Pergamon

Tetrahedron Letters 39 (1998) 5455–5458

TETRAHEDRON
LETTERS

A New Slippage Synthesis

**Peter R. Ashton,[a] Matthew C. T. Fyfe,[a] Cesare Schiavo,[a]
J. Fraser Stoddart,[a],* Andrew J. P. White[b] and David J. Williams[b]**

[a] School of Chemistry, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK.
[b] Department of Chemistry, Imperial College, South Kensington, London SW7 2AY, UK.

Received 15 April 1998; revised 11 May 1998; accepted 12 May 1998

Abstract: At elevated temperatures, the crown ether dibenzo[30]crown-10 (DB30C10) slips over the (relatively) bulky 3,5-(t-Bu)$_2$C$_6$H$_3$CH$_2$ termini of a bisammonium dication—bearing two secondary ammonium centers separated through a *p*-xylylene spacer—to form primarily a three-component rotaxane-like entity—stabilized by, *inter alia*, [N$^+$–H···O] and [C–H···O] hydrogen bonds—that has been characterized by liquid secondary ion (LSI) mass spectrometry (in the "gas phase"), ^{1}H NMR spectroscopy (in solution) and X-ray crystallography (in the solid state). However, this species equilibrates, in solution, with the free DB30C10 macrocycle and its two-component rotaxane-like congener, a result that demonstrates that the products obtained from the slippage synthesis are pseudorotaxanes.

Keywords: Crown Ethers; Pseudorotaxanes; Self-assembly; Supramolecular chemistry

The so-called pseudorotaxanes are attractive targets for the synthetic supramolecular chemist[1] since, in addition to being the precursors for their interlocked counterparts, the rotaxanes,[2] they form[3] the basis of several device-like systems. Recently, we have uncovered[4] novel routes to the noncovalent synthesis of pseudorotaxanes that involve (Figure 1) the self-assembly[5] of various crown ethers with bis(secondary dialkylammonium) ions by means of, amongst other interactions, [N$^+$–H···O] and [C–H···O] hydrogen bonds. For instance, the (comparatively) small macrocyclic polyether dibenzo[24]crown-8 (DB24C8) can only accommodate one dialkylammonium center (NH$_2^+$) within its cavity—it self-assembles with, for example, the dication $\mathbf{1}^{2+}$ to pro-

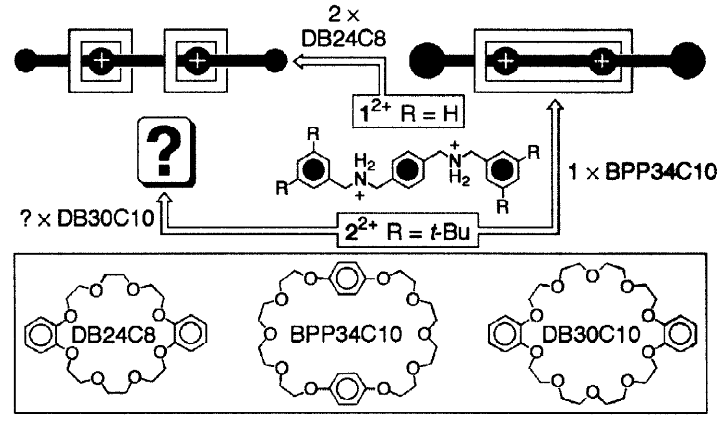

Figure 1. Different crown ethers, such as DB24C8 and BPP34C10, self-assemble with dications, bearing two NH$_2^+$ centers, to generate pseudorotaxanes with distinct stoichiometries. The question is—how does DB30C10 self-assemble with the dication 2^{2+}?

---

* Current address: Department of Chemistry and Biochemistry, University of California, Los Angeles, CA 90095, USA. Fax: +(310)206-1843. E-mail: stoddart@chem.ucla.edu.

0040-4039/98/$19.00 © 1998 Elsevier Science Ltd. All rights reserved.
PII: S0040-4039(98)01071-5

duce[4a–b] a doubly-encircled [3]pseudorotaxane. On the other hand, the larger crown ether bis-*p*-phenylene[34]crown-10 (BPP34C10) can support two NH_2^+ centers within its interior—this leads[4d] to the creation of doubly-docked [2]pseudorotaxanes upon self-assembly with suitable bis(NH_2^+)-containing dications, such as $\mathbf{2}^{2+}$. These findings persuaded us to study the complexation behavior associated with dibenzo[30]crown-10 (DB30C10)—*i.e.*, a crown ether of intermediate size—and the dication $\mathbf{2}^{2+}$. The question we asked ourselves was: would the polyether loops of individual DB30C10 macrocycles interact with only one NH_2^+ center of the dication $\mathbf{2}^{2+}$ to generate a [3]pseudorotaxane, like the $[(DB24C8)_2\cdot\mathbf{1}]^{2+}$ complex, or would they interact with two NH_2^+ centers to form a doubly-docked [2]pseudorotaxane, like the $[BPP34C10\cdot\mathbf{2}]^{2+}$ complex? Here, we report the results of research designed to answer this question.

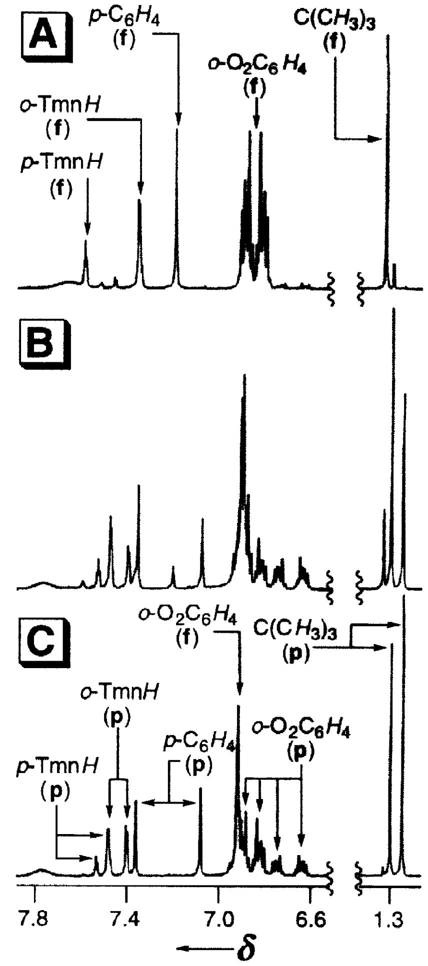

Figure 2. Partial ^1H NMR spectra (300.1 MHz, CD_2Cl_2, 20 °C) of a 3:1 mixture of DB30C10 and $\mathbf{2}\cdot 2PF_6$ recorded (A) shortly after dissolution, (B) following heating for 2 d, and (C) after 7 d heating. The peaks associated with the face-to-face and pseudorotaxane complexes are denoted by the descriptors (f) and (p), respectively. The signals labeled *o*- and *p*-Tmn*H* correspond to the protons of the 3,5-(t-Bu)$_2C_6H_3$ termini (Tmn) that are located *ortho* and *para* with respect to the $C–CH_2$ linkage.

The solubility of the salt $\mathbf{2}\cdot 2PF_6$ increases markedly in nonpolar organic solvents, such as CH_2Cl_2 or $CHCl_3$, in the presence of ≥1 molar equivalent of DB30C10, indicating[4] the formation of a complex in solution. The ^1H NMR spectrum of a 3:1 mixture of DB30C10 and $\mathbf{2}\cdot 2PF_6$ displays (Figure 2A) several sets of time-averaged resonances, which undergo moderate chemical shift alterations ($\Delta\delta$s), implying[4] that the complex is equilibrating rapidly with its free constituents on the NMR timescale. The largest $\Delta\delta$ value (–0.25 ppm) was noted for the protons of the dication's central *p*-C_6H_4 unit, an outcome that presumably indicates the formation of a complex with a face-to-face[4d] co-conformation, *i.e.*, a species in which the *p*-C_6H_4 unit is sandwiched by the macroring's catechol rings, with the ammonium centers interacting with the polyether oxygen atoms so as to coerce the 3,5-(t-Bu)$_2C_6H_3CH_2$ termini to protrude from the same face of the macrocycle. After this mixture had been heated under reflux for 2 d, the ^1H NMR spectrum exhibited (Figure 2B), in addition to each component's original resonances, two new sets of signals, with weaker intensities, that presumably arise as a result of the thermally-promoted slippage[6] of the DB30C10 macroring over the dication's bulky termini. No further spectral changes were noted following an additional 5 d of heating, after which, the resonances[7] associated with the free cation $\mathbf{2}^{2+}$ were (Figure 2C) barely observable. Essentially, the only peaks present in the spectrum have to be ascribed to the excess of the crown ether and the rotaxane-like complexes. The liquid secondary ion (LSI) mass spectrum of the reaction mixture corroborated the formation of these complexes—it displayed peaks at m/z = 1761, 1615 and 1078, which correspond to the species $[(DB30C10)_2 \cdot \mathbf{2} \cdot PF_6]^+$, $[(DB30C10)_2 \cdot \mathbf{2}]^{+\bullet}$ and $[DB30C10 \cdot \mathbf{2}]^{+\bullet}$, respectively. Purification of a preparative-scale reaction mixture by column chromatography (SiO_2: CH_2Cl_2–AcOEt–MeOH–AcOH (32:6:1:1)) furnished a mixture of the complexes $[DB30C10 \cdot \mathbf{2}][PF_6]_2$ and $[(DB30C10)_2 \cdot \mathbf{2}][PF_6]_2$ in a 1:5 ratio, as ascertained from a comparison of the relative intensities of each species' p-C_6H_4 protons[7] in the ^1H NMR spectrum. However, when the mixture was allowed to stand for 7 d, in CD_2Cl_2 at 20 °C, ^1H NMR spectroscopy showed that the concentrations of the uncomplexed DB30C10 macrocycle and $[DB30C10 \cdot \mathbf{2}][PF_6]_2$ complex (new $[DB30C10 \cdot \mathbf{2}][PF_6]_2/[(DB30C10)_2 \cdot \mathbf{2}][PF_6]_2$ ratio = 3:1) had increased substantially. Nevertheless, no *free* salt (or face-to-face complex) $\mathbf{2} \cdot 2PF_6$ was observed in this mixture, *i.e.*, the complex $[DB30C10 \cdot \mathbf{2}][PF_6]_2$ does not appear to dissociate, probably because it achieves optimal stabilization by way of the double-docking[4d] of the cation's NH_2^+ units within the crown ether's cavity. Obviously, however, the stopper units of the complex $[(DB30C10)_2 \cdot \mathbf{2}][PF_6]_2$ are not large enough to prevent the slow extrusion of the DB30C10 macroring under ambient conditions. Consequently, both complexes must be considered to be ***pseudorotaxanes*** that have a high degree of rotaxane-like character.[6e]

Single crystals of the complex $[(DB30C10)_2 \cdot \mathbf{2}][PF_6]_2$ were obtained from a n-C_6H_{14}–CH_2Cl_2 solution. The X-ray crystallographic analysis[8] of one of these crystals reveals (Figure 3) that the dication $\mathbf{2}^{2+}$ is threaded, in a C_i-symmetric manner, through the cavities of two DB30C10 macrorings to generate a [3]pseudorotaxane that is stabilized principally *via* a combination of $[N^+–H \cdots O]$ and $[C–H \cdots O]$ hydrogen bonds. Supplementary stabilization of this supermolecule is achieved through (1) π–π stacking interactions, involving the sandwiching of the central p-C_6H_4 unit between the C_i-related catechol rings of the two DB30C10 macrocycles (the centroid–centroid distance is 3.87 Å, the rings being inclined by *ca.* 13°), and (2) $[C–H \cdots \pi]$ interactions between two diametrically-opposite phenoxymethylene C–H moieties and each of the dication's 3,5-(t-Bu)$_2C_6H_3CH_2$ termini (vectors **d** and **e**, between the hydrogen atoms and the ring center, are inclined by 90 and 78° to the benzyl ring plane, respectively, and by 172° to

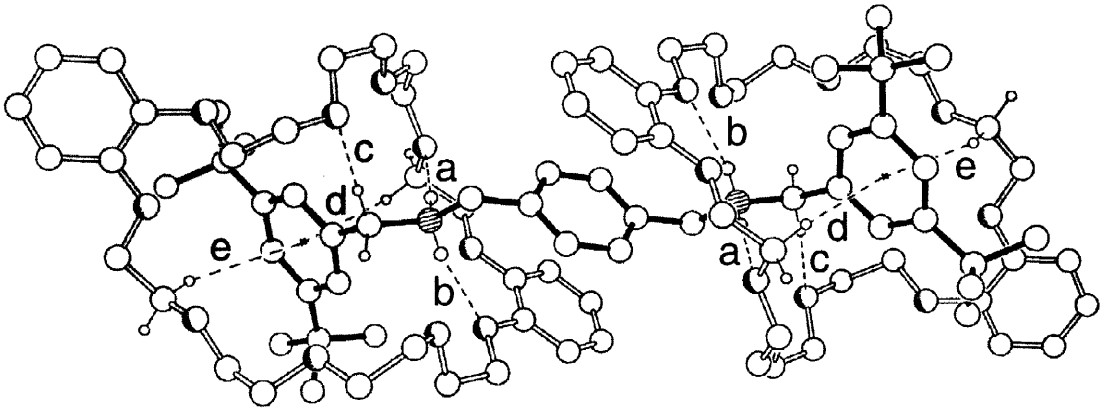

Figure 3. View of the crystal structure of the C_i-symmetric [3]pseudorotaxane $[(DB30C10)_2 \cdot 2]^{2+}$, illustrating the intracomplex noncovalent bonding interactions that serve to facilitate its self-assembly. $[X–H \cdots O]$ Hydrogen bonding geometries {$[X \cdots O]$, $[H \cdots O]$ distances (Å), $[X–H \cdots O]$ angles (°)}: (a) 2.85, 1.95, 172; (b) 3.15, 2.26, 178; (c) 3.37, 2.44, 163. Geometries for the $[C–H \cdots \pi]$ interactions {$[H \cdots \pi]$ distances (Å), $[C–H \cdots \pi]$ angles (°)}: (d) 2.73, 152; (e) 3.08, 158. The $[N^+ \cdots N^+]$ distance is 7.38 Å.

each other). An inspection of the pseudorotaxane's packing does not reveal any significant intercomplex interactions.

In summary, we have broadened our research effort pertaining to the association of crown ethers with NH_2^+-containing cations and have demonstrated, for the first time, that DB30C10 also self-assembles with these cations to generate pseudorotaxane complexes. Moreover, we have found that the 3,5-$(t\text{-Bu})_2C_6H_3CH_2$ unit acts as a stopper that permits the slippage synthesis of rotaxane-like entities with this crown ether. Nonetheless, this unit is not sufficiently bulky to permit the extrusion of one DB30C10 macroring from the $[(\text{DB30C10})_2\cdot\mathbf{2}][PF_6]_2$ complex, its two-component congener apparently being stabilized to a greater extent as a result of the highly cooperative nature of the hydrogen bonding interactions between both NH_2^+ centers and the crown ether's polyether arcs.

Acknowledgments: This research was funded in the UK by the ZENECA Strategic Research Fund and the Engineering and Physical Sciences Research Council.

---

[1] Fyfe, M. C. T.; Stoddart, J. F. *Acc. Chem. Res.* **1997**, *30*, 393–401.

[2] (a) Chambron, J. C.; Dietrich-Buchecker, C. O.; Sauvage, J.-P. *Top. Curr. Chem.* **1993**, *165*, 131–162. (b) Amabilino, D. A.; Stoddart, J. F. *Chem. Rev.* **1995**, *95*, 2725–2828. (c) Gibson, H. W. In *Large Ring Molecules*; Semlyen, J. A., Ed.; Wiley: Chichester, **1996**; pp 191–262. (d) Jäger, R.; Vögtle, F. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 930–944.

[3] Balzani, V.; Gómez-López, M.; Stoddart, J. F. *Acc. Chem. Res.* In press.

[4] (a) Ashton, P. R.; Chrystal, E. J. T.; 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. (b) Glink, P. T.; Schiavo, C.; Stoddart, J. F.; Williams, D. J. *Chem. Commun.* **1996**, 1483–1490. (c) Ashton, P. R.; Fyfe, M. C. T.; Glink, P. T.; Menzer, S.; Stoddart, J. F.; White, A. J. P.; Williams, D. J. *J. Am. Chem. Soc.* **1997**, *119*, 12514–12524. (d) Ashton, P. R.; Fyfe, M. C. T.; Martínez-Díaz, M.-V.; Menzer, S.; Schiavo, C.; Stoddart, J. F.; White A. J. P.; Williams, D. J. *Chem. Eur. J.* In press.

[5] (a) Whitesides, G. M.; Simanek, E. E.; Mathias, J. P.; Seto, C. T.; Chin, D. N.; Mammen, M.; Gordon, D. M. *Acc. Chem. Res.* **1995**, *28*, 37–44. (b) Lawrence, D. S.; Jiang, T.; Levett, M. *Chem. Rev.* **1995**, *95*, 2229–2260. (c) Philp, D.; Stoddart, J. F. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 1154–1196. (d) Conn, M. M.; Rebek, J., Jr. *Chem. Rev.* **1997**, *97*, 1647–1668. (e) Linton, B.; Hamilton, A. D. *Chem. Rev.* **1997**, *97*, 1669–1680. (f) Gillard, R. E.; Raymo, F. M.; Stoddart, J. F. *Chem. Eur. J.* **1997**, *3*, 1933–1940.

[6] (a) Ashton, P. R.; Ballardini, R.; Balzani, V.; Belohradsky, M.; Gandolfi, M. T.; Philp, D.; Prodi, L.; Raymo, F. M.; Reddington, M. V.; Spencer, N.; Stoddart, J. F.; Venturi, M.; Williams, D. J. *J. Am. Chem. Soc.* **1996**, *118*, 4931–4951. (b) Macartney, D. H. *J. Chem. Soc., Perkin Trans. 2* **1996**, 2775–2778. (c) Asakawa, M.; Ashton, P. R.; Ballardini, R.; Balzani, V.; Belohradsky, M.; Gandolfi, M. T.; Kocian, O.; Prodi, L.; Raymo, F. M.; Stoddart, J. F.; Venturi, M. *J. Am. Chem. Soc.* **1997**, *119*, 302–310. (d) Händel, M.; Plevoets, M.; Gestermann, S.; Vögtle, F. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 1199–1201. (e) Ashton, P. R.; Baxter, I.; Fyfe, M. C. T.; Raymo, F. M.; Spencer, N.; Stoddart, J. F.; White, A. J. P.; Williams, D. J. *J. Am. Chem. Soc.* **1998**, *120*, 2297–2307.

[7] δ Values for the *p*-Tmn*H*, *o*-Tmn*H*, $p\text{-}C_6H_4$ and $C(CH_3)_3$ protons in the complexes: face-to-face—7.57, 7.38, 7.18 and 1.35; $[\text{DB30C10}\cdot\mathbf{2}][PF_6]_2$—7.52, 7.46, 7.34 and 1.30; $[(\text{DB30C10})_2\cdot\mathbf{2}][PF_6]_2$—7.47, 7.40, 7.08 and 1.24.

[8] Crystal data for $[(\text{DB30C10})_2\cdot\mathbf{2}][PF_6]_2$: $C_{94}H_{138}N_2O_{20}\cdot 2PF_6$, M = 1906, monoclinic, a = 19.122(8), b = 12.345(9), c = 22.273(8) Å, β = 110.03(3)°, V = 4940(5) Å^3, space group $P2_1/n$, Z = 2 (the complex has crystallographic C_i symmetry), D_c = 1.281 g cm^{-3}, μ(Cu-Kα) = 11.62 cm^{-1}, $F(000)$ = 2028. 6208 Independent reflections ($2\theta < 110°$) for a crystal of dimensions 0.26 × 0.50 × 0.60 mm were measured on a Siemens P4 diffractometer with Cu-Kα radiation (graphite monochromated) using ω-scans. Of these, 4020 had $|F_o| > 4\sigma(|F_o|)$ and were considered to be observed. The data were corrected for Lorentz and polarization effects, but not for absorption. The structure was solved by direct methods and the non-hydrogen atoms were refined anisotropically. The PF_6^- anions both exhibited high anisotropic thermal motion/disorder, but this could not be resolved into alternate partial occupancy orientations. The positions of the hydrogen atoms were determined from a ΔF map, idealized, assigned isotropic thermal parameters, $U(H) = 1.2U_{eq}(C)$, $[U(H) = 1.5U_{eq}(C\text{–Me})]$ and allowed to ride on their parent atoms. Refinement was by full-matrix least squares based on F^2 to give R_1 = 0.0719 and wR_2 = 0.1906. The maximum and minimum residual electron densities in the final ΔF map were 0.51 and –0.33 eA^{-3}, respectively.