Tetrahedron 64 (2008) 8411–8416

Contents lists available at ScienceDirect

Tetrahedron

journal homepage: www.elsevier.com/locate/tet

An ammonium/bis-ammonium switchable molecular shuttle

David A. Leigh *, Andrew R. Thomson

School of Chemistry, University of Edinburgh, The King's Buildings, West Mains Road, Edinburgh EH9 3JJ, UK

ARTICLE INFO

Article history:
Received 1 April 2008
Received in revised form 22 May 2008
Accepted 30 May 2008
Available online 5 June 2008

ABSTRACT

A pH shuttle has been developed in which the mean position of the macrocycle can be switched between dialkylammonium stations of differing acidities. With only the most basic binding site protonated (dibenzylammonium), the macrocycle resides almost exclusively on the protonated station; when the second ammonium group (diethylammonium) is generated by further protonation, a mixture of translational diastereomers is observed in CD_2Cl_2 at 298 K, with the diethylammonium binding site preferred by the crown ether macrocycle in a ratio of ~2:1.

1. Introduction

Recent years have seen the synthesis of many different types of addressable rotaxane-based molecular shuttles that operate via a variety of stimuli.[1] A net change in the position of the ring on the thread has been achieved in structurally diverse molecular shuttles using inputs such as changes in configuration,[2] oxidation state,[3] covalent structure[4] and binding events.[5] One of the chemical stimuli most frequently exploited for this purpose is a change in the protonation level of the molecule.[3a,6] The dialkylammonium–crown ether recognition pair has been widely employed in the synthesis of interlocked molecules,[7] and naturally lends itself to the construction of protonation-controlled molecular shuttles.[6a–d,f–h] Previous examples of this type of shuttle have largely functioned by switching the position of a crown ether macrocycle between an amine/ammonium group and another pH-independent station derived from an *N*-alkylpyridinium moiety. Here we report on the synthesis of a molecular shuttle in which a crown ether macrocycle can be switched between two dialkylammonium binding sites of differing acidities.

While investigating possible designs, which would allow for the incorporation of ratchet mechanisms into synthetic molecular structures,[8] we became interested in the ammonium–crown ether rotaxane system[7] because of its compatibility[9] with sensitised stilbene isomerisation photochemistry. However, we were concerned with the possibility of competition with other photochemistry involving alkylpyridinium species and sought a less photoactive set of distinct and different binding sites for a series of multi-station molecular shuttles. The degree of inclusion of a dialkylammonium species within a [24]crown-8 type macrocycle is known to be strongly dependant on ability of the alkyl substituents to moderate the hydrogen-bond donating character of the ammonium group.[10] Early investigations showed that dibenzylammonium (DBA^+) species are bound more strongly than dibutylammonium groups within a dibenzo[24]crown-8 (DB24C8) macrocycle, partly as a consequence of additional favourable aromatic stacking interactions and a higher degree of preorganisation, but primarily because of the disparity in the ability of the two ammonium species to act as hydrogen bond donors. Similarly, DBA^+ species bearing electron donating substituents on their aromatic rings are less strongly bound than those bearing electron withdrawing substituents.[10d] The hydrogen-bond donating ability and Brönsted acidity of an ammonium species are closely linked as they are governed by similar electronic factors. On this basis, we decided to investigate whether the difference in hydrogen bond and Brönsted[11] acidity between a DBA^+ and a diethylammonium derived station could be exploited as the basis of a protonation-controlled molecular shuttle.

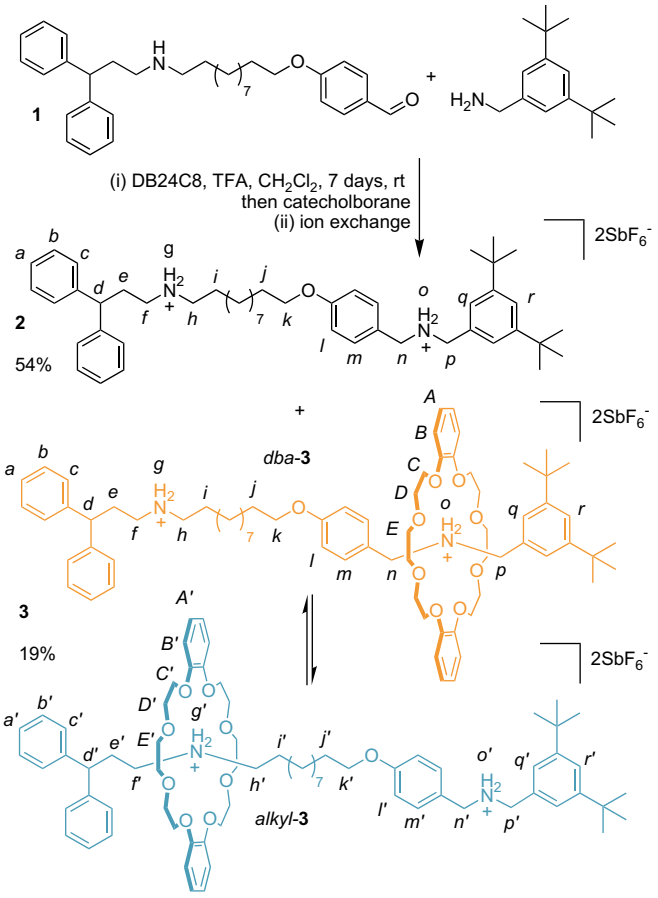
2. Results and discussion

Rotaxane **3** was selected as a target that incorporated all of the required structural features. A reductive amination reaction was chosen as the key synthetic step, allowing the introduction of one of the ammonium stations at the same time as forming the rotaxane (Scheme 1).[6c,12] Of the two possible disconnections presented by this approach, the one at the DBA^+ station allows the use of the aromatic aldehyde, which is stable and undergoes facile imine-forming reactions. The penalty for this approach is that the lower affinity diethylammonium station must be used as the template for the macrocycle.

The aldehyde-terminated half-stoppered thread **1** was prepared in four steps from commercially available materials (see Supplementary data). A solution of **1**, DB24C8, 3,5-di-*tert*-

* Corresponding author. Tel.: +44 131 650 4721; fax: +44 650 6453.
E-mail address: david.leigh@ed.ac.uk (D.A. Leigh).

0040-4020/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tet.2008.05.130



Scheme 1. Synthesis of **2**·$(HSbF_6)_2$ and **3**·$(HSbF_6)_2$.

butylbenzylamine and 2 equiv of trifluoroacetic acid in dichloromethane was stirred at room temperature for 1 week. At low pH values imine formation is slow,[13] but an excess of acid is necessary to maintain the ammonium template required for inclusion of the thread in the DB24C8 macrocycle.[14] After 1 week, the imine was reduced to the corresponding amine using catecholborane. Chromatographic purification of the final product proved problematic. It was eventually found that pretreating a silica preparative TLC plate with a solution of ammonium chloride prior to chromatography allowed the separation of the [2]rotaxane product from the non-interlocked thread (no [3]rotaxane was observed). Following chromatography, the [2]rotaxane was ion-exchanged to the SbF_6 salt to ensure uniformity, giving a pure sample of rotaxane **3**·$(HSbF_6)_2$ in a yield of 19%.

Comparison of the ^{1}H NMR spectrum of rotaxane **3**·$(HSbF_6)_2$ with its non-interlocked components (Fig. 1) confirms the interlocked nature of the product. Rotaxane **3**·$(HSbF_6)_2$ exists as two translational co-conformational isomers (co-conformers) that interconvert at a rate slower than the NMR timescale, and therefore appear as separate sets of signals. In the most abundant translational isomer (orange resonances in Fig. 1b), the signals for H_p and H_n are shifted downfield by approximately 0.25 ppm compared to those of the non-interlocked thread, an effect characteristic of the DBA^+ station being occupied by the DB24C8 macrocycle. This is further supported by the presence of aromatic shielding effects in the H_l, H_m, H_q and H_r resonances due to intercomponent aromatic stacking between the aromatic rings of the DBA^+ station and the macrocycle. The H_l and H_m resonances are shifted upfield by around 0.3 and 0.1 ppm, respectively, while the resonances for H_q and H_r are shifted upfield to a much smaller degree, presumably as a consequence of the steric interference of the flanking *tert*-butyl groups disfavouring aromatic stacking with the macrocycle. A slight upfield shift is exhibited by the macrocycle catechol protons H_A and H_B compared to the free macrocycle, again indicating the presence of aromatic stacking. The signals for the diethylammonium station of the major translational isomer (H_d, H_e, H_f and H_h) closely

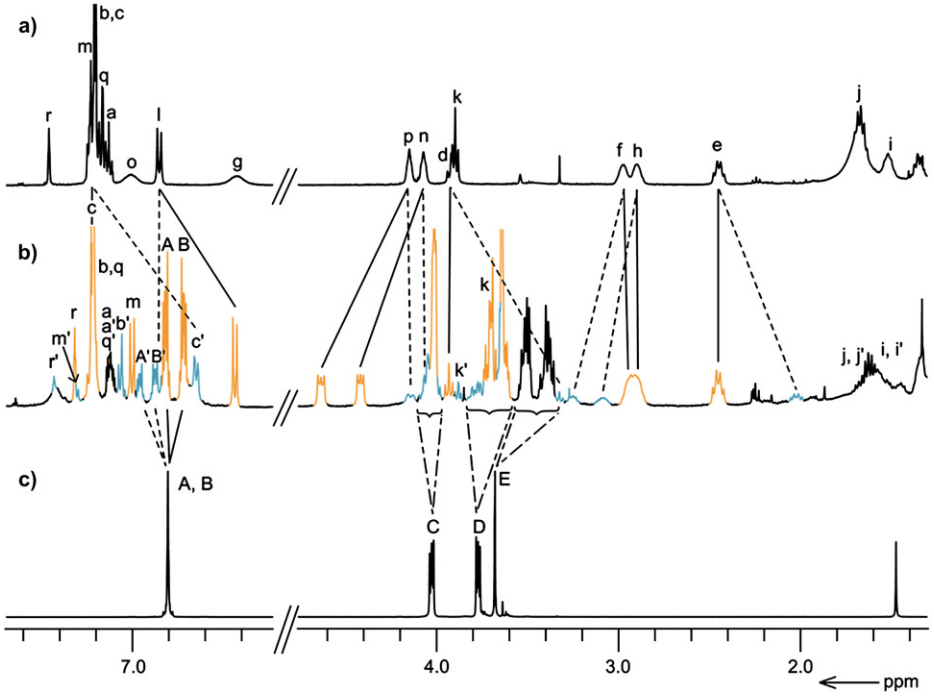


Figure 1. Partial ^{1}H NMR spectra (400 MHz, 298 K, CD_2Cl_2) of (a) **2**·$(HSbF_6)_2$, (b) **3**·$(HSbF_6)_2$ and (c) DB24C8. Peaks corresponding to the *dba*-co-conformer of **3**·$(HSbF_6)_2$ are coloured orange, and are compared with related signals in spectra (a) and (c) with solid lines. Signals arising from the *alkyl*-co-conformer are shown in blue, and are marked with dashed lines. Peaks arising from overlapping resonances of both co-conformers have not been colour coded. Signal assignments refer to the proton labels shown in Scheme 1.

resemble the corresponding resonances of the non-interlocked thread. The minor translational co-conformer of **3**·$(HSbF_6)_2$ (blue resonances in Fig. 1b) exhibits a downfield shift of approximately 0.1 ppm for the signals arising from the methylene units adjacent to the ammonium group of the diethylammonium station ($H_{f'}$ and $H_{h'}$), an effect that is again indicative of hydrogen bonding to the macrocycle. The $H_{A'}$ and $H_{B'}$ resonances of the macrocycle are shifted slightly downfield, indicating that the inductive effects of hydrogen bonding dominate over aromatic stacking interactions. Aromatic shielding effects are evident in the resonances close to the diethylammonium station, particularly those on the 'stopper side'. The $H_{c'}$, $H_{d'}$ and $H_{e'}$ resonances are shifted upfield by 0.3, 0.3 and 0.25 ppm, respectively. Less effect is evident in the $H_{i'}$ resonance, indicating that the macrocycle is held close to the phenyl groups of the stopper by aromatic stacking. The signals for the DBA^+ station ($H_{l'}$, $H_{m'}$, $H_{n'}$, $H_{p'}$, $H_{q'}$ and $H_{r'}$) of the minor isomer are nearly identical to those of the non-interlocked thread. In both translational isomers, the ethylene protons of the macrocycle (H_C, H_D, H_E, $H_{C'}$, $H_{D'}$ and $H_{E'}$) are diastereotopic due to the non-symmetrical nature of the thread, and result in complex and overlapping sets of signals.

These observations are consistent with rotaxane **3**·$(HSbF_6)_2$ existing as a mixture of translational isomers, the major one being that in which the DBA^+ station is occupied (*dba*-co-conformer in Scheme 1), and the minor one having the macrocycle over the diethylammonium station (*alkyl*-co-conformer in Scheme 1). The population distribution of approximately 2:1 in favour of the dibenzyl isomer reflects the differing hydrogen bond-donor strengths of the two ammonium groups. Interconversion of the isomers is slow compared to the NMR timescale due to the steric impediment presented by the benzyl group of the DBA^+ station.[10a] The stations in either translational isomer are effectively isolated from each other, i.e., the unoccupied stations are not perturbed by any folding or intermolecular association with the occupied ones, and therefore resemble the non-interlocked thread.

The rotaxane **3**·$(HSbF_6)_2$ was treated with an excess of a solid-supported tertiary amine base. This was found to result in the loss of only one of the two ammonium protons of the rotaxane, whereas the thread **2**·$(HSbF_6)_2$ was completely neutralised under identical conditions. The reduced acidity of **3**·$(HSbF_6)_2$ is a consequence of the additional stability afforded to the ammonium group by the encircling crown ether macrocycle.[15] The macrocycle is only able to 'protect' a single ammonium group from deprotonation, therefore treatment of **3**·$(HSbF_6)_2$ with base results in the mono-protonated rotaxane **3**·$HSbF_6$. A comparison of the ^{1}H NMR spectra of the rotaxanes **3**·$(HSbF_6)_2$ and **3**·$HSbF_6$ and the threads **2**·$(HSbF_6)_2$ and **2** illustrates the effect of changing the protonation level of the shuttle (Fig. 2).

The ^{1}H NMR spectrum of **3**·$HSbF_6$ (Fig. 2c) displays two sets of signals, each of which is similar to those of the two translational isomers of **3**·$(HSbF_6)_2$, indicating that counterparts of the *alkyl*- and *dba*-co-conformer are still present in the singly protonated rotaxane. In each set of signals the key resonances for the occupied stations of **3**·$(HSbF_6)_2$ are conserved, whereas the signals for the unoccupied stations in either case match those of the non-protonated thread **2**. For example, the *alkyl*-co-conformer of **3**·$HSbF_6$

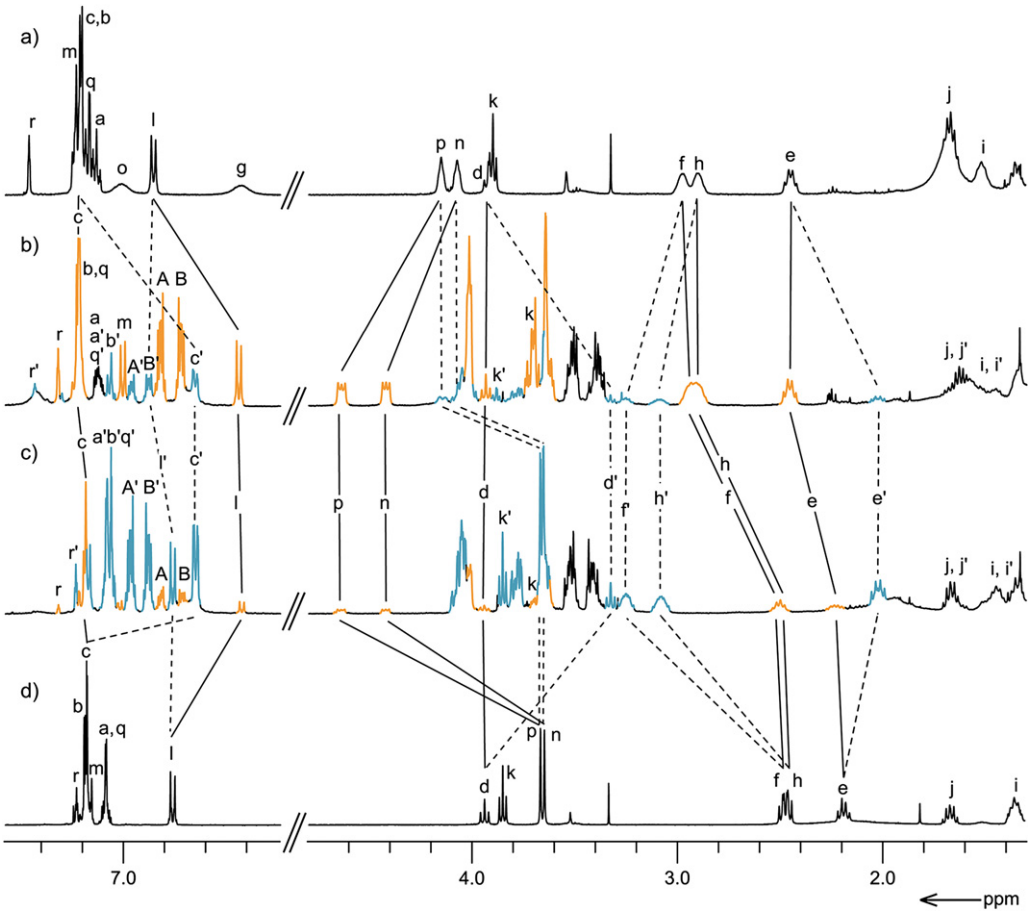
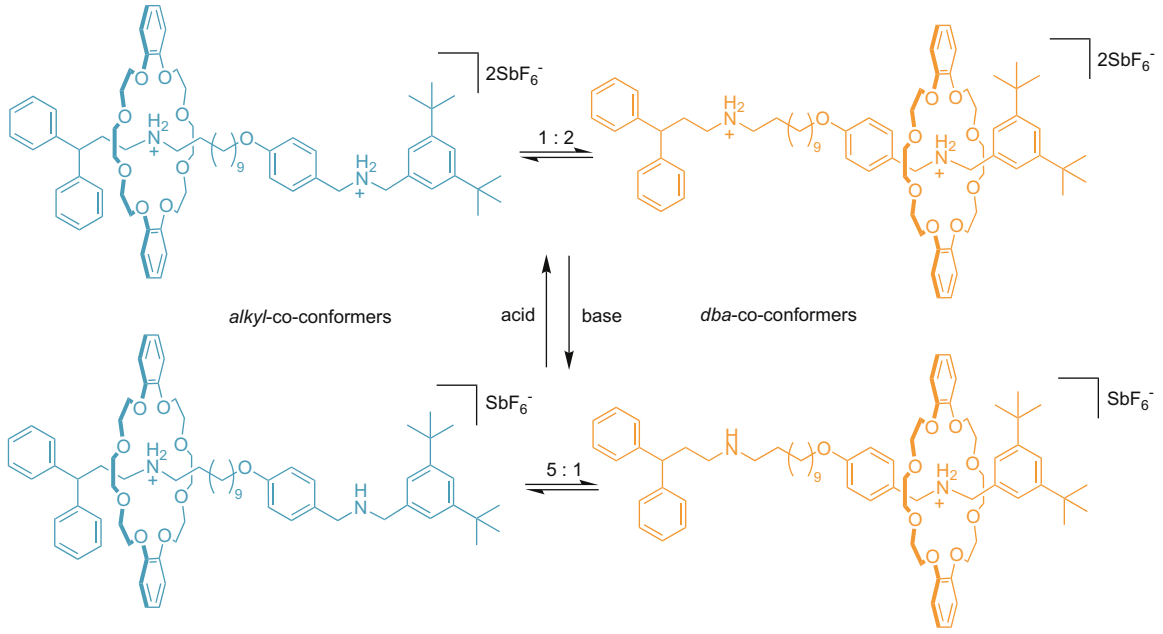


Figure 2. Partial ^{1}H NMR spectra (400 MHz, 298 K, CD_2Cl_2) of (a) **2**·$(HSbF_6)_2$, (b) **3**·$(HSbF_6)_2$, (c) **3**·$HSbF_6$ and (d) **2**. Peaks corresponding to the *dba*-co-conformer of **3**·$(HSbF_6)_2$ and **3**·$HSbF_6$ are coloured orange, and are compared with related signals in spectra (a) and (c) with solid lines. Signals arising from the *alkyl*-co-conformer are shown in blue, and are marked with dashed lines. Peaks arising from overlapping resonances of both translational isomers have not been colour coded.



Scheme 2. Macrocycle position in rotaxane **3** in its doubly (top) and singly (bottom) protonated forms.

has H_l, H_m, H_p, H_n, etc. resonances at near identical chemical shifts to those of **3**·$(HSbF_6)_2$, whereas the H_c, H_d, H_e, H_f, H_h, etc. resonances lie at similar chemical shifts as those of the corresponding protons of **2**. Similarly, the H_d, H_e, H_f and H_h resonances of the *alkyl*-co-conformer of **3**·$HSbF_6$ match those of **3**·$(HSbF_6)_2$, whereas the H_l, H_m, H_p, H_n, etc. resonances match those of **2**. Therefore in either translational isomer of **3**·$HSbF_6$ the macrocycle resides on a protonated station, leaving the other station neutral. No signals are observed for the protonation of an unoccupied station in **3**·$HSbF_6$, suggesting that the macrocycle and ammonium proton are for the most part closely associated with each other. It may be that shuttling predominantly occurs via a 'proton-ferry' type mechanism, in which the ammonium proton and macrocycle move in unison from station to station (Scheme 2).[15a]

The most abundant translational isomer in the rotaxane **3**·$HSbF_6$ is the *alkyl*-co-conformation, which is approximately five times more abundant than the *dba*-co-conformer. The determining factor in this case is the differing abilities of the two stations to compete for the single ammonium proton, and with it the macrocycle. That there is any significant competition from the dibenzyl station is perhaps surprising, considering that it is less basic by approximately 1.5 pKa units,[11] however, the protonated dibenzyl station binds the macrocycle more strongly than the alkyl one, a factor that presumably acts to offset the disparity between the two stations. Deprotonation of the shuttle from **3**·$(HSbF_6)_2$ to **3**·$HSbF_6$ therefore changes preferred co-conformation of the molecule from the *dba*- to the *alkyl*-translational isomer.

3. Conclusions

We have shown that the difference in acidity (hydrogen bond and Brönsted) of two stations differing only in the substituents about the same central $-CH_2NH_2^+CH_2-$ unit is sufficient to form the basis of a switchable molecular shuttle that operates by a change in protonation level. The positional discrimination exhibited by this system is rather modest, but there is scope to fine-tune the system by varying the substituents of each station. Nevertheless, the functional groups involved are rather less photo- and redox-sensitive than other switchable molecular shuttles and may be more suitable for elaboration into more complex nanoscale devices and machines.

4. Experimental section

4.1. General information

All reagents were purchased from Aldrich chemicals and used without further purification. Thin-layer chromatography was performed on precoated silica gel plates (Merck, Germany) and compounds were visualised under UV light. All ^1H and ^{13}C NMR spectra were recorded on a Bruker AV 400 instrument, at a constant temperature of 298 K. Melting points were determined using a Sanyo Gallenkamp apparatus and are uncorrected. Accurate mass data were obtained from the EPSRC National Mass Spectrometry Service Centre (Swansea, UK).

4.2. Thread 2 and rotaxane 3

A solution of **1** (120 mg, 0.2 mmol), di-*tert*-butylbenzylamine (48 mg 0.22 mmol) and dibenzo[24]crown-8 (180 mg, 0.4 mmol) and trifluoroacetic acid (0.44 mmol) in CH_2Cl_2 (5 ml) was stirred for 1 week at room temperature. After this time, a 1 M catecholborane solution in THF (1 mmol, 1 ml) was added dropwise and the mixture was stirred for 12 h at room temperature. The solution was then diluted with CH_2Cl_2 (50 ml) and washed with 1 M HCl (aq) (50 ml), saturated ammonium bicarbonate (aq) (50 ml) and then brine (50 ml). The organic phase was dried ($MgSO_4$) and the solvent removed under reduced pressure. The resultant mixture was purified by preparative thin-layer chromatography using silica plates pre-treated by dipping in a saturated solution of ammonium chloride in acetonitrile. The plates were developed using a 5% solution of MeOH in $CHCl_3$ as eluent to give **2** and **3**, which were treated with the following procedure to ensure uniformity of their counterions: purified **2** or **3** was dissolved in CH_2Cl_2 and acidified by dropwise addition of a 1 M solution of HCl in diethyl ether. The solvent was removed under reduced pressure and the resultant material was redissolved in CH_2Cl_2 and then agitated overnight over an excess of Dowex-22 chloride ion-exchange resin. The solvent was removed under reduced pressure and the residue was

redissolved in a 25% solution of MeOH in CH_2Cl_2 and then stirred overnight in the presence of excess solid $NaSbF_6$. The resultant suspension was filtered and the solvent removed under reduced pressure. The resultant solids were suspended in CH_2Cl_2 and filtered followed by evaporation of the solvent to yield **2**·$(HSbF_6)_2$ (125 mg, 54%) and **3**·$(HSbF_6)_2$ (61 mg, 19%) as colourless solids. Thread **2**·$(HSbF_6)_2$: ^{1}H NMR (400 MHz, CD_2Cl_2) δ=1.13–1.29 (m, 30H, 6×CH_2, 6×CH_3), 1.35 (m, 2H, CH_2), 1.52 (m, 2H, CH_2), 1.67 (m, 2H, CH_2), 2.45 (m, 2H, CH_2), 2.90 (br m, 2H, CH_2CH_2N), 2.97 (br m, 2H, CH_2CH_2N), 3.90 (t, 2H, J=6.5, CH_2O), 3.92 (t, 1H, J=7.9, Ph_2CHCH_2), 4.07 (br t, 2H, $ArCH_2N$), 4.15 (br t, 2H, $ArCH_2N$), 6.85 (d, 2H, J=8.5, ArH), 7.10–7.26 (m, 14H, ArH), 7.46 (s, 1H, ArH); ^{13}C NMR (100 MHz, CD_2Cl_2) δ=25.9, 26.38, 26.45, 28.97, 29.01, 29.1, 29.2, 29.3, 30.1, 31.4, 31.7, 35.3, 48.8, 49.0, 50.0, 51.5, 52.6, 68.5, 115.9, 121.2, 124.3, 124.9, 127.4, 127.8, 128.8, 129.4, 131.6, 143.1, 153.1, 161.0; HRMS (FAB) $C_{48}H_{68}N_2O$ calcd m/z [(M+H)$^+$]=689.5410, found 689.5412. Rotaxane **3**·$(HSbF_6)_2$: ^{1}H NMR (400 MHz, CD_2Cl_2) δ=1.01–1.38 (m, 32H+32H′, 6×CH_2, 6×CH_3, 6×CH'_2, 6×CH'_3), 1.30–1.71 (m, 4H+4H′, 2×CH_2, 2×CH'_2), 2.02 (m, 2H′, CH'_2), 2.45 (m, 2H, CH_2), 2.91 (br m, 4H, 2×CH_2), 3.08 (br m, 2H′, CH'_2), 3.25 (br m, 2H′, CH'_2), 3.32 (t, H′, J=7.6, Ph_2CH'), 3.33–3.44 (m, 4H+4H′, OCH_2+OCH'_2 diastereotopic signals), 3.46–3.56 (m, 4H+4H′, OCH_2+OCH'_2 diastereotopic ethylene signals), 3.57–3.83 (m, 10H+8H′, OCH_2+OCH'_2 diastereotopic ethylene signals OCH_2), 3.87 (t, 2H′, J=6.6, OCH'_2), 3.93 (t, 1H, J=8.0, Ph_2CH'), 3.96–4.19 (m, 8H+12H′, OCH_2+OCH'_2 diastereotopic ethylene signals 2×$ArCH'_2$), 4.41 (m, 2H, $ArCH_2$), 4.63 (m, 2H, $ArCH_2$), 6.43 (d, 2H, J=8.7, ArH), 6.64 (m, 4H′, ArH′), 6.71 (m, 4H, ArH), 6.82 (m, 4H, ArH), 6.85–6.90 (m, 6H′, ArH′), 6.96 (m, 4H′, ArH′), 7.00 (d, 2H, J=8.7, ArH), 7.03–7.15 (m, 2H+8H′, ArH+ArH′), 7.18–7.25 (m, 10H, ArH), 7.29–7.32 (m, H+2H′, ArH+ArH′), 7.43 (s, H′, ArH′); ^{13}C NMR (100 MHz, $CDCl_3$) (major translational isomer) δ=25.5, 26.1, 26.4, 28.4, 28.6, 28.8, 28.9, 29.2, 29.7, 30.2, 31.3, 34.8, 47.1, 48.2, 49.0, 52.4, 52.8, 67.9, 70.1, 70.5, 70.9, 112.6, 114.4, 121.7, 122.6, 123.6, 126.2, 127.2, 127.8, 128.5, 130.6, 131.3, 143.7, 147.3, 151.5, 159.7; $C_{72}H_{99}N_2O_9$ calcd m/z [(M+H)$^+$]=1137.7507, found 1137.7516.

4.3. Deprotonation of 2·$(HSbF_6)_2$ and 3·$(HSbF_6)_2$

In a disposable polypropylene reaction tube fitted with a frit and a tap, diethylaminopolystyrene resin (200 mg, 0.2 molar equiv) was swelled in CH_2Cl_2 and the excess solvent drained off. A solution of **2**·$(HSbF_6)_2$ or **3**·$(HSbF_6)_2$ (2 μmol) in CH_2Cl_2 (2 ml) was added and the mixture was agitated on an orbital shaker for 1 h. After this time, the reaction mixture was drained and the resin was washed with additional CH_2Cl_2 (3×2 ml), the mixture being agitated for 5 min during each wash. The solvent and washes were combined and evaporated to give **2**·$HSbF_6$ or **3** with >95% recovery of material.

Acknowledgements

This work was supported by the EPSRC. D.A.L. is an EPSRC Senior Research Fellow and holds a Royal Society-Wolfson Research Merit Award. We thank the EPSRC National Mass Spectrometry Service Centre (Swansea, UK) for accurate mass data.

Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.tet.2008.05.130.

References and notes

1. (a) Balzani, V.; Credi, A.; Raymo, F. M.; Stoddart, J. F. *Angew. Chem., Int. Ed* **2000**, *39*, 3349–3391; (b) Kay, E. R.; Leigh, D. A. *Top. Curr. Chem.* **2005**, *262*, 133–177; (c) Tian, H.; Wang, Q.-C. *Chem. Soc. Rev.* **2006**, *35*, 361–374; (d) Saha, S.; Stoddart, J. F. *Chem. Soc. Rev.* **2007**, *36*, 77–92; (e) Kay, E. R.; Leigh, D. A.; Zerbetto, F. *Angew. Chem., Int. Ed.* **2007**, *46*, 72–191.
2. (a) Murakami, H.; Kawabuchi, A.; Kotoo, K.; Kunitake, M.; Nakashima, N. *J. Am. Chem. Soc.* **1997**, *119*, 7605–7606; (b) Stanier, C. A.; Alderman, S. J.; Claridge, T. D. W.; Anderson, H. L. *Angew. Chem., Int. Ed.* **2002**, *41*, 1769–1772; (c) Altieri, A.; Bottari, G.; Dehez, F.; Leigh, D. A.; Wong, J. K. Y.; Zerbetto, F. *Angew. Chem., Int. Ed.* **2003**, *42*, 2296–2300; (d) Wang, Q.-C.; Qu, D.-H.; Ren, J.; Chen, K.; Tian, H. *Angew. Chem., Int. Ed.* **2004**, *43*, 2661–2665; (e) Pérez, E. M.; Dryden, D. T. F.; Leigh, D. A.; Teobaldi, G.; Zerbetto, F. *J. Am. Chem. Soc.* **2004**, *126*, 12210–12211; (f) Qu, D.-H.; Wang, Q.-C.; Tian, H. *Angew. Chem., Int. Ed.* **2005**, *44*, 5296–5299; (g) Murakami, H.; Kawabuchi, A.; Matsumoto, R.; Ido, T.; Nakashima, N. *J. Am. Chem. Soc.* **2005**, *127*, 15891–15899; (h) Berná, J.; Leigh, D. A.; Lubomska, M.; Mendoza, S. M.; Pérez, E. M.; Rudolf, P.; Teobaldi, G.; Zerbetto, F. *Nat. Mater.* **2005**, *4*, 704–710; (i) Chatterjee, M. N.; Kay, E. R.; Leigh, D. A. *J. Am. Chem. Soc.* **2006**, *128*, 4058–4073.
3. (a) Bissell, R. A.; Córdova, E.; Kaifer, A. E.; Stoddart, J. F. *Nature* **1994**, *369*, 133–136; (b) Collin, J.-P.; Gaviña, P.; Sauvage, J.-P. *New J. Chem.* **1997**, 525–528; (c) Ashton, P. R.; Ballardini, R.; Balzani, V.; Credi, A.; Dress, K. R.; Ishow, E.; Kleverlaan, C. J.; Kocian, O.; Preece, J. A.; Spencer, N.; Stoddart, J. F.; Venturi, M.; Wenger, S. *Chem.—Eur. J.* **2000**, *6*, 3558–3574; (d) Brouwer, A. M.; Frochot, C.; Gatti, F. G.; Leigh, D. A.; Mottier, L.; Paolucci, F.; Roffia, S.; Wurpel, G. W. H. *Science* **2001**, *291*, 2124–2128; (e) Altieri, A.; Gatti, F. G.; Kay, E. R.; Leigh, D. A.; Martel, D.; Paolucci, F.; Slawin, A. M. Z.; Wong, J. K. Y. *J. Am. Chem. Soc.* **2003**, *125*, 8644–8654; (f) Tseng, H.-R.; Vignon, S. A.; Stoddart, J. F. *Angew. Chem., Int. Ed* **2003**, *42*, 1491–1495; (g) Long, B.; Nikitin, K.; Fitzmaurice, D. *J. Am. Chem. Soc.* **2003**, *125*, 15490–15498; (h) Kihara, N.; Hashimoto, M.; Takata, T. *Org. Lett.* **2004**, *6*, 1693–1696; (i) Steuerman, D. W.; Tseng, H.-R.; Peters, A. J.; Flood, A. H.; Jeppesen, J. O.; Nielsen, K. A.; Stoddart, J. F.; Heath, J. R. *Angew. Chem., Int. Ed.* **2004**, *43*, 6486–6491; (j) Jeppesen, J. O.; Nygaard, S.; Vignon, S. A.; Stoddart, J. F. *Eur. J. Org. Chem.* **2005**, 196–220; (k) Cooke, G.; Garety, J. F.; Mabruk, S.; Rabani, G.; Rotello, V. M.; Surpateanu, G.; Woisel, P. *Tetrahedron Lett.* **2006**, *47*, 783–786; (l) Fioravanti, G.; Haraszkiewicz, N.; Kay, E. R.; Mendoza, S. M.; Bruno, C.; Marcaccio, M.; Wiering, P. G.; Paolucci, F.; Rudolf, P.; Brouwer, A. M.; Leigh, D. A. *J. Am. Chem. Soc.* **2008**, *130*, 2593–2601.
4. (a) Leigh, D. A.; Pérez, E. M. *Chem. Commun.* **2004**, 2262–2263; (b) Abraham, W.; Grubert, L.; Grummt, U. W.; Buck, K. *Chem.—Eur. J.* **2004**, *10*, 3562–3568.
5. (a) Armaroli, N.; Balzani, V.; Collin, J.-P.; Gaviña, P.; Sauvage, J.-P.; Ventura, B. *J. Am. Chem. Soc.* **1999**, *121*, 4397–4408; (b) Vignon, S. A.; Jarrosson, T.; Iijima, T.; Tseng, H.-R.; Sanders, J. K. M.; Stoddart, J. F. *J. Am. Chem. Soc.* **2004**, *126*, 9884–9885; (c) Iijima, T.; Vignon, S. A.; Tseng, H.-R.; Jarrosson, T.; Sanders, J. K. M.; Marchioni, F.; Venturi, M.; Apostoli, E.; Balzani, V.; Stoddart, J. F. *Chem.—Eur. J.* **2004**, *10*, 6375–6392; (d) Marlin, D. S.; González Cabrera, D.; Leigh, D. A.; Slawin, A. M. Z. *Angew. Chem., Int. Ed.* **2006**, *45*, 77–83; (e) Marlin, D. S.; González Cabrera, D.; Leigh, D. A.; Slawin, A. M. Z. *Angew. Chem., Int. Ed.* **2006**, *45*, 1385–1390; (f) Tokunaga, Y.; Nakamura, T.; Yoshioka, M.; Shimomura, Y. *Tetrahedron Lett.* **2006**, *47*, 5901–5904; (g) Goldup, S. M.; Leigh, D. A.; Lusby, P. J.; McBurney, R. T.; Slawin, A. M. Z. *Angew. Chem., Int. Ed.* **2008**, *47*, 3381–3384.
6. (a) Martínez-Díaz, M. V.; Spencer, N.; Stoddart, J. F. *Angew. Chem., Int. Ed.* **1997**, *36*, 1904–1907; (b) Ashton, P. R.; Ballardini, R.; Balzani, V.; Baxter, I.; Credi, A.; Fyfe, M. C. T.; Gandolfi, M. T.; Gomez-Lopez, M.; Martínez-Díaz, M. V.; Piersanti, A.; Spencer, N.; Stoddart, J. F.; Venturi, M.; White, A. J. P.; Williams, D. J. *J. Am. Chem. Soc.* **1998**, *120*, 11932–11942; (c) Elizarov, A. M.; Chiu, S.-H.; Stoddart, J. F. *J. Org. Chem.* **2002**, *67*, 9175–9181; (d) Badjić, J. D.; Balzani, V.; Credi, A.; Silvi, S.; Stoddart, J. F. *Science* **2004**, *303*, 1845–1849; (e) Keaveney, C. M.; Leigh, D. A. *Angew. Chem., Int. Ed.* **2004**, *43*, 1222–1224; (f) Badjić, J. D.; Ronconi, C. M.; Stoddart, J. F.; Balzani, V.; Silvi, S.; Credi, A. *J. Am. Chem. Soc.* **2006**, *128*, 1489–1499; (g) Clemente-León, M.; Credi, A.; Martínez-Díaz, M. V.; Mingotaud, C.; Stoddart, J. F. *Adv. Mater.* **2006**, *18*, 1291–1296; (h) Leigh, D. A.; Thomson, A. R. *Org. Lett.* **2006**, *8*, 5377–5379; (i) Crowley, J. D.; Leigh, D. A.; Lusby, P. J.; McBurney, R. T.; Perret-Aebi, L.-E.; Petzold, C.; Slawin, A. M. Z.; Symes, M. D. *J. Am. Chem. Soc.* **2007**, *129*, 15085–15090; (j) Berná, J.; Goldup, S. M.; Lee, A.-L.; Leigh, D. A.; Symes, M. D.; Teobaldi, G.; Zerbetto, F. *Angew. Chem., Int. Ed.* **2008**, *47*, 4392–4396.
7. (a) Kolchinski, A. G.; Busch, D. H.; Alcock, N. W. *J. Chem. Soc., Chem. Commun.* **1995**, 1289–1291; (b) Ashton, P. R.; Glink, P. T.; Stoddart, J. F.; Tasker, P. A.; White, A. J. P.; Williams, D. J. *Chem.—Eur. J.* **1996**, *2*, 729–735; (c) Kolchinski, A. G.; Alcock, N. W.; Roesner, R. A.; Busch, D. H. *Chem. Commun.* **1998**, 1437–1438; (d) Watanabe, N.; Yagi, T.; Kihara, N.; Takata, T. *Chem. Commun.* **2002**, 2720–2721; (e) Iwamoto, H.; Itoh, K.; Nagamiya, H.; Fukazawa, Y. *Tetrahedron Lett.* **2003**, *44*, 5773–5776; (f) Zhu, X.-Z.; Chen, C.-F. *J. Am. Chem. Soc.* **2005**, *127*, 13158–13159; (g) Aricó, F.; Chang, T.; Cantrill, S. J.; Khan, S. I.; Stoddart, J. F. *Chem.—Eur. J.* **2005**, *11*, 4655–4666; (h) Northrop, B. H.; Aricó, F.; Tangchiavang, N.; Badjić, J. D.; Stoddart, J. F. *Org. Lett.* **2006**, *8*, 3899–3902.
8. (a) Serreli, V.; Lee, C.-F.; Kay, E. R.; Leigh, D. A. *Nature* **2007**, *445*, 523–527; (b) Alvarez-Pérez, M.; Goldup, S. M.; Leigh, D. A.; Slawin, A. M. Z. *J. Am. Chem. Soc.* **2008**, *130*, 1836–1838.
9. Tokunaga, Y.; Akasaka, K.; Hisada, K.; Shimomura, Y.; Kakuchi, S. *Chem. Commun.* **2003**, 2250–2251.
10. (a) Ashton, P. R.; Campbell, P. J.; Chrystal, E. J. T.; Glink, P. T.; Menzer, S.; Philp, D.; Spencer, N.; Stoddart, J. F.; Tasker, P. A.; Williams, D. J. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 1865–1869; (b) Glink, P. T.; Schiavo, C.; Stoddart, J. F.; Williams, D. J. *Chem. Commun.* **1996**, 1483–1490; (c) Ashton, P. R.; Chrystal, E. T. J.; Glink, P. T.; Menzer, S.; Schiavo, C.; Spencer, N.; Stoddart, J. F.; Tasker, P. A.; White, A. J. P.; Williams, D. J. *Chem.—Eur. J.* **1996**, *2*, 709–728; (d) Ashton, P. R.; Fyfe, M. C. T.; Hickingbottom, S. K.; Stoddart, J. F.; White, A. J. P.; Williams, D. J. *J. Chem. Soc.,*

Perkin Trans. 2 **1998**, 2117–2128; (e) Clifford, T.; Abushamleh, A.; Busch, D. H. *Proc. Natl. Acad. Sci. U.S.A.* **2002**, *99*, 4830–4836.
11. Graton, J.; Berthelot, M.; Laurence, C. *J. Chem. Soc., Perkin Trans. 2* **2001**, 2130–2135.
12. (a) Cantrill, S. J.; Rowan, S. J.; Stoddart, J. F. *Org. Lett.* **1999**, *1*, 1363–1366; (b) Rowan, S. J.; Stoddart, J. F. *Org. Lett.* **1999**, *1*, 1913–1916.
13. Layer, R. W. *Chem. Rev.* **1963**, *63*, 489–510.
14. (a) Montalti, M.; Ballardini, R.; Prodi, L.; Balzani, V. *Chem. Commun.* **1996**, 2011–2012; (b) Ashton, P. R.; Ballardini, R.; Balzani, V.; Gómez-López, M.; Lawrence, S. E.; Martínez-Díaz, M. V.; Montalti, M.; Piersanti, A.; Prodi, L.; Stoddart, J. F.; Williams, D. J. *J. Am. Chem. Soc.* **1997**, *119*, 10641–10651.
15. (a) Cao, J.; Fyfe, M. C. T.; Stoddart, J. F.; Cousins, G. R. L.; Glink, P. T. *J. Org. Chem.* **2000**, *65*, 1937–1946; (b) Kihara, N.; Tachibana, Y.; Kawasaki, H.; Takata, T. *Chem. Lett.* **2000**, *29*, 506–507.