H_2·2PF_6⊂(DB24C8)$_2$, together with cartoon representations of bis-ammonium thread **4**-H_2·2PF_6, [2]pseudorotaxane **4**-H_2·2PF_6⊂DB24C8, and [3]pseudorotaxane **4**-H_2·2PF_6⊂(DB24C8)$_2$.

though the ^{1}H NMR spectrum (Figure 4) clearly indicates that complexation between **4**-H_2·2PF_6 and DB24C8 takes place, it does not give a clear picture on whether the complexation event leads to the formation of [2]pseudorotaxane **4**-H_2·2PF_6⊂DB24C8 or to [3]pseudorotaxane **4**-H_2·2PF_6⊂(DB24C8)$_2$ – or a mixture of both. Consequently, further ^{1}H NMR spectroscopic investigations (Figures 5 and 6) of the complexation between **4**-H_2·2PF_6 and DB24C8 were carried out by changing the ratio between **4**-H_2·2PF_6 and DB24C8 from 5:1 to 1:1 and then finally to 1:5. A comparison of the ^{1}H NMR spectra (Figures 5 and 6) reveal that the molar amount of DB24C8 has a significant impact on the appearances of the spectra, both in the aromatic and in the aliphatic region. In the ^{1}H NMR spectrum recorded (Figure 5a and Figure 6a) of a 5:1 mixture of **4**-H_2·2PF_6 and DB24C8, ammonium thread **4**-H_2·2PF_6 is as expected the dominant species, but it should be noted that virtually no uncomplexed DB24C8 is present. These results indicate that the complexation of **4**-H_2·2PF_6 by DB24C8 is strong at this temperature and that the equilibrated solution predominantly consist of a mixture of uncomplexed thread **4**-H_2·2PF_6 and [2]pseudorotaxane **4**-H_2·2PF_6⊂DB24C8.[15] By changing the molar ratio from 5:1 to 1:1, **4**-H_2·2PF_6 is no longer observed to be the predominant species in the ^{1}H NMR spectrum (Figure 5b). The most important thing to notice, however, is the appearance (Figure 6b) of a signal resonating at δ = 4.54 ppm and the increased complexity of the multiplet resonating at δ = 4.75 ppm. These observations can most likely be ascribed to the formation of a new species in solution, namely, [3]pseudorotaxane **4**-H_2·2PF_6⊂(DB24C8)$_2$. This was further substantiated by the fact that the ^{1}H NMR spectrum (Figure 5c and Figure 6c) recorded on a 1:5 mixture of **4**-H_2·2PF_6 and DB24C8 leads to simplification in the signals observed in the region from 4.5 to 4.8 ppm, an observation which is consistent with the conversion of [2]pseudorotaxane **4**-H_2·2PF_6⊂DB24C8 into [3]pseudorotaxane **4**-H_2·2PF_6⊂(DB24C8)$_2$. Consequently, the multiplets at δ = 4.67–4.75 and 4.78–4.86 ppm can be used as a signature

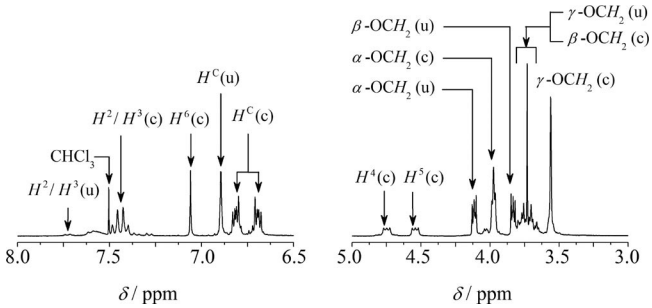


Figure 4. Partial ^{1}H NMR spectrum recorded of a 1:2 mixture of **4**-H_2·2PF_6 and DB24C8 [300 MHz, $CDCl_3$/CD_3CN (1:1), 298 K]. The descriptions c and u refer to *complexed* and *uncomplexed* components, respectively.

for the presence of [2]pseudorotaxane **4**-H_2·2PF_6⊂DB24C8, whereas the multiplets at δ = 4.50–4.60 and 4.72–4.80 ppm can be used as a signature for the presence of [3]pseudorotaxane **4**-H_2·2PF_6⊂(DB24C8)$_2$.

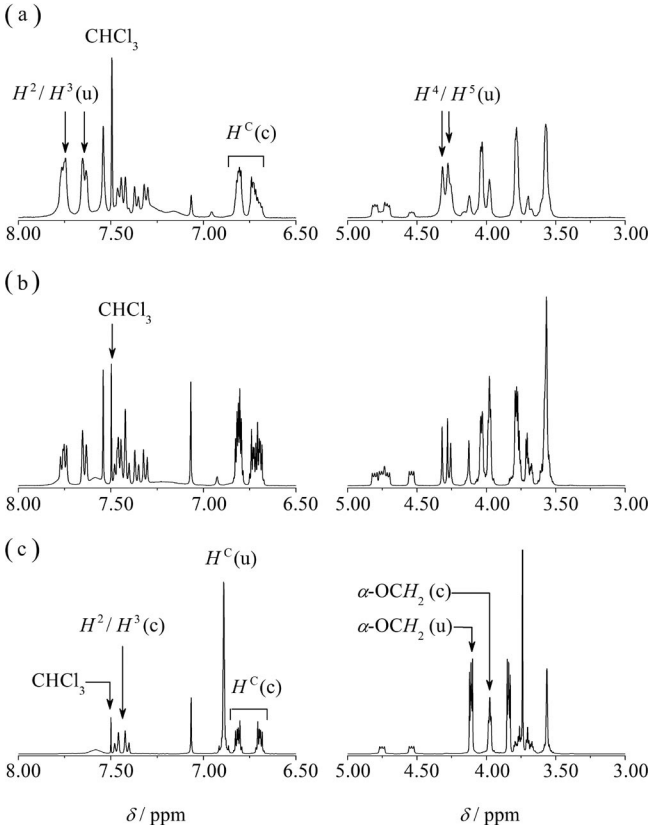


Figure 5. Partial ^{1}H NMR spectra (400 MHz, 298 K) recorded in $CDCl_3$/CD_3CN (1:1) of **4**-H_2·2PF_6 and DB24C8 at different molar ratios: (a) 5:1, (b) 1:1, and (c) 1:5.

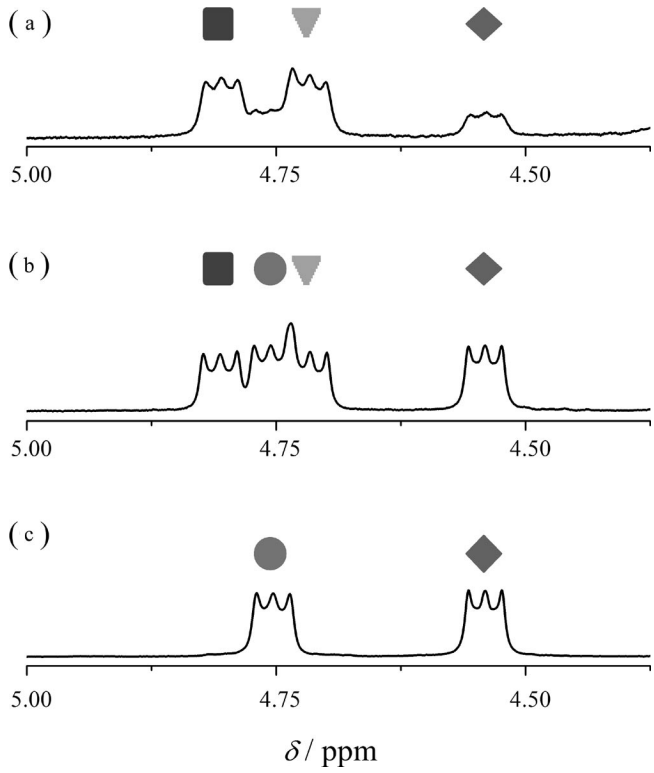


Figure 6. Partial ^{1}H NMR spectra (400 MHz, 298 K) recorded in $CDCl_3$/CD_3CN (1:1) of **4**-H_2·2PF_6 and DB24C8 at different molar ratios: (a) 5:1, (b) 1:1, and (c) 1:5. The multiplets centered at δ = 4.71 (upside-down filled grey triangle) and 4.81 (filled black square) ppm correspond to the benzylic CH_2N$^+$ resonances when DB24C8 encircles one of the ammonium recognition sites in thread **4**-H_2·2PF_6, whereas the multiplets centered at δ = 4.54 (filled grey diamond) and 4.75 (filled grey circle) ppm correspond to the benzylic CH_2N$^+$ resonances when DB24C8 encircles both ammonium recognition sites in thread **4**-H_2·2PF_6. The labels (upside-down filled grey triangle, filled black square, filled grey circle, and filled grey diamond) used to assign the different signals refer to the benzylic CH_2N$^+$ protons as shown in the cartoons in Scheme 5.

In the case of the complexation between **4**-H_2·2PF_6 and DB24C8, the simple single-point method (vide supra) is no longer a valid method for determination of the binding constants (i.e., K_1 and K_2). Instead K_1 and K_2 were obtained by taking the weighted average of a series of K_1 and K_2 values obtained through single-point determinations of two independent titration curves. For the complexation of **4**-H_2·2PF_6 with DB24C8 recorded in $CDCl_3$/CD_3CN (1:1) at 298 K, this yielded K_1 = 2500 M^{-1} and K_2 = 600 M^{-1}.[16] These findings indicate a weak anticooperative effect in the formation of **4**-H_2·2PF_6⊂(DB24C8)$_2$. A similar approach was employed for the complexation of **2**-H_2·2PF_6 with DB24C8, affording K_1 = 2900 M^{-1} and K_2 = 1100 M^{-1}.[16] When comparing the two bis-ammonium threads, it is evident that the K_1 values are comparable in size. The anticooperative effect on K_2 is also present in this case, but for **4**-H_2·2PF_6⊂(DB24C8)$_2$ the size of K_2 is reduced to approximately half that of **2**-H_2·2PF_6⊂(DB24C8)$_2$. A comparison of the K_1 and K_2 values for the complexation between **4**-H_2·2PF_6 and DB24C8 with those for the complexation between **2**-H_2·2PF_6 with DB24C8 reveals that the positive effect on the binding strength exhibited by the appended CF_3 groups is absent in the case of **4**-H_2·2PF_6. This observation can most likely be accounted for by the fact that in the single-site ammonium thread **3**-H·PF_6 both CF_3 groups are appended in close proximity to the ammonium recognition site, whereas in the double-site ammonium thread **4**-H_2·2PF_6 only one of the CF_3 groups is located close to the ammonium recognition site.

X-ray Diffraction Analysis

Diffraction-grade single crystals of [3]pseudorotaxane **4**-H_2·2PF_6⊂(DB24C8)$_2$ were obtained by slow vapor diffusion of *i*Pr_2O into a solution of **4**-H_2·2PF_6 and DB24C8 (2 equiv.) in CH_3CN. The resulting X-ray crystal structure (Figure 7) confirms the 2:1 ratio between DB24C8 and **4**-H_2·2PF_6 and reveals that the two DB24C8 adopt an *S*-shaped conformation around the ammonium centers. The complex is centrosymmetric and occupies a crystallographic inversion center in the solid state. Four N^+–H···O hydrogen

bonds are formed between the two ammonium centers and DB24C8. In addition, face-to-face π–π stacking interactions between the central *p*-xylyl ring on bis-ammonium thread **4**-H_2·2PF_6 and one of the catechol rings on each DB24C8 can be observed. The distance between the centroid of each catechol ring and that of the central *p*-xylyl ring is 3.731 Å.[17]

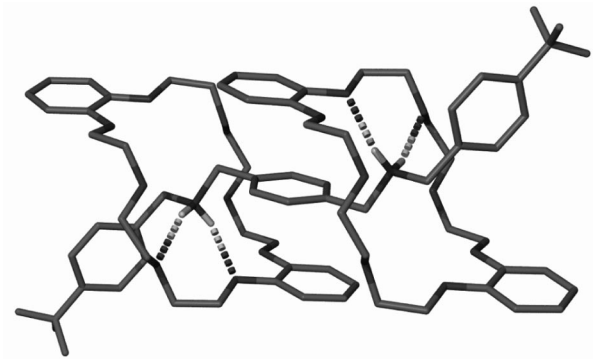


Figure 7. X-ray crystal structure of [3]pseudorotaxane **4**-H_2·2PF_6⊂$(DB24C8)_2$. The dashed lines denote N^+–H···O hydrogen bonds.

Conclusions

In summary, we have successfully prepared ammonium threads **3**-H·PF_6 and **4**-H_2·2PF_6 appended with two electron-withdrawing CF_3 groups. In both cases, the threads are able to bind DB24C8, leading to the formation of [2]-pseudorotaxanes and [3]pseudorotaxanes. ^{1}H NMR spectroscopic studies show that attachment of two electron-withdrawing CF_3 groups to single-site ammonium thread **3**-H·PF_6 enhances the binding strength between the DB24C8 ring and the ammonium thread by a factor of two. In the case of double-site ammonium thread **4**-H_2·2PF_6, the relative amount of the [2]pseudorotaxane and the [3]pseudorotaxane can be controlled by changing the ratio between **4**-H_2·2PF_6 and DB24C8. Quantitative analysis reveal that thread **4**-H_2·2PF_6 exhibits negative cooperativity towards DB24C8 – an observation that most likely can be accounted for by steric hindrance upon binding of a second DB24C8 ring to the [2]pseudorotaxane **4**-H_2·2PF_6⊂DB24C8. The findings reported herein are undoubtedly not unimportant when it comes to the future design and construction of [2]-rotaxanes and [3]rotaxanes incorporating bis-alkyl ammonium recognition elements and DB24C8.

Experimental Section

General Methods: Chemicals were purchased from Aldrich and used as received unless indicated otherwise. The compounds dibenzylammonium hexafluorophosphate (**1**-H·PF_6)[5d] and α,α′-bis-benzylammonium-*p*-xylene bis(hexafluorophosphate) (**2**-H_2·2PF_6)[8] were prepared according to literature procedures. Thin-layer chromatography (TLC) was carried out by using aluminum sheets precoated with silica gel 60F (Merck 5554). The plates were inspected under UV light (254 nm) and developed with I_2 vapor. Column chromatography was carried out by using silica gel 60F (Merck 9385, 0.040–0.063 mm). Melting points were determined with a Büchi melting point apparatus. ^{1}H NMR spectra were recorded with a Varian (500 MHz) instrument, a Bruker Avance III (400 MHz) instrument, a Varian Gemini instrument (300 MHz), or a Varian Mercury instrument (200 MHz) by using the residual solvent as internal standard. ^{13}C NMR spectra were recorded at room temperature with a Varian Gemini instrument (75 MHz) or a Bruker Avance III (100 MHz) by using the residual solvent as internal standard. Samples were prepared by using $CDCl_3$ and CD_3CN purchased from Cambridge Isotope Labs. Electron ionization mass spectrometry (EI MS) was performed with a Finnegan MAT TSQ 700 instrument, matrix-assisted laser-desorption/ionization time-of-flight mass spectrometry (MALDI-TOF-MS) was performed with an Ionspec 4.7 Tesla Ultima Fourier Transform instrument by utilizing a 2,5-dihydroxybenzoic acid matrix, whereas electrospray ionization (ESI) analysis was performed with a Bruker microTOF-Q II ESI-Qq-TOF mass spectrometer. Microanalyses were performed by the Atlantic Microlab, Inc., Atlanta, Georgia.

***N*-(4-Trifluoromethylbenzylidene)-4-trifluoromethylbenzylamine (7):** A solution of 4-trifluoromethylbenzaldehyde (**5**; 2.03 g, 11.7 mmol) and 4-trifluoromethylbenzylamine (**6**; 2.03 g, 11.6 mmol) was heated under reflux in PhMe (100 mL) overnight, and the water liberated from the reaction was removed from the reaction mixture by means of a Dean–Stark apparatus. The organic phase was removed in vacuo, yielding imine **7** as a clear yellow oil, which crystallized upon cooling to a white solid (3.78 g, 99%). M.p. 34–35 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 4.90 (s, 2 H, NCH_2), 7.47 (d, $^3J_{H,H}$ = 8.0 Hz, 2 H, 2 Ar-H), 7.61 (d, $^3J_{H,H}$ = 8.0 Hz, 2 H, 2 Ar-H), 7.69 (d, $^3J_{H,H}$ = 8 Hz, 2 H, Ar-H), 7.90 (d, $^3J_{H,H}$ = 8.0 Hz, 2 H, Ar-H), 8.46 (s, 1 H, N=CH) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 64.6, 124.2 (q, $^1J_{F,C}$ = 270 Hz, CF_3), 125.6 (q, $^3J_{F,C}$ = 4 Hz), 125.8 (q, $^3J_{F,C}$ = 4 Hz), 128.3, 128.6, 129.6 (q, $^2J_{F,C}$ = 32 Hz), 132.7 (q, $^2J_{F,C}$ = 32 Hz), 139.1, 143.1, 161.2 ppm. MS (ESI): *m*/*z* (%) = 332 (4) $[M]^+$, 159 (100). $C_{16}H_{11}F_6N$ (331.3): calcd. C 58.01, H 3.35, N 4.23; found C 57.77, H 3.17, N 4.25.

***N*,*N*-Bis(4-trifluoromethylbenzyl)amine (8):** Imine **7** (2.04 g, 6.16 mmol) was dissolved in anhydrous MeOH (70 mL), whereafter $NaBH_4$ (1.14 g, 30.1 mmol) was added. The reaction mixture was stirred for 2 h at room temperature, followed by the addition of another portion of $NaBH_4$ (1.14 g, 30.1 mmol). After stirring the reaction mixture overnight under N_2, the excess amount of $NaBH_4$ was destroyed by slow addition of an aqueous solution of HCl (2 M, 200 mL). After washing with $CHCl_3$ (50 mL), an aqueous solution of NaOH (2 M) was added until pH≈14. The aqueous phase was extracted with $CHCl_3$ (5 × 100 mL), whereafter the combined organic phases were dried ($MgSO_4$) and concentrated in vacuo, affording **8** as a clear yellow oil (1.13 g, 56%). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 2.72 (br. s, 1 H, NH), 3.87 (s, 4 H, 2 NCH_2), 7.48 (d, $^3J_{H,H}$ = 8.0 Hz, 4 H, 4 Ar-H), 7.59 (d, $^3J_{H,H}$ = 8.0 Hz, 4 H, 4 Ar-H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 52.8, 124.4 (q, $^1J_{F,C}$ = 270 Hz, 2 CF_3), 125.5 (q, $^3J_{F,C}$ = 4 Hz), 128.4, 129.6 (q, $^2J_{F,C}$ = 32 Hz), 144.3 ppm. MS (ESI): *m*/*z* (%) = 332 (4) $[M + H]^+$, 159 (100). $C_{16}H_{13}F_6N$ (333.3): calcd. C 57.66, H 3.93, N 4.20; found C 57.88, H 3.80, N 4.23.

***N*,*N*-Bis(4-trifluoromethylbenzyl)ammonium Hexafluorophosphate (3-H·PF_6):** A concentrated aqueous solution of HCl was added to a solution of amine **8** (1.02 g, 3.06 mmol) in MeOH (50 mL) until pH≈2, and the mixture was stirred for 1 h. The solvent was evapo-

rated, and the residue was dissolved in Me_2CO (50 mL). Upon dropwise addition of an aqueous solution (20 mL) of NH_4PF_6 (1.63 g, 10 mmol), the product precipitated. The organic solvent was removed in vacuo, and the product was isolated by filtration, washed with H_2O (50 mL), and air dried, yielding **3**-H·PF_6 as a fine white powder (1.34 g, 92%). M.p. >230 °C. ^{1}H NMR (300 MHz, CD_3CN): δ = 4.34 (s, 4 H, 2 NCH_2), 7.41 (br. s, 2 H, NH_2^+), 7.67 (d, $^3J_{H,H}$ = 8.3 Hz, 4 H, 4 Ar-H), 7.78 (d, $^3J_{H,H}$ = 8.3 Hz, 4 H, 4 Ar-H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 52.0, 125.1 (q, $^1J_{F,C}$ = 270 Hz, CF_3), 126.9 (q, $^3J_{F,C}$ = 3.5 Hz), 132.1 (s), 132.1 (q, $^2J_{F,C}$ = 32 Hz), 135.5 ppm. MS (ESI): *m*/*z* (%) = 336 (100) $[M + H]^+$, 159 (88) $[CF_3Bn]^+$. $C_{16}H_{14}F_{12}NP$ (479.24): calcd. C 40.10, H 2.94, N 2.91; found C 40.01, H 2.85, N 2.95.

***N*-(4-Carboxymethoxybenzylidene)-*p*-trifluoromethylbenzylamine (10):** A solution of 4-trifluoromethylbenzylamine (**6**; 1.77 g, 10 mmol) and methyl-4-formylbenzoate (**9**; 1.64 g, 10 mmol) was heated under reflux in PhMe (160 mL) overnight, and the H_2O liberated from the reaction was removed from the reaction mixture by means of a Dean–Stark apparatus. The organic phase was cooled to room temperature, whereafter the solvent was removed in vacuo, yielding imine **10** as a white solid (3.21 g, quant.). M.p. 78–80 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 3.94 (s, 3 H, CH_3), 4.89 (s, 2 H, NCH_2), 7.47 (d, $^3J_{H,H}$ = 8.0 Hz, 2 H, 2 Ar-H), 7.76 (d, $^3J_{H,H}$ = 8.0 Hz, 2 H, 2 Ar-H), 7.85 (d, $^3J_{H,H}$ = 8.4 Hz, 2 H, 2 Ar-H), 8.10 (d, $^3J_{H,H}$ = 8.4 Hz, 2 H, 2 Ar-H), 8.46 (s, 1 H, N=CH) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 52.4, 64.6, 125.6 (q, $^3J_{F,C}$ = 4 Hz), 124.4 (q, $^1J_{F,C}$ = 271 Hz, CF_3), 128.3, 128.3, 129.6 (q, $^2J_{F,C}$ = 32 Hz), 130.1, 132.3, 139.9, 143.2, 161.8, 166.7 ppm. MS (EI): *m*/*z* (%) = 321 (100) $[M]^+$, 306 (15) $[M - CH_3]^+$, 262 (8) $[M - CF_3]^+$. $C_{17}H_{14}F_3NO_2$ (321.3): calcd. C 63.55, H 4.39, N 4.36; found C 63.70, H 4.34, N 4.37.

***N*-(4-Trifluoromethylbenzyl)-4-carboxymethoxybenzylamine (11):** Imine **10** (2.90 g, 9.03 mmol) was dissolved in a mixture of anhydrous THF/MeOH (1:1, 100 mL), whereafter $NaBH_4$ (0.35 g, 9.25 mmol) was added. The reaction mixture was stirred for 4 h at room temperature, followed by the addition of another portion of $NaBH_4$ (0.43 g, 11.4 mmol). After stirring the reaction mixture overnight at room temperature under N_2, the excess amount of $NaBH_4$ was destroyed by slow addition of an aqueous solution of HCl (4 M, 40 mL). The solvent was removed in vacuo, providing a white powder, which was partitioned between an aqueous solution of NaOH (1 M, 100 mL) and CH_2Cl_2 (100 mL). The aqueous phase was extracted with CH_2Cl_2 (2 × 100 mL), whereafter the combined organic phases were dried ($MgSO_4$) and concentrated in vacuo, affording **11** as a pale-yellow oil (2.16 g, 74%). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.68 (s, 1 H, NH), 3.86 (s, 4 H, 2 NCH_2), 3.91 (s, 3 H, OCH_3), 7.41 (d, $^3J_{H,H}$ = 8.4 Hz, 2 H, 2 Ar-H), 7.46 (d, $^3J_{H,H}$ = 8.1 Hz, 2 H, 2 Ar-H), 7.58 (d, $^3J_{H,H}$ = 8.1 Hz, 2 H, 2 Ar-H), 8.00 (d, $^3J_{H,H}$ = 8.4 Hz, 2 H, 2 Ar-H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 52.2, 52.7, 52.9, 124.4 (q, $^1J_{F,C}$ = 272 Hz, CF_3), 125.5 (q, $^3J_{F,C}$ = 4 Hz), 128.1, 128.5, 129.2, 129.6 (q, $^2J_{F,C}$ = 32 Hz), 129.9, 144.2, 145.4, 167.1 ppm. MS (EI): *m*/*z* (%) = 324 (100) $[M + 1]^+$, 264 (22) $[M - COOMe]^+$. $C_{17}H_{16}F_3NO_2$ (323.3): calcd. C 63.15, H 4.99, N 4.33; found C 62.88, H 5.09, N 4.17.

***N*-(*tert*-Butoxycarbonyl)-*N*-(4-trifluoromethylbenzyl)-4-carboxymethoxybenzylamine (12):** Compound **11** (1.64 g, 5.07 mmol), Boc_2O (1.26 g, 5.77 mmol), and DMAP (6 mg, 0.05 mmol) were dissolved in CH_2Cl_2 (50 mL), and the mixture was stirred overnight under N_2 at room temperature. Thereafter, the solvent was evaporated in vacuo to yield **12** as a colorless oil (2.08 g, 97%), which was used without any further purification. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.48 (s, 9 H, 3 Boc-CH_3), 3.92 (s, 3 H, OCH_3), 4.40 (br. s, 2 H, NH_2), 4.48 (br. s, 2 H, NCH_2), 7.20–7.35 (m, 4 H, 4 Ar-H), 7.58 (d, $^3J_{H,H}$ = 8.4 Hz, 2 H, 2 ArH), 8.00 (d, $^3J_{H,H}$ = 8.4 Hz, 2 H, 2 ArH) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 28.5, 49.6, 52.3, 80.9, 124.2 (q, $^1J_{F,C}$ = 271 Hz, CF_3), 125.7 (q, $^3J_{F,C}$ = 3 Hz), 130.1, 142.1, 143.1, 156.0, 167.0 (five signals missing/overlapping) ppm. MS (EI): *m*/*z* (%) = 424 (2) $[M + H]^+$, 392 (3) $[M - CH_3O]^+$, 367 (61) $[M - (CH_3)_3C]^+$, 57 (100) $[(CH_3)_3C]^+$. $C_{22}H_{24}F_3NO_4$ (423.4): calcd. C 62.40, H 5.71, N 3.31; found C 62.33, H 5.72, N 3.31.

***N*-(*tert*-Butoxycarbonyl)-*N*-(4-trifluoromethylbenzyl)-4-hydroxymethylbenzylamine (13):** A solution of **12** (1.35 g, 3.19 mmol) dissolved in anhydrous THF (30 mL) was added dropwise to a solution of $LiAlH_4$ (0.36 g, 9.49 mmol) in anhydrous THF (20 mL) over a period of 15 min. After stirring overnight at room temperature, the mixture was treated with H_2O (1 mL), an aqueous solution of NaOH (5 M, 1 mL), and finally more H_2O (2 mL). The resulting suspension was stirred for another 5 min and subsequently filtered through a thin layer of Celite 545 (1 cm). The filtrate was concentrated in vacuo, whereafter the residue was dissolved in CH_2Cl_2 (50 mL) and washed with H_2O (50 mL). Thereafter, the aqueous phase was extracted with CH_2Cl_2 (2 × 50 mL). Finally, the organic phases were combined, dried ($MgSO_4$), and concentrated in vacuo, affording **13** as a colorless oil (1.06 g, 84%), which was used without any further purification. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.48 (s, 9 H, 3 Boc-CH_3), 1.80 (br. s, 1 H, OH), 4.37 (br. s, 2 H, NCH_2), 4.43 (br. s, 2 H, NCH_2), 4.69 (s, 2 H, OCH_2), 7.20 (br. s, 2 H, 2 Ar-H), 7.31 (br. s, 2 H, 2 Ar-H), 7.33 (d, $^3J_{H,H}$ = 8.1 Hz, 2 H, 2 Ar-H), 7.56 (d, $^3J_{H,H}$ = 8.1 Hz, 2 H, 2 Ar-H) ppm. MS (EI): *m*/*z* (%) = 396 (4) $[M + H]^+$, 339 (66) $[M + H - (CH_3)_3C]^+$, 57 (100) $[(CH_3)_3C]^+$. $C_{21}H_{24}F_3NO_3$ (395.4): calcd. C 63.79, H 6.12, N 3.54; found C 63.89, H 6.05, N 3.43.

***N*-(*tert*-Butoxycarbonyl)-*N*-(4-trifluoromethylbenzyl)-4-bromomethylbenzylamine (14):** To a solution of **13** (0.90 g, 2.28 mmol) and CBr_4 (1.59 g, 4.79 mmol) in anhydrous THF (75 mL) was added Ph_3P (1.51 g, 5.76 mmol) in small portions over a period of 1 h. After stirring overnight at room temperature, the reaction mixture was concentrated in vacuo. The resulting residue was purified by column chromatography (SiO_2; *n*-hexane/EtOAc, 5:1; R_f = 0.6), affording **14** as a yellow oil (1.00 g, 96%). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.49 (s, 9 H, 3 Boc-CH_3), 4.42 (br. s, 4 H, NCH_2), 4.49 (s, 2 H, CH_2Br), 7.17 (br. s, 2 H, 2 Ar-H), 7.29 (br. s, 2 H, 2 Ar-H), 7.35 (d, $^3J_{H,H}$ = 8.1 Hz, 2 H, 2 Ar-H), 7.57 (d, $^3J_{H,H}$ = 8.1 Hz, 2 H, 2 Ar-H) ppm. MS (EI): *m*/*z* (%) = 458 (15) $[M + H]^+$, 402 (29) $[M + H - (CH_3)_3C]^+$, 57 (100) $[(CH_3)_3C]^+$.

α-[*N*-(*tert*-Butoxycarbonyl)-4-trifluoromethylbenzylamino]-α′-(4-trifluoromethylbenzylamino)-*p*-xylene (15): Compound **14** (0.85 g, 1.85 mmol) and 4-trifluoromethylbenzylamine (**6**; 0.65 g, 3.71 mmol) were dissolved in MeCN (50 mL), and the mixture was heated under reflux for 3 h. After cooling to room temperature, the reaction mixture was filtered and the filtrate was concentrated in vacuo. The resulting residue was subjected to column chromatography (SiO_2; $CHCl_3$/*n*-hexane, 4:1; R_f = 0.1), yielding **15** as a yellow oil (0.55 g, 54%). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.48 (s, 9 H, 3 Boc-CH_3) 1.62 (s, 1 H, NH) 3.80 (s, 2 H, NCH_2), 3.87 (s, 2 H, NCH_2), 4.38 (br. s, 4 H, 2 NCH_2), 7.18 (br. s, 2 H, 2 Ar-H), 7.29 (d, $^3J_{H,H}$ = 8.1 Hz, 4 H, 4 Ar-H), 7.47 (d, $^3J_{H,H}$ = 8.1 Hz, 2 H, 2 Ar-H), 7.51–7.62 (m, 4 H, 4 Ar-H) ppm. MS (MALDI): *m*/*z* (%) = 553 (8) $[M + H]^+$, 519 (37), 497 (14) $[M + H - (CH_3)_3C]^+$, 322 (100), 304 (34). $C_{29}H_{30}F_6N_2O_2$ (552.6): calcd. C 63.04, H 5.47, N 5.07; found C 63.22, H 5.60, N 4.91.

α,α′-Bis(4-trifluoromethylbenzylamino)-*p*-xylene (16) (Route 1): A solution of **15** (0.27 g, 0.65 mmol) in $CHCl_3$ (20 mL) and TFA

(1.04 g, 9.1 mmol) was stirred at 70 °C for 3 d. The organic phase was washed with an aqueous solution of NaOH (1 M, 2 × 50 mL), dried ($MgSO_4$), and concentrated in vacuo, affording **16** as a white solid (0.14 g, 64%). The product was used without any further purification. M.p. 41–43 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.64 (s, 2 H, 2 NH), 3.80 (s, 4 H, 2 NCH_2), 3.86 (s, 4 H, 2 NCH_2), 7.31 (s, 4 H, 4 Ar-H), 7.47 (d, $^3J_{H,H}$ = 8.0 Hz, 4 H, 4 Ar-H), 7.58 (d, $^3J_{H,H}$ = 8.0 Hz, 4 H, 4 Ar-H) ppm. MS (EI): *m*/*z* (%) = 452 (10) $[M]^+$, 159 (100) $[CF_3Bn]^+$.

α,α′-Bis(4-trifluoromethylbenzylimino)-*p*-xylene (18): A solution of terephthaldehyde (**17**; 1.34 g, 9.99 mmol) and 4-trifluoromethylbenzylamine (**6**; 3.61 g, 20.6 mmol) in PhMe (100 mL) was heated under reflux overnight; H_2O was liberated from the reaction was removed from the reaction mixture by means of a Dean–Stark apparatus. The organic phase was cooled to room temperature, whereafter the solvent was removed in vacuo, affording **18** as a white powder (4.49 g, quant.), which was used without any further purification. M.p. 120–122 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 4.88 (s, 4 H, 2 NCH_2), 7.47 (d, $^3J_{H,H}$ = 8.1 Hz, 4 H, 4 Ar-H), 7.61 (d, $^3J_{H,H}$ = 8.1 Hz, 4 H, 4 Ar-H), 7.85 (s, 4 H, 4 Ar-H), 8.44 (s, 2 H, 2 N=CH) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 64.7, 124.4 (q, $^1J_{F,C}$ = 271 Hz, CF_3), 125.6 (q, $^3J_{F,C}$ = 4 Hz), 128.3, 128.8, 129.5 (q, $^2J_{F,C}$ = 32 Hz), 138.3, 143.4, 162.1 ppm. MS (EI): *m*/*z* (%) = 448 (27) $[M]^+$, 429 (5), 289 (56), 262 (15), 186 (4), 159 (100) $[CF_3Bn]^+$, 109 (14). $C_{24}H_{18}F_6N_2$ (448.4): calcd. C 64.29, H 4.26, N 6.25; found C 64.37, H 3.97, N 6.10.

α,α′-Bis(4-trifluoromethylbenzylamino)-*p*-xylene (16) (Route 2): To a solution of **18** (4.41 g, 9.83 mmol) in MeOH (150 mL) was added $NaBH_4$ (1.87 g, 49.4 mmol) cautiously in small portions. After stirring for 2 h at room temperature another portion of $NaBH_4$ (1.84 g, 49 mmol) was added, and the reaction mixture was stirred overnight at room temperature, whereafter the solvent was removed in vacuo. The residue was cautiously treated with an aqueous solution of HCl (2 M, 200 mL), and the resulting solution was washed with $CHCl_3$ (150 mL). Subsequently, the aqueous phase was treated with an aqueous solution of NaOH (2 M, until pH ≈ 14) and then extracted with $CHCl_3$ (5 × 100 mL). The combined organic phases were dried ($MgSO_4$), and the solvent was removed in vacuo, yielding **16** as a white solid (3.04 g, 68%). M.p. 41–43 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.64 (s, 2 H, 2 NH), 3.79 (s, 4 H, 2 NCH_2), 3.86 (s, 4 H, 2 NCH_2), 7.30 (s, 4 H, 4 Ar-H), 7.46 (br. s, 4 H, 4 Ar-H), 7.56 (br. s, 4 H, 4 Ar-H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 52.7, 53.0, 124.4 (q, $^1J_{F,C}$ = 270 Hz, CF_3), 125.4 (q, $^3J_{F,C}$ = 3 Hz), 128.4, 128.5, 129.4 (q, $^2J_{F,C}$ = 32 Hz), 139.0, 144.6 ppm. MS (EI): *m*/*z* (%) = 452 (8) $[M]^+$, 413 (2), 361 (2), 293 (7), 279 (20), 264 (18), 188 (18), 174 (9), 159 (100) $[CF_3Bn]^+$, 139 (4), 118 (12), 104 (22), 91 (17). $C_{24}H_{22}F_6N_2$ (452.4): calcd. C 63.71, H 4.90, N 6.19; found C 63.50, H 4.80, N 6.10.

α,α′-Bis(4-trifluoromethylbenzylammonium)-*p*-xylene Bis(hexafluorophosphate) (4-H_2·2PF_6): A concentrated aqueous solution of HCl was added to a solution of **16** (0.30 g, 0.66 mmol) in MeOH (30 mL) until pH < 2 and then stirred for 1 h. The solvent was evaporated, affording a white powder, which was suspended in Me_2CO (30 mL), whereupon an aqueous solution of NH_4PF_6 (6.11 g, 37.5 mmol) was added dropwise until all the suspended material was dissolved. The solvent was removed in vacuo, and the product was isolated by filtration, washed with H_2O (20 mL), and air dried, providing **4**-H_2·2PF_6 as a fine-white powder in (0.49 g, quant.). The product can be recrystallized from Me_2CO/H_2O to afford **4**-H_2·2PF_6 as a white powder. M.p. >230 °C. ^{1}H NMR (400 MHz, CD_3CN): δ = 4.30 (s, 4 H, 2 NCH_2), 4.35 (s, 4 H, 2 NCH_2), 7.18 (br. s, 4 H, 2 NH_2^+), 7.55 (s, 4 H, 4 Ar-H), 7.67 (d, $^3J_{H,H}$ = 8 Hz, 4 H, 4 Ar-H), 7.80 (d, $^3J_{H,H}$ = 8 Hz, 4 H, 4 Ar-H) ppm. ^{13}C NMR (100 MHz, CD_3CN): δ = 52.0, 52.1, 125.1 (q, $^1J_{F,C}$ = 271 Hz, CF_3), 127.0 (q, $^3J_{F,C}$ = 4 Hz), 132.0, 132.1, 132.9 (q, $^2J_{F,C}$ = 32 Hz), 132.9, 135.6 ppm. MS (MALDI): *m*/*z* (%) = 599 (50) $[M - PF_6]^+$, 453 (45) $[M + H - 2PF_6]^+$, 295 (100), 159 $[CF_3Bn]^+$. $C_{24}H_{24}F_{18}N_2P_2$ (744.4): calcd. C 38.72, H 3.25, F 45.94, N 3.76; found C 38.60, H 3.21, F 45.82, N 3.82.

General Procedure for Preparation of Pseudorotaxanes for ^{1}H NMR Spectroscopic Studies: The crown ether DB24C8 and the investigated ammonium thread (10 mM) in question were mixed in the required molar ratio and dissolved in $CDCl_3/CD_3CN$ (3:1, 800 μL) or $CDCl_3/CD_3CN$ (1:1). Subsequently, a ^{1}H NMR spectrum was acquired at 298 K based on 64 scans.

Determination of Binding Constants (K_a Values) by using the ^{1}H NMR Single-Point Method: An equimolar amount of the ammonium thread in question and DB24C8 were dissolved in $CDCl_3/CD_3CN$ (1:1, 800 μL) to achieve a 10 mM solution (solution A). This solution was diluted to 1 mM by transferring an aliquot of solution A (80 μL) to a vial containing the solvent mixture (720 μL). Thereafter, a ^{1}H NMR spectrum (400 MHz, 298 K) was recorded. The integrals of the signals in the ^{1}H NMR spectrum associated with the benzylic CH_2N$^+$ protons in both uncomplexed and complexed species were determined. These integrals, together with the initial molar concentrations of the ammonium thread (≈1 mM) in question and DB24C8 (≈1 mM), were used to determine the K_a value according to Equation (1).

$$K_a = \frac{I_c}{I_u\left(c_{DB24C8} - \left(\frac{I_c}{I_u + I_c}\right)c_{Thread}\right)} \quad (1)$$

where I_c and I_u are the integrals of the benzylic CH_2N$^+$ protons (i.e., H^4) in the complexed (c) and uncomplexed (u) species, respectively and c_{DB24C8} and c_{Thread} are the initial molar concentrations of DB24C8 and the ammonium thread in question, respectively.

Single-Crystal X-ray Diffraction: X-ray analysis of **4**-H_2·2PF_6⊂$(DB24C8)_2$ was performed with a Bruker-Nonius X8-APEXII instrument at 180(2) K by using graphite-monochromated Mo-K_α radiation (λ = 0.7107 Å): $C_{24}H_{24}F_6N_2^{2+}$·2PF_6^-·$(C_{24}H_{32}O_8)_2$·2C_2H_3N, M_r = 1723.49, F(000) = 3592, colorless plate crystals, 0.25 × 0.25 × 0.05 mm, monoclinic, space group *C*2/*c*, Z = 4, a = 15.7109(7) Å, b = 16.1101(7) Å, c = 32.3046(14) Å, β = 93.084(2)°, V = 8164.6(6) Å^3, $D_{calcd.}$ = 1.402 g cm^{-3}, θ_{max} = 26.39°. Min/max transmission 0.84/0.99, μ = 0.161 mm^{-1}. From a total of 32559 reflections, 8315 were independent (merging R = 0.039) and were used to refine 512 parameters. 8 restraints were placed on the geometry of the acetonitrile solvent molecules. R_1 = 0.065 [4557 data with $I > 2\sigma(I)$], wR_2 = 0.216 (all data), GOF = 1.07. Max/min residual electron density –0.65/0.93 e Å^{-3}. CCDC-791631 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Acknowledgments

This work was funded in part by a Ph.D. Scholarship from the University of Southern Denmark to C. J. O. We also gratefully

acknowledge the Strategic Research Council in Denmark through the Programme for Nanoscience, Technology, Biotechnology, and IT (project no. 2106-07-0031 to J. O. J.), the Danish Natural Science Research Council (FNU, projects no. 272-08-0047 to K. A. N. and no. 272-08-0578 to J. O. J.), and the Danish Strategic Research Council in Denmark through the Young Researchers Programme (no. 2117-05-0115 to J. O. J.) for financial support.

[1] C. J. Pedersen, *J. Am. Chem. Soc.* **1967**, *89*, 7017–7036.

[2] a) G. Schill, *Catenanes, Rotaxanes and Knots*, Academic, New York, **1971**; b) P. R. Ashton, D. Philp, N. Spencer, J. F. Stoddart, *J. Chem. Soc., Chem. Commun.* **1991**, *23*, 1677–1679; c) P. R. Ashton, D. Philp, N. Spencer, J. F. Stoddart, *J. Chem. Soc., Chem. Commun.* **1991**, *23*, 1680–1683; d) P. L. Anelli, P. R. Ashton, R. Ballardini, V. Balzani, M. Delgado, M. T. Gandolfi, T. T. Goodnow, A. E. Kaifer, D. Philp, M. Pietraszkiewicz, L. Prodi, M. V. Reddington, A. M. Z. Slawin, N. Spencer, J. F. Stoddart, C. Vicent, D. J. Williams, *J. Am. Chem. Soc.* **1992**, *114*, 193–218; e) F. Voegtle, W. M. Mueller, U. Mueller, M. Bauer, K. Rissanen, *Angew. Chem. Int. Ed. Engl.* **1993**, *32*, 1295–1297; f) P. R. Ashton, R. Ballardini, V. Balzani, M. T. Gandolfi, D. J. F. Marquis, L. Perez-Garcia, L. Prodi, J. F. Stoddart, M. Venturi, *J. Chem. Soc., Chem. Commun.* **1994**, *2*, 177–180; g) D. B. Amabilino, P. R. Ashton, A. S. Reder, N. Spencer, J. F. Stoddart, *Angew. Chem. Int. Ed. Engl.* **1994**, *33*, 433–437; h) D. B. Ambilino, P. R. Ashton, C. L. Brown, E. Cordova, L. A. Godinez, T. T. Goodnow, A. E. Kaifer, S. P. Newton, M. Pietraszkiewicz, *J. Am. Chem. Soc.* **1995**, *117*, 1271–1293; i) M. Asakawa, P. R. Ashton, W. Dehaen, G. L′abbe, S. Menzer, J. Nouwen, F. M. Raymo, J. F. Stoddart, M. S. Tolley, *Chem. Eur. J.* **1997**, *3*, 788–798; j) R. Ballardini, V. Balzani, M. T. Gandolfi, R. E. Gillard, J. F. Stoddart, E. Tabellini, *Chem. Eur. J.* **1998**, *4*, 449–459; k) B. Cabezon, J. Cao, F. M. Raymo, J. F. Stoddart, A. J. P. White, D. J. Williams, *Angew. Chem. Int. Ed.* **2000**, *39*, 148–151; l) A. L. Hubbard, G. J. E. Davidson, R. H. Patel, J. A. Wisner, S. J. Loeb, *Chem. Commun.* **2004**, 138–139; m) R. L. Halterman, D. E. Martyn, X. Pan, D. B. Ha, M. Frow, K. Haessig, *Org. Lett.* **2006**, *8*, 2119–2121; n) R. L. Halterman, D. E. Martyn, *J. Org. Chem.* **2007**, *72*, 7841–7848; o) Y.-L. Zhao, L. Liu, W. Zhang, C.-H. Sue, Q. Li, O. S. Miljanic, O. M. Yaghi, J. F. Stoddart, *Chem. Eur. J.* **2009**, *15*, 13356–13380.

[3] a) P. R. Ashton, D. Philp, N. Spencer, J. F. Stoddart, *J. Chem. Soc., Chem. Commun.* **1992**, *16*, 1124–1128; b) Y. Shen, D. Xie, H. W. Gibson, *J. Am. Chem. Soc.* **1994**, *116*, 537–548; c) P. R. Ashton, P. J. Campbell, E. J. T. Chrystal, P. T. Glink, S. Menzer, D. Philp, N. Spencer, J. F. Stoddart, P. A. Tasker, D. J. Williams, *Angew. Chem. Int. Ed. Engl.* **1995**, *34*, 1865–1869; d) P. R. Ashton, P. J. Campbell, E. J. T. Chrystal, P. T. Glink, S. Menzer, D. Philp, N. Spencer, J. F. Stoddart, P. A. Tasker, D. J. Williams, *Angew. Chem. Int. Ed. Engl.* **1995**, *34*, 1869–1871; e) P. R. Ashton, P. T. Glink, J. F. Stoddart, P. A. Tasker, A. J. P. White, D. J. Williams, *Chem. Eur. J.* **1996**, *2*, 729–736; f) M. V. Martinez-Diaz, N. Spencer, J. F. Stoddart, *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 1904–1907; g) P. R. Ashton, I. Baxter, M. C. T. Fyfe, F. M. Raymo, N. Spencer, J. F. Stoddart, A. J. P. White, D. J. Williams, *J. Am. Chem. Soc.* **1998**, *120*, 2297–2307; h) F. M. Raymo, K. N. Houk, J. F. Stoddart, *J. Am. Chem. Soc.* **1998**, *120*, 9318–9322; i) P. R. Ashton, R. Ballardini, V. Balzani, I. Baxter, A. Credi, M. C. T. Fyfe, M. T. Gandolfi, M. Gómez-López, M. V. Martínez-Díaz, A. Piersanti, N. Spencer, J. F. Stoddart, M. Venturi, A. J. P. White, D. J. Williams, *J. Am. Chem. Soc.* **1998**, *120*, 11932–11942; j) C. Gong, H. W. Gibson, *Angew. Chem. Int. Ed.* **1998**, *37*, 310–314; k) S. J. Rowan, S. J. Cantrill, J. F. Stoddart, *Org. Lett.* **1999**, *1*, 129–132; l) T. Chang, A. M. Heiss, S. J. Cantrill, M. C. T. Fyfe, A. R. Pease, S. J. Rowan, J. F. Stoddart, D. J. Williams, *Org. Lett.* **2000**, *2*, 2943–2946; m) S. Chiu, S. J. Rowan, S. J. Cantrill, J. F. Stoddart, A. J. P. White, D. J. Williams, *Chem. Eur. J.* **2002**, *8*, 5170–5183; n) J. W. Jones, H. W. Gibson, *J. Am. Chem. Soc.* **2003**, *125*, 7001–7004; o) S. A. Vignon, T. Jarrosson, T. Iijima, H. Tseng, J. K. M. Sanders, J. F. Stoddart, *J. Am. Chem. Soc.* **2004**, *126*, 9884–9885; p) T. Iijima, S. A. Vignon, H. Tseng, T. Jarrosson, J. K. M. Sanders, F. Marchioni, M. Venturi, E. Apostoli, V. Balzani, J. F. Stoddart, *Chem. Eur. J.* **2004**, *10*, 6375–6392; q) J. D. Badjic, C. M. Ronconi, J. F. Stoddart, V. Balzani, S. Silvi, A. Credi, *J. Am. Chem. Soc.* **2006**, *128*, 1489–1499; r) A. R. Williams, B. H. Northrop, T. Chang, J. F. Stoddart, A. J. P. White, D. J. Williams, *Angew. Chem. Int. Ed.* **2006**, *45*, 6665–6669; s) S. Saha, A. H. Flood, J. F. Stoddart, S. Impellizzeri, S. Silvi, M. Venturi, A. Credi, *J. Am. Chem. Soc.* **2007**, *129*, 12159–12171; t) J. Wu, K. C.-F. Leung, D. Benitez, J.-Y. Han, S. J. Cantrill, L. Fang, J. F. Stoddart, *Angew. Chem. Int. Ed.* **2008**, *47*, 7470–7474; u) E. Lestini, K. Nikitin, H. Müller-Bunz, D. Fitzmaurice, *Chem. Eur. J.* **2008**, *14*, 1095–1106; v) W. Jiang, H. D. F. Winkler, C. A. Schalley, *J. Am. Chem. Soc.* **2008**, *130*, 13852–13853; w) K. M. Mullen, K. D. Johnstone, D. Nath, N. Bampos, J. K. M. Sanders, M. J. Gunter, *Org. Biomol. Chem.* **2009**, *7*, 293–303; x) W. Jiang, C. A. Schalley, *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 10425–10429; y) W. Jiang, A. Schäfer, P. C. Mohr, C. A. Schalley, *J. Am. Chem. Soc.* **2010**, *132*, 2309–2320.

[4] a) A. J. Moore, L. M. Goldenberg, M. R. Bryce, M. C. Petty, A. P. Monkman, C. Marenco, J. Yarwood, M. J. Joyce, S. N. Port, *Adv. Mater.* **1998**, *10*, 395–398; b) Y. Suzuki, T. Morozumi, H. Nakamura, M. Shimomura, T. Hayashita, R. A. Bartsh, *J. Phys. Chem. B* **1998**, *102*, 7919–7917; c) M. R. Bryce, *J. Mater. Chem.* **2000**, *10*, 589–598; d) M. R. Bryce, A. S. Batsanov, T. Finn, T. K. Hansen, A. J. Moore, J. A. K. Howard, M. Kamenjicki, I. K. Lednev, S. A. Asher, *Eur. J. Org. Chem.* **2001**, 933–940; e) J.-P. Desvergne, N. Lahrahar, M. Gotta, Y. Zimmermann, H. Bouas-Laurent, *J. Mater. Chem.* **2005**, *15*, 2873–2880; f) M. Licchelli, A. O. Biroli, A. Poggi, *Org. Lett.* **2006**, *8*, 915–918; g) D. Demeter, P. Blanchard, I. Grosu, J. Roncali, *J. Inclusion Phenom. Macrocyclic Chem.* **2008**, *61*, 227–239; h) D. Cavenet, M. Sallé, G. Zhang, D. Zhang, D. Zhu, *Chem. Commun.* **2009**, 2245–2269.

[5] a) Ref.[3]; b) ref.[3d]; c) A. G. Kolchinski, D. H. Busch, N. W. Alcock, *J. Chem. Soc., Chem. Commun.* **1995**, 1289–1291; d) P. R. Ashton, E. J. T. Chrystal, P. T. Glink, S. Menzer, C. Schiavo, N. Spencer, J. F. Stoddart, P. A. Tasker, A. J. P. White, D. J. Williams, *Chem. Eur. J.* **1996**, *2*, 709–728; e) P. T. Glink, C. Schiavo, J. F. Stoddart, D. J. Williams, *Chem. Commun.* **1996**, 1483–1490; f) P. R. Ashton, M. C. T. Fyfe, P. T. Glink, S. Menzer, J. F. Stoddart, A. J. P. White, D. J. Williams, *J. Am. Chem. Soc.* **1997**, *119*, 12514–12524.

[6] P. R. Ashton, M. C. T. Fyfe, S. K. Hickingbottom, J. F. Stoddart, A. J. P. White, D. J. Williams, *J. Chem. Soc. Perkin Trans. 2* **1998**, 2117–2128.

[7] S. J. Loeb, J. Tiburcio, S. J. Vella, *Org. Lett.* **2005**, *7*, 4923–4926.

[8] D. A. Fulton, S. J. Cantrill, J. F. Stoddart, *J. Org. Chem.* **2002**, *67*, 7968–7981.

[9] P. R. Ashton, J. Becher, M. C. T. Fyfe, M. B. Nielsen, J. F. Stoddart, A. J. P. White, D. J. Williams, *Tetrahedron* **2001**, *57*, 947–956.

[10] J. C. Adrian Jr., C. S. Wilcox, *J. Am. Chem. Soc.* **1991**, *113*, 678–680.

[11] The ^{1}H NMR single-point method has often been used to determine the binding constants between ammonium threads and crown ethers, see for example: Ref.[3,6,7] and P. R. Ashton, E. J. T. Chrystal, P. T. Glink, S. Menzer, C. Schiavo, N. Spencer, J. F. Stoddart, P. A. Tasker, A. J. P. White, D. J. Williams, *Chem. Eur. J.* **1996**, *2*, 709–728.

[12] A more detailed procedure for the use of the single-point ^{1}H NMR method, although on a different system, is described by M. B. Nielsen, J. O. Jeppesen, J. Lau, C. Lomholt, D. Damgaard, J. P. Jacobsen, J. Becher, J. F. Stoddart, *J. Org. Chem.* **2001**, *66*, 3559–3563.

[13] Estimated error on K_a: **3**-H·PF_6, ±10%; **1**-H·PF_6, ±20%.

[14] The solvent ratio between $CDCl_3$ and CD_3CN was changed from 3:1 to 1:1 on account of the low solubility of thread **4**-H_2·$2PF_6$ in a 3:1 mixture of $CDCl_3$ and CD_3CN.
[15] Careful examination of the 4.5–4.8 ppm region in the ^1H NMR spectrum shown in Figure 6a reveals that a small amount of [3]pseudorotaxane **4**-H_2·$2PF_6$⊂$(DB24C8)_2$ is present in the 5:1 mixture of **4**-H_2·$2PF_6$ and DB24C8.
[16] Estimated error on K_1 and K_2: **4**-H_2·$2PF_6$, ±15 and ±10%, respectively; **2**-H_2·$2PF_6$, ±10% for both.
[17] The X-ray crystal structure of **4**-H_2·$2PF_6$⊂$(DB24C8)_2$ is similar to that of earlier reported systems; see ref.[3e,3m]

Received: September 12, 2010
Published Online: December 17, 2010

