Rotaxane construction with a binaphthol-derived crown ether

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Secondary dialkylammonium ions thread through the cavity of (*RS*)-benzo-2,2′-binaphtho[26]crown-8 to create [2]pseudorotaxanes, one of which was stoppered to produce a [2]rotaxane—incorporating the chiral binaphthyl unit—that was characterised by NMR spectroscopy, mass spectrometry and X-ray crystallography.

There is currently a resurgence of interest in the employment of binaphthyl-containing macrocyclic hosts in supramolecular chemistry,[1] principally because of the potential for the chiral binaphthyl unit to associate diastereoselectively with racemic guest mixtures. However, the pioneering studies in this area took place more than a quarter of a century ago when, in 1973, Cram and his associates[2] described the synthesis of chiral binaphthyl-incorporating crown ethers, *e.g.* (*R*)-2,2′-binaphtho[20]crown-6 [(*R*)-BN20C6, Fig. 1], that exhibit enantiomeric recognition[3] of racemic *primary alkylammonium* ($R^1R^2CHNH_3^+$) ions, *e.g.* (*RS*)-α-methoxycarbonylbenzylammonium [(*RS*)-**1**$^+$], during the formation of face-to-face complexes. More recently, we discovered that crown ethers with suitably sized cavities, *e.g.* dibenzo[24]crown-8 (DB24C8), are pierced by *secondary dialkylammonium* ($R^1CH_2NH_2^+CH_2R^2$) ions, *e.g.* dibenzylammonium (**2**$^+$), producing[4] [2]pseudorotaxanes—and, ultimately, rotaxanes[5]—by means of, *inter alia*, hydrogen bonds. Here, we demonstrate that the expanded racemic binaphthol-derived crown ether (*RS*)-benzo-2,2′-binaphtho[26]crown-8 [(*RS*)-BBN26C8†] can be penetrated by $R^1CH_2NH_2^+CH_2R^2$ ions to produce (Fig. 1) [2]pseudorotaxanes.[6] This observation has resulted in the synthesis of a racemic binaphthyl-containing [2]rotaxane that has been characterised by NMR spectroscopy, mass spectrometry and X-ray crystallography.

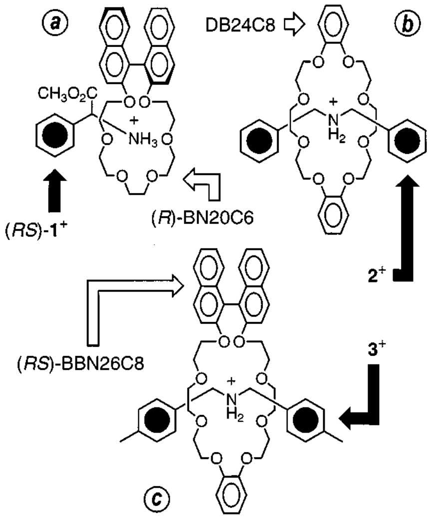
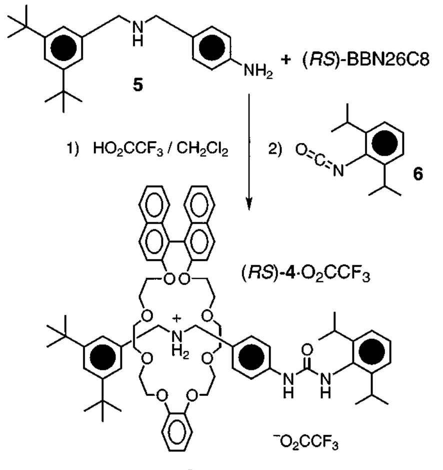


Fig. 1 Several complexes produced by the intermolecular association of crown ethers with ammonium ions. (*a*) Face-to-face complex [(*R*)-BN20C6·(*RS*)-**1**]$^+$. (*b*) [2]Pseudorotaxane [DB24C8·**2**]$^+$. (*c*) [2]Pseudorotaxane [(*RS*)-BBN26C8·**3**]$^+$.

The first indication that (*RS*)-BBN26C8 forms pseudorotaxane complexes with $R^1CH_2NH_2^+CH_2R^2$ ions was provided by FAB mass spectrometry. The FAB mass spectrum of a 1 : 1 CH_2Cl_2 solution of (*RS*)-BBN26C8 and bis(*p*-methylbenzyl)ammonium hexafluorophosphate[4a] (**3**·PF_6) reveals a strong supramolecular ion at *m/z* 851, corresponding to [(*RS*)-BBN26C8·**3**]$^+$. Complex formation was also indicated in solution by ^1H NMR spectroscopy. The ^1H NMR spectrum [400 MHz, $CDCl_3$–CD_3CN (3 : 1), 300 K] of an equimolar solution of (*RS*)-BBN26C8 and **3**·PF_6 shows that, like[4] [DB24C8·**2**]$^+$, the complex [(*RS*)-BBN26C8·**3**]$^+$ exchanges slowly with its uncomplexed constituents on the NMR timescale, signals being observed for (1) [(*RS*)-BBN26C8·**3**]$^+$ itself, (2) free (*RS*)-BBN26C8 and (3) uncomplexed **3**$^+$. In other words, even though the 26-membered macroring of (*RS*)-BBN26C8 is two atoms larger than that of DB24C8, the cavity is still small enough for the relatively bulky aryl rings of the cation to have some difficulty threading. The fact that so many different species are equilibrating slowly with one another on the NMR timescale, coupled with the crown ether's C_2 symmetry, means that the signals associated with the polyether/benzylic CH_2 and aromatic CH portions of the spectrum, located at δ 2.84–4.15 and 6.53–7.80, respectively, are extremely complicated. However, the signals for the CH_3 protons in both the free and complexed states of **3**$^+$ are well separated from one another, resonating at δ 2.23 and 2.13, respectively. From an analysis of the relative intensities of these signals, an association constant (K_a) of 960 ± 100 M^{-1} was calculated for [(*RS*)-BBN26C8·**3**][PF_6] by using the single-point method.[4] Noticeably, this K_a is much lower than that obtained for the [DB24C8·**3**][PF_6] complex (1900 ± 200 M^{-1}) under identical conditions, indicating that replacing one of DB24C8's catechol units with the less preorganised binaphthol residue lowers the complex stability.‡

Next, we investigated the application of the (*RS*)-BBN26C8–$R^1CH_2NH_2^+CH_2R^2$ recognition motif to rotaxane synthesis. Gratifyingly, the [2]rotaxane (*RS*)-**4**·O_2CCF_3 was isolated§ in 42% yield when (*RS*)-BBN26C8 was reacted (Scheme 1) with



Scheme 1

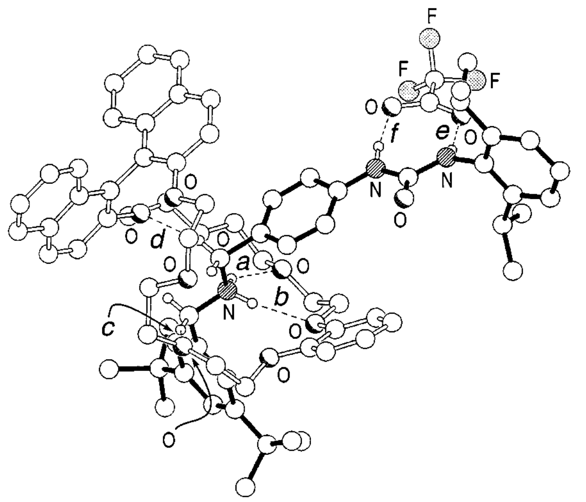


Fig. 2 X-Ray crystal structure of the (*R*)-enantiomer of [2]rotaxane (*RS*)-**4**·O_2CCF_3. Hydrogen bonding distances and angles {[X···O], [H···O] distances (Å), [X–H···O] angles (°)}: (*a*) 2.86, 2.12, 139; (*b*) 2.95, 2.08, 160; (*c*) 3.28, 2.39, 153; (*d*) 3.21, 2.29, 160; (*e*) 2.86, 2.00, 161; (*f*) 2.89, 2.00, 168.

p-aminobenzyl-*m*,*m*′-di-*tert*-butylbenzylamine (**5**), HO_2CCF_3 and *o*,*o*′-diisopropylphenyl isocyanate (**6**).[5] This interlocked compound is completely stable to column chromatography, indicating that the *m*,*m*′-di-*tert*-butylphenyl and *o*,*o*′-diisopropylphenyl termini of the rotaxane's 'dumbbell' component are sufficiently bulky to ensure that dissociation does not occur. Further evidence for the stability of the [2]rotaxane architecture is provided by the FAB mass spectrum of (*RS*)-**4**·O_2CCF_3, where the base peak, observed at *m/z* 1153, corresponds to the ion [(*RS*)-**4**]$^+$. Although the ^{1}H NMR spectrum (400 MHz, CD_3CN, 300 K) of (*RS*)-**4**·O_2CCF_3 displays numerous sets of complicated multiplets, a comparison of the integrals associated with resonances for both (*RS*)-BBN26C8 and the dumbbell component reveals that both species are present in a 1 : 1 ratio in the rotaxane. Interestingly, the peaks associated with the benzylic $CH_2NH_2^+$ protons do not lie in the 'expected' δ 4.45–4.75 range,[5] presumably as a direct consequence of the binaphthyl unit's shielding effect. In this instance, a ^{1}H–^{13}C HMQC experiment revealed that two sets of signals, ranging from δ 3.78–3.94 and 4.01–4.24, occur for these protons. The ^{13}C NMR spectrum (100 MHz, CD_3CN, 300 K) of (*RS*)-**4**·O_2CCF_3 is also intriguing and demonstrates that the crown ether is desymmetrised, *i.e.* the C_2 axis is negated, upon its incorporation into the [2]rotaxane architecture. The presence of the unsymmetrical dumbbell makes BBN26C8's two halves heterotopic and, hence, *all* of its 38 carbon atoms anisochronous. A total of 55 of the 60 ^{13}C NMR signals anticipated¶ for (*RS*)-**4**·O_2CCF_3 were observed in the spectrum (several of the heterotopic carbon atoms resonate at the same frequency).

The X-ray analysis|| of the rotaxane (*RS*)-**4**·O_2CCF_3 reveals (Fig. 2) that the binaphthol-derived crown ether BBN26C8 encircles the dumbbell's NH_2^+ centre. Stabilisation of the [2]rotaxane architecture occurs principally *via* a combination of [N^+–H···O] and [C–H···O] hydrogen bonding involving the NH_2^+ centre, its adjacent CH_2 groups and the crown ether's oxygen atoms. There is also a near-parallel (5°), partial overlap between one of the BBN26C8 naphthalene rings and the *p*-toluidinyl ring of the dumbbell (mean interplanar separation 3.6 Å), indicative of a supplementary weak π–π stacking interaction. The $^-O_2CCF_3$ anion hydrogen bonds to the two urea NH groups.[5] There are no inter-[2]rotaxane interactions of note.

To summarise, we have established that $R^1CH_2NH_2^+CH_2R^2$ ions penetrate the cavity of binaphthol-derived crown ether (*RS*)-BBN26C8, generating [2]pseudorotaxanes that may be capped to form [2]rotaxanes. The preparation of these pseudorotaxanes and rotaxanes, which incorporate the chiral binaphthyl unit, augurs well for future studies on (1) the concepts of supramolecular chirality,[7] (2) the preferential recognition[3] of a chiral $R^1CH_2NH_2^+CH_2R^2$ ion over its enantiomer by either (*R*)- or (*S*)-BBN26C8 in the production of diastereoisomeric pseudorotaxanes[8] and (3) the synthesis of optically active rotaxanes.[9]

Notes and references

† (*RS*)-BBN26C8 was acquired in 42% yield by reaction of (*RS*)-1,1′-bi-2-naphthol with *o*-bis(2-{2-[2-(*p*-tolylsulfonyloxy)ethoxy]ethoxy}ethoxy)benzene (which was prepared using a method similar to that employed to obtain the corresponding *p*-derivative: M. J. Gunter, D. C. R. Hockless, M. R. Johnston, B. W. Skelton and A. H. White, *J. Am. Chem. Soc.*, 1994, **116**, 4810) in MeCN in the presence of Cs_2CO_3 and CsOTs.

‡ By the same token, Cram's group discovered (D. S. Lingenfelter, R. C. Helgeson and D. J. Cram, *J. Org. Chem.*, 1981, **46**, 393) that the binaphthol-derived crown ether BN20C6 binds RNH_3^+ ions less well than its 2,3-dihydroxynaphthalene-derived congener.

§ It should be noted that **4**·O_2CCF_3 was obtained as a racemic mixture, the rotaxane's chirality arising only by virtue of the C_2-symmetric binaphthyl unit. Here, cycloenantiomerism (C. Yamamoto, Y. Okamoto, T. Schmidt, R. Jäger and F. Vögtle, *J. Am. Chem. Soc.*, 1997, **119**, 10 547), a phenomenon that would lead to the formation of two diastereoisomeric pairs of enantiomers, does not occur, because (*RS*)-BBN26C8 has two homotopic faces by virtue of its C_2 axis of rotation.

¶ Free (*RS*)-BBN26C8, dumbbell and anion give rise to 19, 20 and two signals, respectively, in their ^{13}C NMR spectra. Thus, the ^{13}C NMR spectrum of rotaxane (*RS*)-**4**·O_2CCF_3 would be expected to exhibit a total of 41 signals if no desymmetrisation were to occur.

|| X-Ray quality single crystals were obtained by vapour diffusion of *n*-C_5H_{12} into a CH_2Cl_2 solution of (*RS*)-**4**·O_2CCF_3. *Crystal data*: $[C_{73}H_{90}N_3O_9][O_2CCF_3]\cdot 2CH_2Cl_2$, M = 1436.4, monoclinic, $P2_1/n$ (no. 14), a = 13.281(3), b = 30.528(2), c = 21.593(2) Å, β = 96.80(1)°, V = 8694(2) Å^3, Z = 4, D_c = 1.097 g cm^{-3}, μ(Cu-Kα) = 17.2 cm^{-1}, $F(000)$ = 3040, T = 173 K; Siemens P4 rotating anode diffractometer, ω-scans, 12673 independent reflections; structure solved by direct methods, all major occupancy non-hydrogen atoms of cations and anions refined anisotropically (non-hydrogen atoms of solvent molecules isotropically) using full-matrix least-squares, based on F^2, to give R_1 = 0.138, wR_2 = 0.342 for 5299 independent observed reflections [$|F_o| > 4\sigma(|F_o|)$, $2\theta \leqslant 120°$] and 950 parameters. CCDC 182/1269.

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