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Crystal Structures of 30-Crown-10 and Its Tetrahydrate

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Detailed characterization of 30-crown-10 (30C10) with NMR spectroscopy, TGA, DSC, and X-ray crystallography is reported. The anhydrous 30C10 crystal is orthorhombic, belonging to space group *Pbca*: $a = 8.606(1)$ Å, $b = 8.260(1)$ Å, and $c = 33.310(4)$ Å. The 30C10·$4H_2O$ crystal is monoclinic, belonging to the space group $P2_1/c$ and having unit-cell parameters of $a = 8.332(4)$ Å, $b = 9.083(2)$ Å, $c = 18.665(5)$ Å, and $b = 90.24(3)°$. The four water molecules located in the cavity are bound to each other and to the crown ether but not to water or crown ether molecules of neighboring units. The stacking of the 30C10 molecules forms channels through the crystal lattice. In 30C10·$4H_2O$ the water molecules occupy the channels formed by the stacking of the crown ether molecules. This study is the first X-ray diffraction study of a simple aliphatic crown ether larger than 18-crown-6 and also the first such study of a tetrahydrate complex of any crown ether in the absence of other guest species.

Introduction

Since the inception, design, and first synthesis of dibenzo-18-crown-6,18-crown-6, and other crown ether macrocycles[1–4] there has been a tremendous growth in the research activities pertaining to synthesis of macrocyclic molecules analogous to the crown ethers. The interest in such macrocycles is derived from the knowledge that such compounds show selectivity in complexing with a variety of neutral and ionic substrates. Modifications of crown ether structural parameters such as size of the cavity, number of ether oxygen atoms, length of aliphatic chains connecting ether oxygens, aromatic groups in the structure, and substitution of oxygen by heteroatoms such as N or S as a part of aliphatic or aromatic units[5] have been reported. The selectivity of the complexation is dependent on the above-mentioned parameters as well as other chemical interactions that may be present,[6] thus giving new directions to the subject of molecular recognition. Other variations in structures of such macrocyclic molecules include three-sided enclosed cavities (cryptands).[5,6]

Of the neutral molecules that complex with crown ethers and related macrocycles water is the most ubiquitous. And while a number of spectroscopic studies have shown that simple aliphatic crown ethers such as 18-crown-6 complex with water in solution,[7] confirmation by X-ray crystallography has been elusive. Cocomplexation of crown ethers by water along with other polar inorganic[8] or polar or ionic organic[9] species has been observed by X-ray diffraction. The presence of ionizable centers such as aliphatic[10] or aromatic[11] amine groups (aza crowns), phenolic hydroxyls,[12] or carboxylic[13] or sulfonic acid[13b,14] moieties has provided water complexes amenable to X-ray characterization. A dibenzo crown ether bearing an alcohol moiety also formed a hydrated crystal.[15]

It is common in the cases noted above for one water molecule to be included in the crystal structure. Occasionally, two water molecules are included,[9c,d,11a,d,14] but as far as we know there is only one case of inclusion of three waters[14] and two cases of inclusion of four water molecules.[10c,13c] In all of these cases, however, one or more of the water molecules is/are hydrogen bonded to atoms other than ether oxygens, i.e., phenolic hydroxyls, basic nitrogens, carboxy or sulfoxy groups, and are not confined to the cavity of the crown ether. To our knowledge the

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(1) Pedersen, C. J. *J. Am. Chem. Soc.* **1967**, *89*, 2495.

(2) Pedersen, C. J. *J. Am. Chem. Soc.* **1967**, *89*, 7017.

(3) Pedersen, C. J. *J. Am. Chem. Soc.* **1970**, *92*, 391.

(4) Pedersen, C. J. *Org. Synth.*, **1972**, *52*, 66.

(5) *Crown Ethers and Analogues*; Patai, S., Rappoport, Z., Eds.; John Wiley & Sons: New York, 1989; *Macrocyclic Chemistry*; Dietrich, B., Viout, P., Lehn, J. M., Eds.; VCH Publishers: New York, 1993.

(6) Franke, J.; Vogtle, F. *Top Curr. Chem.*, **1986**, *132*, 135. Diederich, F. *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 362; *Cation Binding by Macrocycles*; Inoue, Y. I., Gokel, G. W., Eds.; John Wiley & Sons: New York, 1990. Izatt, R. M.; Bradshaw, J. S.; Pawlak, K.; Bruening, R. L.; Tarbet, B. J. *Chem. Rev.* **1992**, *92*, 1261.

(7) (a) Golovkova, L. L.; Telyatnik, A. I.; Bidzilya, V. A. *Theor. Exp. Chem.* (*Engl. Trans.*) **1984**, *20*, 219. (b) Fukushima, K.; Ito, M.; Sakurada, K.; Shiraishi, S. *Chem. Lett.* **1988**, 323. (c) Bryan, S. A.; Willis, R. R.; Moyer, B. A. *J. Phys. Chem.* **1990**, *94*, 5230.

(8) (a) Elbasyouny, A.; Brügge, H. J.; von Deuten, K.; Dickel, M.; Knöchel, A.; Koch, K. U.; Kopf, J.; Melzer, D.; Rudolph, G. *J. Am. Chem. Soc.* **1983**, *105*, 6568. (b) Cusack, P. A.; Patel, B. N.; Smith, P. J.; Allen, D. W.; Nowell, I. W. *J. Chem. Soc., Dalton Trans.* **1984**, 1239. (c) Korber N.; Jansen, M. *J. Chem. Soc., Chem. Commun.* **1990**, 1654.

(9) (a) Hughes, D. L.; Wingfield, J. N. *J. Chem. Soc., Chem. Commun.*, **1977**, 317. (b) Metcalfe, J. C.; Stoddart, J. F.; Jones, G.; Crawshaw, T. H.; Gavuzzo, E.; Williams, D. J. *J. Chem. Soc., Chem. Commun.* **1981**, 432. (c) Grossie, D. A.; Watson, W. H.; Vögtle, F.; Müller, W. M. *Acta Crystallogr.* **1982**, *B38*, 3157. (d) Caira, M. R.; Watson, W. H.; Vögtle, F.; Müller, W. *Acta Crystallogr.*, **1984**, *C40*, 491.

(10) (a) Gokel, G. W.; Garcia, B. J. *Tetrahedron Lett.*, **1977**, *18*, 317. (b) Watson, W. H.; Galloy, J.; Grossie, D. A.; Vögtle, F.; Müller, W. M. *J. Am. Chem. Soc.* **1984**, *106*, 347. (c) Arnold, K. A.; Visariello, A. M.; Kim, M.; Gandour, R. D.; Fronczek, F. R.; Gokel, G. W. *Tetrahedron Lett.* **1988**, *29*, 3025.

(11) (a) Newkome, G. R.; Fronczek, F. R.; Kohli, D. K. *Acta Crystallogr.*, **1981**, *B37*, 2114. (b) Newkome, G. R.; Taylor, H. C. R.; Fronczek, F. R.; Delord, T. J.; Kohli, D. K. *J. Am. Chem. Soc.* **1981**, *103*, 7376. (c) Bradshaw, J. S.; Chamberlin, D. A.; Harrison, P. E.; Wilson, B. E.; Arena, G.; Dalley, N. K.; Lamb, J. D.; Izatt, R. M. *J. Org. Chem.* **1985**, *50*, 3065. (d) Grootenhuis, P. D. J.; Uiterwijk, J. W. H. M.; Reinhoudt, D. N.; van Staveren, C. J.; Sudholter, E. J. R.; Bos, M.; vanEerden, J.; Klooster, W. T.; Kruise, L.; Harkema, S. *J. Am. Chem. Soc.* **1986**, *108*, 780.

(12) Goldberg, I. *Acta Crystallogr.*, **1978**, *B34*, 3387.

(13) (a) Newcomb, M.; Moore, S. S.; Cram, D. J. *J. Am. Chem. Soc.* **1977**, *99*, 6405. (b) Reinhoudt, D. N.; den Hertog, H. J., Jr. *Bull. Soc. Chim. Belg.* **1988**, *97*, 645. (c) Dutton, P. J.; Fronczek, F. R.; Fyles T. M.; Gandour, R. D. *J. Am. Chem. Soc.* **1990**, *112*, 8984. (d) Dutton, P. J.; Fyles, T. M.; Suresh, V. V.; Fronczek, F. R.; Gandour, R. D. *Can. J. Chem.* **1993**, *71*, 239.

(14) van Eerden, J.; Skowronska-Ptasinska, M.; Grootenhuis, P. D. J.; Harkema, S.; Reinhoudt, D. N. *J. Am. Chem. Soc.* **1989**, *111*, 700.

(15) Olsher, U.; Frolow, F.; Bartsch, R. A.; Puglia, J. J.; Shoham, G. *J. Am. Chem. Soc.* **1989**, *111*, 9217.

0022-3263/94/1959-1694$04.50/0

only crown ether without such functional groups whose simple H_2O complex has been characterized by its crystal structure is a 22-crown-6 derived from two D-mannitol units,[16] in which the crown ether folds around the water in basket-like fashion.

In this paper, the synthesis, purification, and detailed characterization of 30-crown-10 (30C10), its tetrahydrate, and their X-ray crystal structures are reported. These X-ray crystal structural analyses of 30C10 represent the first such study of a large aliphatic crown ether macrocycle and the first structural determination of a hydrate derived from a simple aliphatic crown ether without a second complexing ion or molecule.

Results and Discussion

a. Synthesis of 30-Crown-10 (30C10). Large crown ethers are ideally suited for the synthesis of rotaxanes and polyrotaxanes. Polyrotaxanes are two-component systems in which macrocyclic species are threaded onto linear or cross-linked polymer backbones such that there is no covalent bond between the cyclic and the backbone polymer species.[17] The linear species may be end blocked using bulky groups[18] to prevent dethreading of the macrocycles. In the synthesis of rotaxanes and polyrotaxanes macrocycles containing more than 27 atoms are needed for significant threading to take place; to use them as solvents for polymerization we require large quantities of pure macrocycles.

Syntheses of large aliphatic crowns on less than a gram scale have been reported in the literature;[19,20] however, there is no mention of detailed characterization of the large crown ethers. Further, from the low melting points of the isolated macrocycles relative to those obtained by us in large-scale syntheses, it is doubtful that pure macrocycles were isolated by earlier workers.

The detailed synthetic and purification techniques utilized for higher homologous aliphatic crown ethers reported by us elsewhere[21] are similar to those used for 30C10. The method of synthesis of 30C10 consists of reaction of the (di)anion of hexa(ethylene glycol), formed by use of sodium hydride, with tetra(ethylene glycol) ditosylate in tetrahydrofuran at modest dilution (~0.1 M) at room temperature. Purification can be accomplished without resorting to expensive column chromatography by filtration through silica gel to remove glycols, followed by low-temperature recrystallizations. In this way >100 g of pure 30C10 can be made at a time.

b. Characterization of 30C10. Figure 1 shows the proton and carbon NMR spectra of 30C10. In the proton and carbon NMR spectra, 30C10 shows single peaks at 3.669 ppm [lit.[19] 3.67 ppm) and at 70.67 ppm (lit.[19] 70.55 ppm), respectively. A singlet in the proton NMR spectrum for the protons of the crown ether of 30C10·4H_2O appears at 3.672 ppm. 60-Crown-20, the major potential impurity, has proton and carbon resonances at 3.646 and 70.53 ppm, respectively;[21] Figure 1 indicates the high purity of the 30-crown-10. Chemical ionization mass spectral data show the protonated parent ion $(M + H)^+$ at $m/z = 441$. Infrared analyses show no detectable hydroxyl groups and a strong peak at 1135–1115 cm^{-1} for ether linkages.

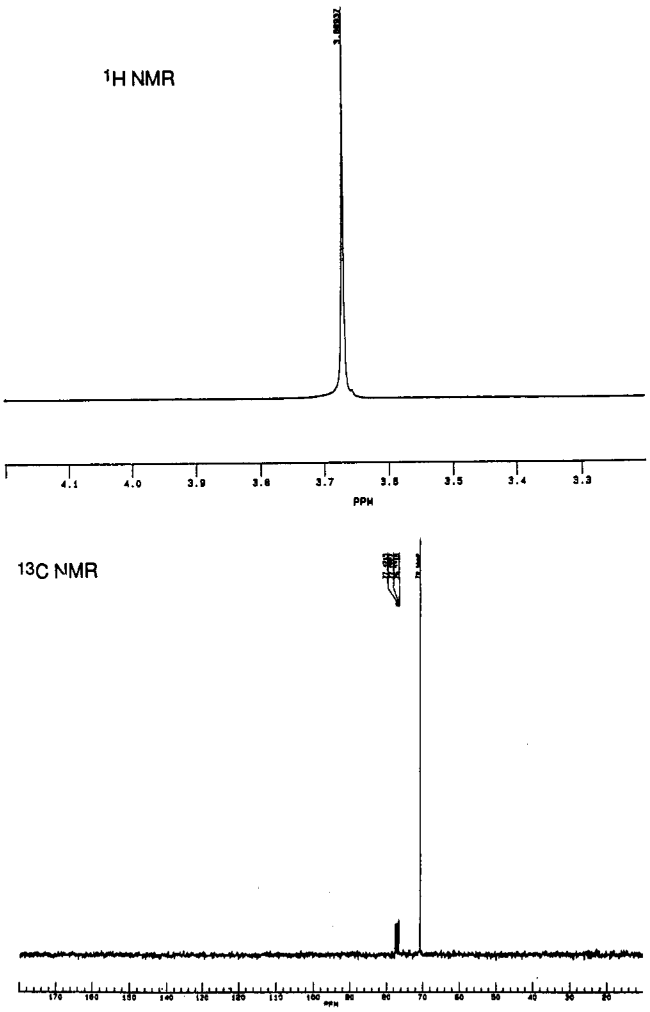
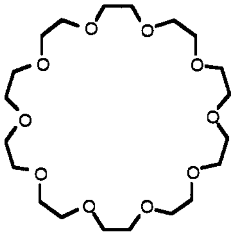


Figure 1. ^1H (270-MHz) and ^{13}C (100-MHz) NMR of 30C10; the peaks at 77 ppm are due to $CDCl_3$.



30C10

Figure 2 shows the DSC analysis of 30C10 (second scan) which reveals the glass transition temperature of −67.7 °C, crystallization temperature of −34.7 °C, and melting temperature of 47.1 °C. The melting point of 30C10 at a heating rate of 2.5 °C/min is 43.8 °C (DSC peak maximum). The capillary melting point is 43.1–45.3 °C (corrected). The 30C10·4H_2O has a capillary melting point of 46.0–48.0 °C (corrected). Chenevert et al.[19] report 30C10

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(16) Fuller, S. E.; Stoddart, J. F.; Williams, D. J. *Tetrahedron Lett.* **1982**, *23*, 1835.

(17) Gibson, H. W.; Bheda, M. C.; Engen, P. T.; Shen, Y. X.; Sze, J.; Wu, C.; Ward, T. C.; Lecavalier, P. R. *Makromol. Chem., Macromol. Symp.* **1991**, *42/43*, 395. Born M.; Ritter, H. *Makromol. Chem., Rapid Commun.* **1991**, *12*, 471. Gibson, H. W.; Engen, P. T.; Shen, Y. X.; Sze, J.; Lim, C.; Bheda, M.; Wu, C. *Makromol. Chem., Macromol. Symp.* **1992**, *54/55*, 519. Wenz G.; Keller, B. *Angew. Chem., Int. Ed. Engl.* **1992**, *31*, 197. Gibson, H. W.; Marand, H. *Adv. Mater.* **1993**, *5*, 11. Gibson, H. W.; Engen, P. T. *New J. Chem.*, **1993**, *17*, 723. Shen, Y. X.; Xie, D.; Gibson, H. W. *J. Am. Chem. Soc.* **1994**, *116*, 537.

(18) Gibson, H. W.; Lee, S.-H; Engen, P. T.; Lecavalier, P.; Sze, S.; Shen, Y. X.; Bheda, M. *J. Org. Chem.* **1993**, *58*, 3748.

(19) Chenevert R.; d'Astous, L. *J. Heterocycl. Chem.* **1986**, *23*, 1785.

(20) Vitali C. A.; Masci, B. *Tetrahedron* **1989**, *45*, 2201.

(21) Gibson, H. W.; Bheda, M. C.; Engen, P.; Shen, Y. X.; Liu, S.; Zhang, H.; Gibson, M. D.; Delaviz, Y.; Lee, S. H.; Wang, L.; Rancourt, J.; Taylor, L. T. *J. Org. Chem.*, submitted.

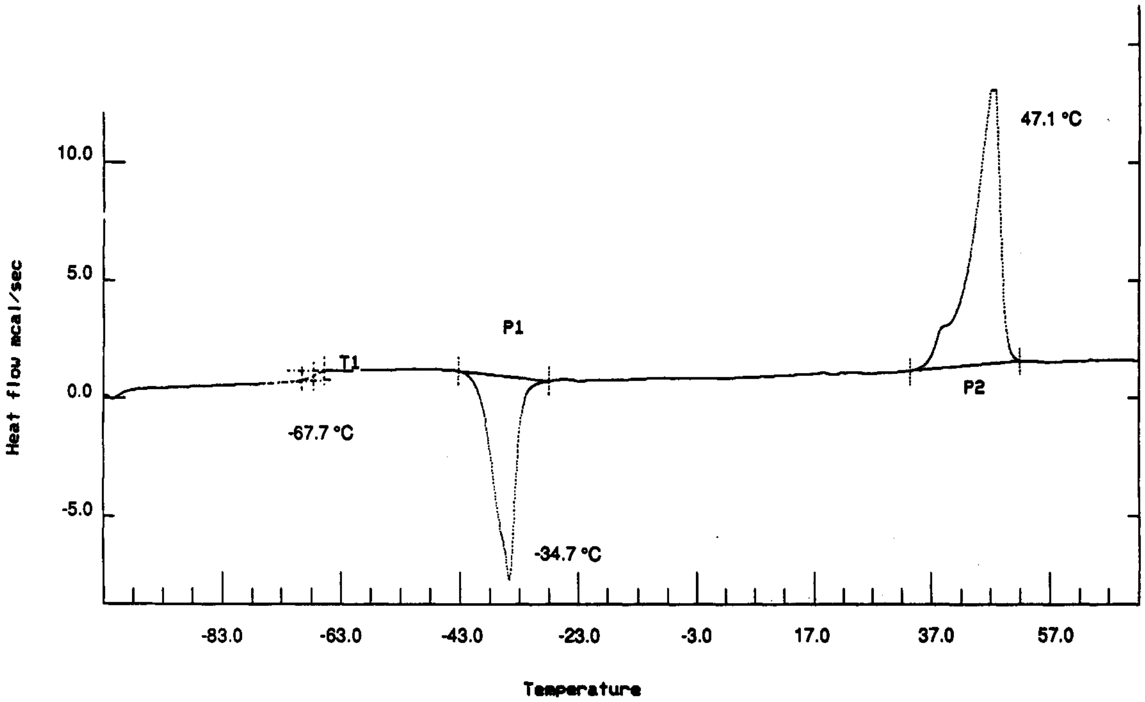

Figure 2. DSC trace (10 °C/min) of 30C10 that had been rapidly cooled from the melt.

as an oil; Vitali et al.[20] report purification of 30C10 by distillation at 210 °C at 0.1 Torr, followed by recrystallization to obtain a product with mp 35.5–36.8 °C.

c. Molecular Structures: Experiment and Modeling. Anhydrous crystals of 30C10 for X-ray structural analysis were grown from hexanes under nitrogen. Crystals of 30C10 tetrahydrate were grown from dichloromethane/hexanes (30:70) solution by slow evaporation, while exposed to air. The X-ray analysis[22] shows that anhydrous 30C10 forms orthorhombic crystals, belonging to space group *Pbca*, having unit-cell parameters of a = 8.606(1) Å, b = 8.260(1) Å, and c = 33.310(4) Å (calculated density = 1.236 g/cm^3 for Z = 4) with only half of the molecule comprising the asymmetric unit and the entire structure being generated by an inversion operation. The 30C10·4H_2O crystal is monoclinic, belonging to the space group $P2_1/c$ and having unit-cell parameters of a = 8.332(4) Å, b = 9.083(2) Å, c = 18.665(5) Å, and b = 90.24(3)° (calculated density = 1.205 g/cm^3 for Z = 2), with only half of the crown (and two of the water molecules) comprising the asymmetric unit and the entire structure being generated by an inversion operation.[32]

The 30C10 molecule in the anhydrous crystal is relatively flat as can be seen in Figure 3, although the ends are slightly puckered. From the best calculated plane through the entire molecule (ignoring H atoms) the mean deviation of C and O atoms is only 0.22 Å. The atoms with the largest deviations are C10 (and C10a) with a deviation of 0.44 Å and O5 (and O5a) with a deviation of 0.42 Å. These atoms are near the "ends" of the molecule where the chain bends around, so it is not surprising that these show the greatest deviation from the plane. The C(4)–C(4a) distance is 3.9 Å; the O(5)–O(5a) distance is 13.6 Å (atomic center to atomic center distances). H_4 and H_{4a} are within ~0.2 Å, taking into account the full van der Waals radii. Therefore, as shown in Figure 3C, this conformation has virtually no cavity! In fact 18-crown-6 (Figure 4) has a larger "cavity" in its crystal.[23] The C–C bonds in the three oxyethylene units from O(1) up to O(4) are all in anti conformations (-OC–CO- torsional angles 167°–179°, Table 1), while the C–C bonds of the other two oxyethylene units from O(4) to O(1A) have gauche (–) (g–) conformations (torsional angles –66° and –75°). The CC–OC torsional angles from O(1) to O(5) are all anti, while that involving O(1A) is gauche. The five CO–CC torsional angles are all anti. The other five oxyethylene units are the same due to the symmetry of the molecule. The first three oxyethylene units described above behave as if they are a part of a linear chain of poly(ethylene oxide) and are in the anti conformation with respect to the C–O bonds. In 18C6 the C–C torsional angles are in order g$^+$g$^-$ag$^-$g$^+$a and the C–O dihedrals are g$^-$aaaaag$^+$aaaaa.[5,23]

In the crystal of 30C10 tetrahydrate, four molecules of water are bound to each other as well as to four oxygen atoms of the crown ether (Figure 5). Table 2 lists the distances between the hydrogen bonding oxygens and hydrogens. The hydrogen atoms on the water molecules were located from electron difference maps, but the quality of the data did not permit refinement. Because of this the hydrogen atom positions cannot be used with a high level of confidence. However, past studies of hydrogen bonding typically show that the O_{donor}--H--$O_{acceptor}$ angle is 165 ± 15°. Therefore, $O_{acceptor}$--O_{donor}--$O_{acceptor}$ angles can be used to give a good indication of the H–O–H angle. In addition, O_{donor}--$O_{acceptor}$ distances can also yield information about the presence of hydrogen bonding; distances on the order of 3 Å or less are clear indicators of hydrogen bonding. Examination of the 30C10 tetrahydrate structure yields the following $O_{acceptor}$--O_{donor}--$O_{acceptor}$ angles (i.e., close to the tetrahedral bonding angle) O2w–O1w–O2wa 111.2°

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[22] The X-ray crystal structures were solved by direct methods and refined by the full-matrix least-squares procedure to R = 0.0427, R_w = 0.0501 for 1644 independent observed reflections [$F > 4s(F)$] for anhydrous 30C10 and R = 0.0573, R_w = 0.0701 for 1370 independent observed reflections [$F > 4s(F)$] for 30C10 tetrahydrate.

[23] Groth, P. *Acta Chem. Scand.* **1978**, *A32*, 279. Dunitz, J. D.; Seiler, P. *Acta Crystallogr.*, **1974**, *B30*, 2739.

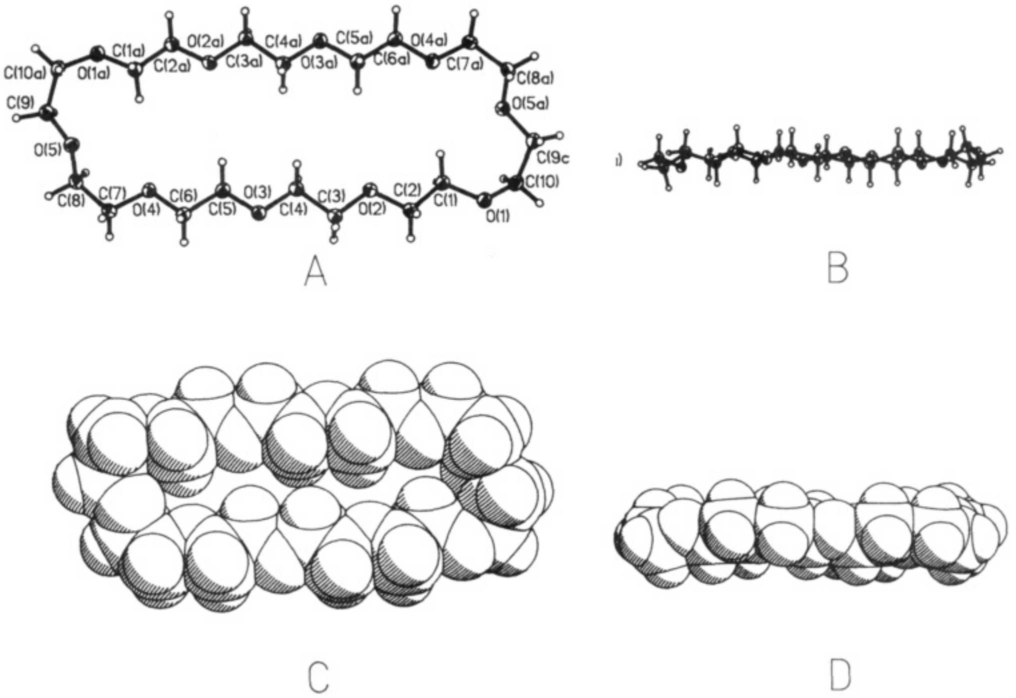

Figure 3. Molecular structure of 30C10 as deduced from the X-ray crystal structure: A and B, ball and stick representations of top and side views, respectively; C and D, space-filling versions with full van der Waals radii for top and side views, respectively.

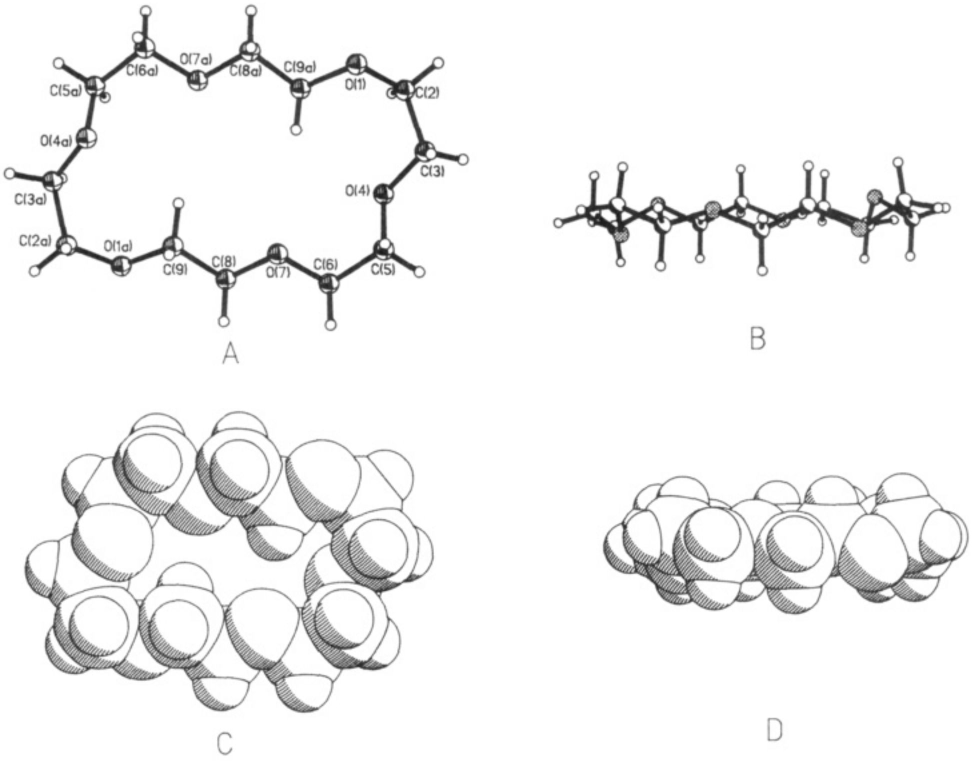

Figure 4. Molecular structure of 18C6 constructed from experimental coordinates given in ref 23: A and B, ball and stick representations of top and side views, respectively; C and D, space-filling versions with full van der Waals radii for top and side views, respectively.

and O5–O2w–O3 104.6°. Moreover, as Table 2 shows, the O_{donor}--$O_{acceptor}$ distances are all less than 3.1Å with the exception of O1w–O1wa. The relative locations of the four oxygen atoms of the crown ether and the four water oxygen atoms are shown in Figure 5E. Similar clusters have been reported in ice.[24]

Due to the inclusion of water molecules, the cavity of the tetrahydrate is wide open as compared to the anhydrous structure. The dimensions of the cavity are 7.5 Å (C(2)–C(2A)) × 11.4 Å (O(4)–O(4A)). In contrast to the anhydrous crystal, the hydrated 30C10 is not flat, but instead has a sigmoidal shape when viewed from the side (Figure 5B,D). Calculations of the best plane through the entire molecule (again excluding hydrogen atoms) show a mean deviation from the plane of 0.68 Å. The most significant deviations are much larger for the hydrated

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[24] Morse, M. D.; Rice, S. A. *J. Chem. Phys.* **1982**, *76*, 650.

Table 1. Torsional Angles (deg) in 30C10 and 30C10·4H$_2$O

	30C10	30C10·4H$_2$O
O(1)C(1)–C(2)O(2)	–174.9	177.4
C(1)C(2)–O(2)C(3)	169.1	167.2
C(2)O(2)–C(3)C(4)	174.6	–177.0
O(2)C(3)–C(4)O(3)	179.8	–70.0
C(3)C(4)–O(3)C(5)	–172.1	178.5
C(4)O(3)–C(5)C(6)	–171.2	175.4
O(3)C(5)–C(6)O(4)	–179.0	–70.4
C(5)C(6)–O(4)C(7)	177.0	–175.0
C(6)O(4)–C(7)C(8)	174.7	–178.8
O(4)C(7)–C(8)O(5)	–66.2	–66.6
C(7)C(8)–O(5)C(9)	169.1	176.6
C(8)O(5)–C(9)C(10A)	–156.3	–178.4
O(5)C(9)–C(10A)O(1A)	–75.4	–65.9
C(9)C(10A)–O(1A)C(1A)	–80.8	179.4
C(10A)O(1A)–C(1A)C(2A)	–167.6	–170.3

Table 2. Distances (Å) between the Hydrogen–Bonding Oxygens and Hydrogens

water cluster	H1w–O2w and H1wa–O2wa	1.93
	H2wa–O2w and H2w–O1wa	1.62
	O1w–O2w and O1wa–O2wa	2.92
	O1w–O2wa and O1wa–O2w	3.04
	O1w–O1wa	3.37
water-crown	H4w–O5a and H4wa–O5	2.41
	H3w–O3a and H3wa–O3	2.18
	O2w–O3 and O2wa–O3a	2.97
	O2w–O5 and O2wa–O5a	3.09

form than for the anhydrous form with the largest deviations being approximately 1.4 Å.

Conformational analysis of 30C10 tetrahydrate (Table 1) shows that only two of the 10 oxyethylene units are in anti conformations about OC–CO linkages (torsional angle ±177.4°), while the other eight OC–CO units have g conformations, torsional angles ranging from 70° to 66°. Here, again, all the CO–CC and CC–OC linkages are in the anti conformation (167°–179.4°). The larger cavity size of the tetrahydrate (Figure 5C) compared to anhydrous 30C10 (Figure 3C) is due to the larger number of gauche C–C conformations in the tetrahydrate.

The modeling efforts were directed toward finding an energy-minimized conformer and comparing it to the single-crystal structure from X-ray data. To perform this task, we constructed a single 30C10 molecule using the organic builder function; the observed crystal structure was *not* used as input. We performed a molecular dynamics run on this molecule at a temperature of 1000 K for 10 ps in order to cross energy barriers and sample a broader conformational domain. From such a run, we chose 10 low-energy conformers for further analysis. These conformers were then subjected to a cycle of annealing dynamics between 308 and 288 K followed by an energy minimization.

In all the above calculations the Drieding II force field[25] was used. The energy minimization was terminated when the total root mean square (rms) of the force between atoms in the sample was less than 0.01 kcal/mol/Å. We used a conjugate-gradient method for the minimization routine with a cutoff radius of 9.0 Å. We performed a similar analysis for 30C10·4H$_2$O. In this case four water molecules were added to the initial structure of a crown ether molecule. For the hydrate the hydrogen-bonding potential included a 10–12 Lennard–Jones-type potential with a distance cutoff equal to 5.0 Å and angle of 180 ± 30°.

The experimental X-ray fractional coordinate data for 30C10 including the space group were used to construct the three-dimensional crystal structures using the builder function. The predicted structure is almost exact compared to the crystal geometry as can be seen in Table 3; any small deviations fall within the experimental errors. The energy of the model conformer is 51.1 kcal/mol with a cavity of 3.98 (C(4)–C(4a)) × 13.84 Å (O(5)–O(5a)). The collapsed nature of this structure resembles the collapsed structure (C_i) observed[23] and calculated[26] for 18-crown-6, which is shown in Figure 4. To our knowledge 18C6 was the largest simple uncomplexed completely aliphatic crown whose X-ray structure had been determined prior to the present work.

Figure 6 shows the predicted hydrate structure, which may be compared to the experimentally determined structure of Figure 5. The error in the predicted structure is noticeable, especially with respect to the locations of the four water molecules and hence the hydrogen bonding. While the experimental evidence points to a symmetric arrangement of the water molecules within the nonplanar crown ether molecule, the predicted structure indicates an unsymmetrical structure. However, the calculations do correctly reproduce the experimentally observed sigmoidal shape of the crown; compare Figures 5B,D and 6B,D. The rms errors for the calculated 30C10·4H$_2$O structure in terms of the bond lengths, angles, and torsions are presented in Table 4. The total energy of the model system is 5.0 kcal/mol. This low energy includes the attractive hydrogen bonding energy of –52.8 kcal/mol. The deviations in the geometry of the predicted structure may be due to high hydrogen bonding energy and/or to poor sampling of the conformers. Further investigations should include an analysis of the sampled conformers as representative structures of a proper statistical ensemble.

Thus, for 30C10 the calculated and observed structures resemble the calculated[26] and observed[23] C_i structure of 18C6. The C–C dihedrals are $g^+g^-ag^-g^+a$ for 18C6 (23) and $g^+g^+aaag^-g^-aaa$ for 30C10; the additional anti conformations account for the longer sides of 30C10. In complexes of 18C6 with hydrogen-bonding guests, calculations and experiment show that the crown ether adopts a D_{3d} (nearly circular) structure, in which all the O–C dihedrals are anti and the C–C dihedrals are gauche;[6,26] calculations further indicate that the D_{3d} conformation is more stable than C_i in polar solvents at low temperature,[26] as shown experimentally.[27] In the 30C10 tetrahydrate similarly the O–C bond conformations are anti and the C–C conformations are predominantly gauche, $ag^-g^-g^-g^-ag^+g^+g^+g^+$, allowing the cavity to expand in order to accommodate the four guest molecules, but not so far as to assume D_{3d} symmetry, which would prevent optimal H bonding.

Chakraborty and Ha have reported Monte Carlo simulations of conformations adopted by macrocyclic crown ethers in polar and nonpolar solvents at various temperatures.[28] The authors report that the –OC–CO– torsional angles of the crown molecules in water are predominantly in gauche conformations (45°–90°). At higher tempera-

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[25] Mayo, S. L.; Olafson, B. D.; Goddard, W. A., III. *J. Phys. Chem.* **1990**, *94*, 8897.

[26] Bovill, M. J.; Chadwick, D. J.; Sutherland, I. O.; Watkin, D. *J. Chem. Soc., Perkin Trans. 2* **1980**, 1529. Wipff, G.; Weiner, P.; Kollman, *J. Am. Chem. Soc.* **1982**, *104*, 3249.

[27] Dale, J. *Isr. J. Chem.*, **1980**, *20*, 3 and references cited therein.

[28] Ha, Y. K.; Chakraborty, A. K. *J. Phys. Chem.* **1991**, *95*, 10781. Ha, Y. K.; Chakraborty, A. K. *J. Phys. Chem.* **1993**, *97*, 11291.

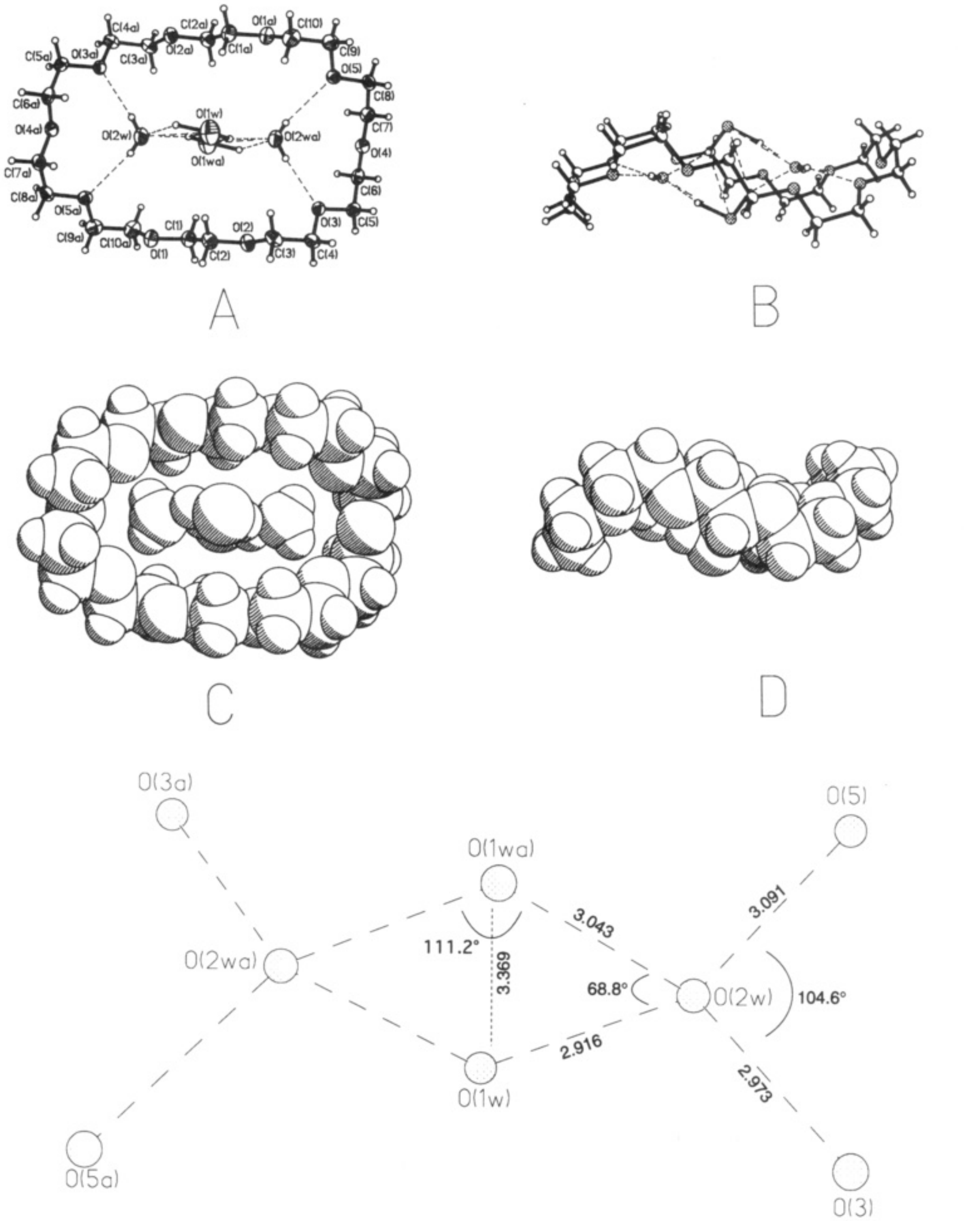

Figure 5. Molecular structure of 30C10·4H_2O as deduced from the X-ray crystal structure: A and B, ball and stick representations of top and side views, respectively; C and D, space-filling versions with full van der Waals radii for top and side views, respectively; bottom, partial structure showing locations of the oxygen atoms of the water molecules (O1w, O2w, O1wa, O2wa) and the four hydrogen-bonded crown ether oxygen atoms (O3, O5, O3a, O5a).

Table 3. Comparative Error Analysis of the Calculated Structure Relative to the Crystal Structure of 30C10[a]

	no.	rms	avg diff	max diff	sum of squares of diff
coordinates (Å)	30	0.193	0.178	0.295	1.113
bonds (Å)	30	0.040	0.037	0.063	0.048
angles (deg)	30	1.104	0.631	1.985	36.58
torsions (deg)	30	7.485	1.071	−17.55	1680.6

[a] Hydrogens were excluded from the analysis.

Table 4. Comparative Error Analysis of the Calculated Structure Relative to the Crystal Structure of 30C10·4H_2O[a]

	no.	rms	avg diff	max diff	sum of squares of diff
coordinates (Å)	42	0.824	0.629	1.891	28.507
bond lengths (Å)	38	0.134	−0.020	0.411	0.682
bond angles (deg)	34	3.946	0.585	15.191	529.30
torsions (deg)	30	8.680	3.655	17.281	2260.18

[a] Hydrogens from the crown ether macrocycles were not included in this analysis. Hydrogens in the water molecule were included, however.

tures, the distribution of the torsional angles is broadened, and the effect is more pronounced in nonpolar solvents than in polar solvents. In nonpolar solvents the fraction of gauche conformations increases with temperature. The authors predicted the cavities of large crowns to be more open in polar solvents such as water where the cavity is circular. In nonpolar solvents such as carbon tetrachloride the crown ethers are less symmetric; this causes the cavity to contract and be shaped like an ellipse.

The results of Monte Carlo simulations in solution are corroborated by the results of our solid-state X-ray crystal structural studies. The –OC–CO– conformations are

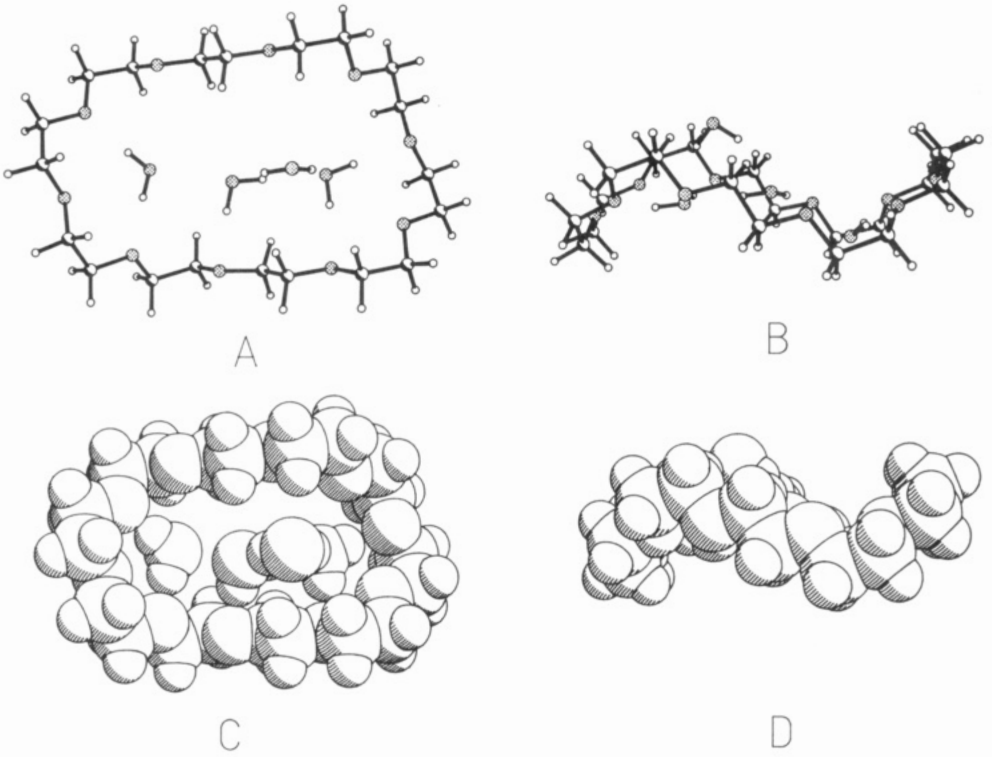

Figure 6. Calculated structure of 30C10·4H_2O: A and B, ball and stick representations of top and side views, respectively; C and D, space-filling versions with full van der Waals radii for top and side views, respectively.

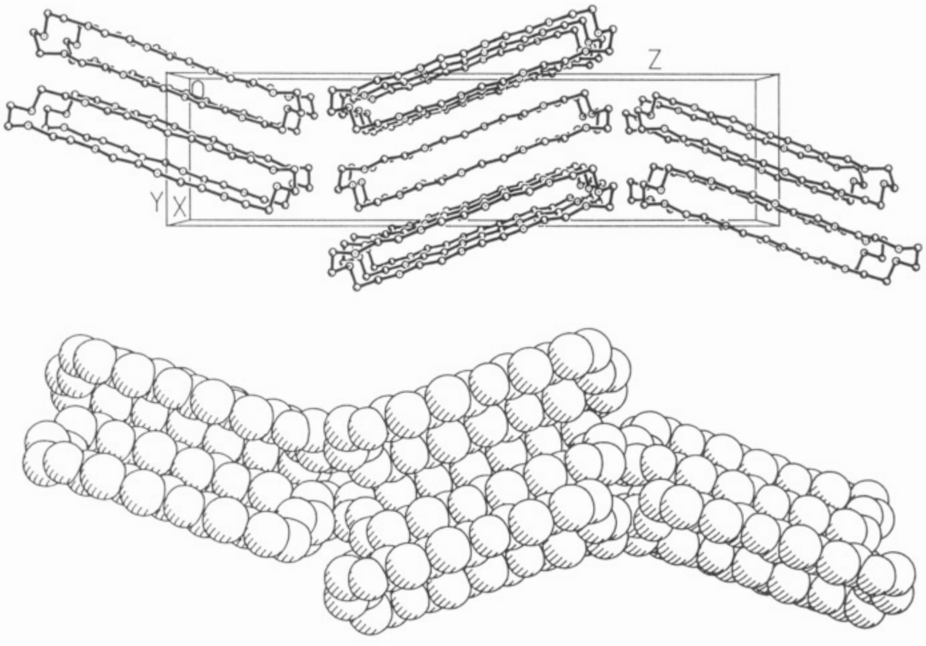

Figure 7. Three-dimensional crystal lattice of 30C10 derived by X-ray diffraction (hydrogens not shown). Unit cell: *Pbca* (orthorhombic), a = 8.606(1) Å, b = 8.260(1) Å, c = 33.310(4) Å. Top: ball and stick representation. Bottom: space-filling version with full van der Waals radii.

predominantly gauche when water molecules are hydrogen bonded to the crown, and that in turn opens the cavity of the macrocycle. Our experimental data further suggest that threading could be optimized for polar monomers and polymers in polar media, while the converse may be true for nonpolar monomers and polymers and may favor threading at higher temperatures.

c. Three-Dimensional Crystal Lattice Studies. The arrangement of the crown ether molecules in a three-dimensional crystal lattice was of specific interest to us because in polyrotaxanes the threaded crown ether molecules may orient themselves in various ways in order to crystallize. This may help explain the solid-state structure of polyrotaxanes in which the macrocyclic crown ether crystallizes.[17] Thus, atomic coordinates obtained from the X-ray crystal data were utilized to generate three-dimensional packing diagrams.

Figure 7 shows the arrangement of crown ether molecules (hydrogens omitted) in a matrix of unit cells of 30C10. In a unit cell, the arrangement of crown ether molecules with respect to each other is according to the space group *Pbca*. The crown ether molecules in the stacks are parallel to

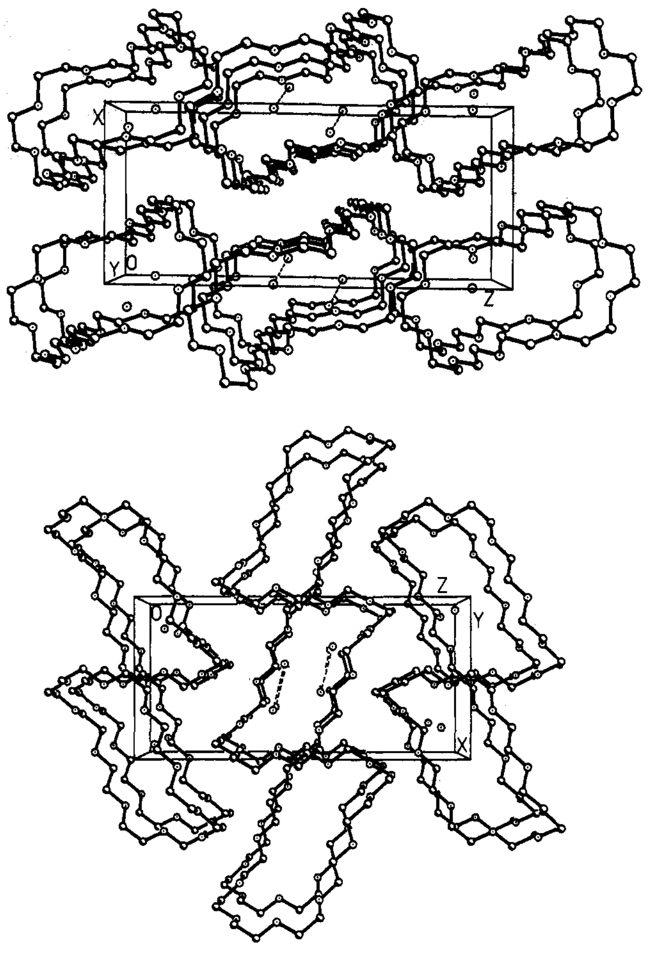

Figure 8. Three-dimensional crystal lattice of 30C10·4H_2O in ball and stick form derived by X-ray diffraction (hydrogens not shown). Unit cell: $P2_1/c$ (monoclinic), a = 8.332(4) Å, b = 9.083(2) Å, c = 18.665(5) Å, b = 90.24°. Top: view along y- or b-direction. Bottom: along x- or a-direction.

each other, and the distance between them is 8.26 Å. The crown ether molecules that comprise the adjacent stacks are interleaved along the long sides of the cavities; the distance between the overlapping long sides is 4.13 Å. The arrangement of three of the oxyethylene repeat units of the overlapped long sides is zig-zag (anti) and out of register to avoid steric crowding. Further, the shortest distance between crown ether molecules in nonoverlapping stacks is 4.06 Å. As can be seen in Figure 7 (bottom), there are no channels in these crystals.

The three-dimensional structure of the crystal lattice of 30C10·4H_2O is shown in Figure 8. In a unit cell, the arrangement of crown ether molecules with respect to each other is according to the space group $P2_1/c$. Again, the crown ether molecules are stacked. The microchannels formed by the stacking of the cavities of the crown ether molecules are occupied by the four water molecules. In this stacked structure, the four molecules of water bound to a given crown molecule are isolated from the other water molecules, and there is no possibility of hydrogen bonding with water in adjacent cavities or with other crowns. In Figure 8, some parts of the crown molecules appear to be interleaved stacks; however, this is not the case when seen from other angles. In fact there are two orthogonal sets of microchannels as can be seen from Figure 8 (top) and 8 (bottom). Figure 9 shows one stack of water and crown ether molecules. The distance between crown ether and the water molecules (O–O and H–H) in the respective stacks is 8.33 Å.

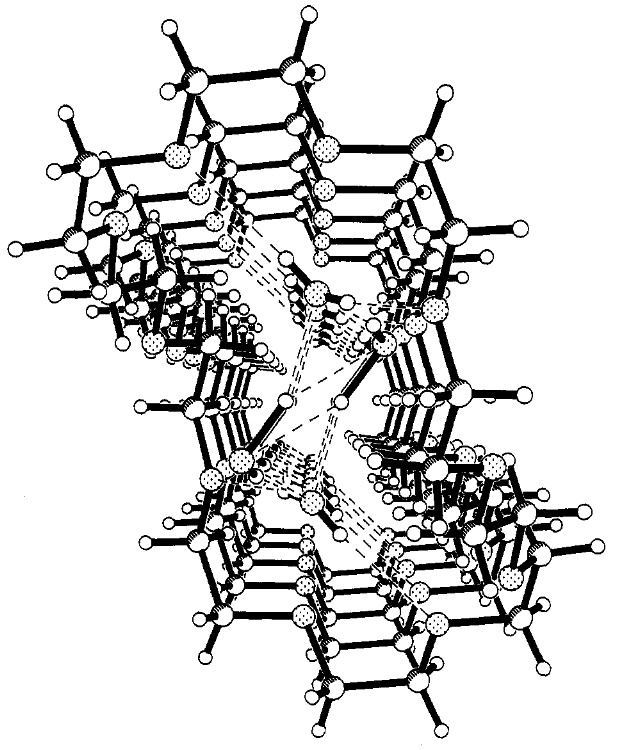

Figure 9. Stacks of water and crown ether molecules with hydrogens seen in three-dimensional crystal lattice of 30C10·4H_2O as viewed along the y-axis as in Figure 8 (top).

Such channeled and microporous structures are of great interest from the viewpoint of molecular filtration devices or selective and efficient chemical reactions utilizing cavities, pores, and channels.[29] Inorganic systems such as zeolites, metallosilicates, metalloaluminates, aluminophosphates, reduced molybdenum phosphates, and other systems have gained prominence in this field. One example of such a structure is cacoxenite in which molecules form 14.2-Å diameter channels which are mainly filled with water.[29]

Owing to its macrocyclic nature, and because the cavities remain intact, 30C10·4H_2O represents an analog to the inorganic microporous crystals. Further, the formation of channels is due to stacking of internal cavities of 30C10 molecules and not due to the voids in the three-dimensional packing of the molecules as seen in many inorganic microporous structures. The utility of such organic microporous crystals is worth exploring. Similar channel structures may also be present in the crystal lattices of the higher homologues of 30C10. Attempts to characterize higher homologues of 30C10 by X-ray crystallography are under way.

Conclusions

This study provides a unique perspective on the ordering of large cyclic molecules in three-dimensions. The X-ray crystal structural studies show that conformations of the oxyethylene units and thus the cavity size of 30C10 are significantly affected by the presence of bound water. The cavities of the crown ether molecules in 30C10·4H_2O form channels when stacked in the crystal lattice; the water

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(29) Haushalter, R. C.; Mundi, L. A. *Chem. Mater.* **1992**, *4*, 31 and references cited therein.

molecules occupy the channels. These X-ray crystal structural analyses of 30C10 represent the first such study of a large aliphatic crown ether macrocycle. The X-ray structure of the tetrahydrate is the first for a simple crown ether without other guest species.

Experimental Section

Melting points were taken in capillary tubes and have been corrected. DSC data were obtained at a scan rate of 10 °C/min. Proton and carbon NMR spectra were obtained on a 270-MHz spectrometer using deuterated chloroform solutions with tetramethylsilane as an internal standard. FTIR spectra were obtained with KBr pellets. X-ray crystallographic data were obtained using a Seimens R_3MV diffractometer and the structures solved using SHELXTL PLUS software. Mass spectral data were obtained using an analytical mass spectrometer. Molecular simulations and the three-dimensional crystal lattice studies were done on the Stardent 3000/750 work station with a G3 Graphics device using Molecular Simulations Inc. Polygraf software (v. 3.2). The distances reported here are from atomic center to atomic center.

30-Crown-10. In a 5 L, three-neck flask equipped with a mechanical stirrer was placed 2.5 L of dry THF under nitrogen, 44.01 g of 80% NaH (1.53 mol) was carefully added, and the suspension was stirred for 20 min. To this suspension was added 84.7 g (0.3 mol) of hexa(ethylene glycol)[30] dropwise over a period of 2–3 h followed by addition of 155.0 g (0.308 mol) of tetra(ethylene glycol) ditosylate[31] in 300 mL of THF over a period of 4–5 h. After the addition was complete, the reaction mixture was stirred for 56 h at room temperature. The reaction was terminated by very slow addition of 100 mL of water. Three such reactions were done, and the combined crude reaction product (about 400 g) in dichloromethane was filtered through a 14- × 1-in. silica gel (ca. 300 g) column to remove linear glycols. After removal of dichloromethane, the product (301 g) was treated with 50:50 water/ethanol to remove oil (from sodium hydride) and unreacted tetra(ethylene glycol) ditosylate, which separated as a separate phase. Solvent removal afforded 261.4 g (65%) of product (mainly a mixture of crown ethers). 30C10 was separated by recrystallization from 75:25 CCl_4/petroleum ether (5–8% solution) at −20 °C. 30C10 remains in solution while 60C20 separates as a solid. A 30C10 fraction (93 g) and 165 g of 60C20 fraction were isolated. The 30C10 fraction was further purified by dissolving it in CH_2Cl_2/hexanes (40:60) and cooling it to −20 °C. The crystals were isolated by decanting the mother liquor and immediately removing the traces of solvents under vacuum. Upon drying, the 30C10 crystals collapsed, and white powder was obtained (78.5 g). An additional ~30 g of pure 30C10 was recovered from the 60C20 fraction, for a total 28% yield. Another method that works well in the separation of 30C10 and 60C20 is extraction with hot hexanes. 30C10 is soluble in hot hexanes while 60C20 is not; thus, very pure 30C10 was obtained by just a few extractions of the crude mixture.

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(30) Bartsch, R. A.; Cason, C. V.; Czech, B. P. *J. Org. Chem.* **1989**, *54*, 857.

(31) Ouchi, M.; Inoue, Y.; Kanzaki, T.; Hakushi, T. *J. Org. Chem.*, **1984**, *49*, 1408.

(32) The authors have deposited atomic coordinates for 30-crown-10 tetrahydrate and anhydrous 30-crown-10 with the Cambridge Crystallographic Data Centre. The coordinates can be obtained, on request, from the Director, Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge, CB2 1EZ, UK.